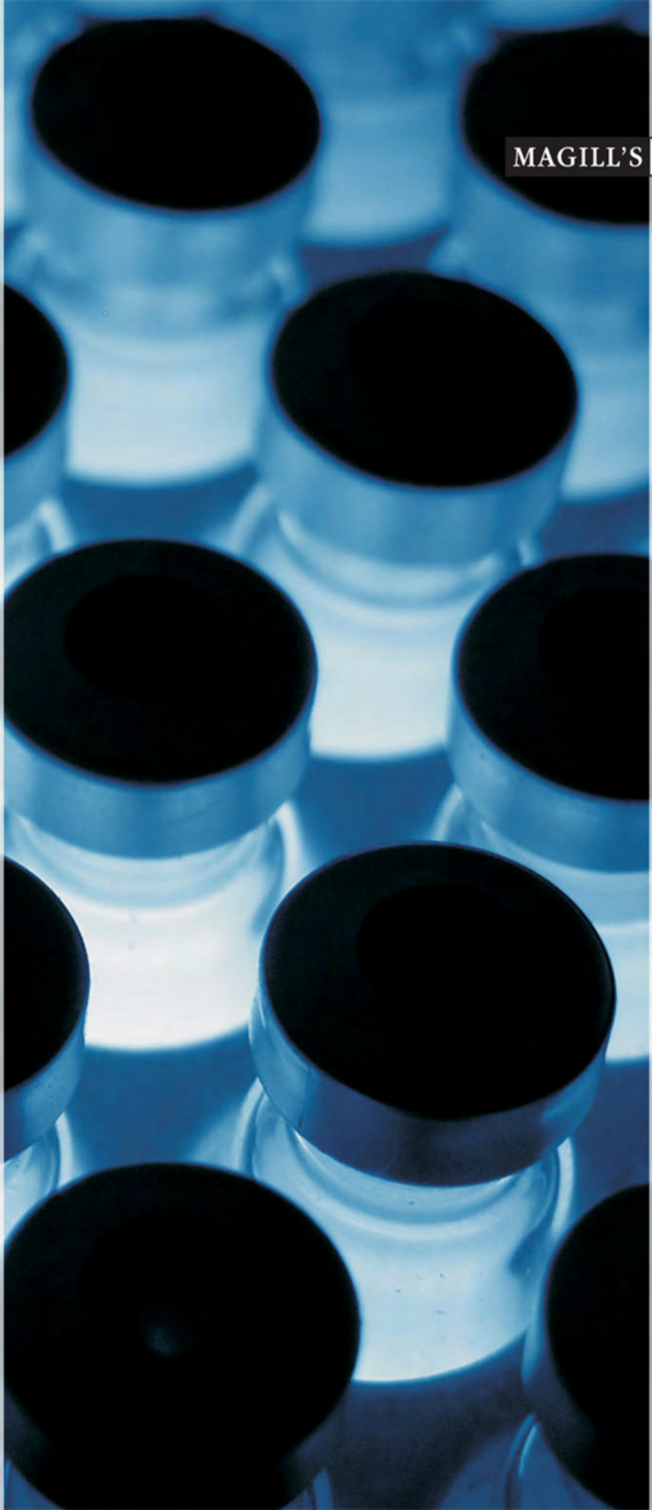
MAGILL'S CHOICE

Science and Scientists



SCIENCE
AND
SCIENTISTS

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SCIENCE AND SCIENTISTS

Volume 1

Abstract Algebra – Global Warming

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PUBLISHER'S NOTE

Lucan's famous dictum that those standing on the shoulders of giants see farther than the giants themselves applies to no human endeavor more thoroughly than to the "pure" sciences: astronomy, chemistry, biology, geology, mathematics, physics, and the many subdisciplines they have spawned. The three volumes of *Science and Scientists* documents 245 of the most important breakthroughs in the history of science, cross-referenced to link those that built on others, from ancient times to the present day. These essays are accompanied by biographical sidebars on many of the giants behind the discoveries, as well as charts and schematics illustrating many of the basic concepts.

The disciplines covered here are broad, including Anthropology, Archaeology, Astronomy and Cosmology, Biology, Chemistry, Computer Science, Earth Science, Environmental Science, Evolution, Genetics, Mathematics, Medicine, Meteorology, Methods, Paleontology, Physics, Psychology, and Space Science. Arranged alphabetically, these essays address the most important breakthroughs in these fields, ranging from Abstract Algebra to Quantum Mechanics, from the Big Bang to X-Ray Astronomy, from Antisepsis to Viruses.

Accompanying the essays are 125 sidebars highlighting the scientists and their accomplishments. An additional 62 charts, diagrams, and drawings illustrate the scientific concepts presented. It is important to note that technological advances and inventions—such as the telephone, the light bulb, and the airplane—are not addressed here but are covered in the companion Magill's Choice set *Inventions and Inventors* (2 vols., 2002). However, a few "crossover" achievements—such as the Personal Computer, the Internet, and Vaccination—are included in these pages for having had as great an impact on the "pure" sciences as on everyday life. The core achievements in space science also appear here, from the Apollo Moon landing to the International Space Station.

Each essay opens with a brief definition of the topic and a summary of its significance, followed by a list of the central scientific figures. The text of each essay is broken into sections with concise subheads. "See also" cross-references to other essays in these volumes follow, and each essay ends with a listing of core resources for "Further Reading." All essays were written by scholars of history or the sciences.

At the end of the third volume students and general readers will find a list of the Nobel Prize winners in science (Chemistry, Medicine, and Physics) and a list of useful Web Sites. Indexes arrange the essays by Category, list Personages discussed, and end with a comprehensive Subject Index.

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SCIENCE AND SCIENTISTS

ABSTRACT ALGEBRA

THE SCIENCE: Ernst Steinitz's studies of the algebraic theory of mathematics provided the basic solution methods for polynomial roots, initiating the methodology and domain of abstract algebra.

THE SCIENTISTS:
Ernst Steinitz (1871-1928), German mathematician
Leopold Kronecker (1823-1891), German mathematician
Heinrich Weber (1842-1913), German mathematician
Kurt Hensel (1861-1941), German mathematician
Joseph Wedderburn (1882-1948), Scottish American mathematician
Emil Artin (1898-1962), French mathematician

NINETEENTH CENTURY BACKGROUND

Before 1900, algebra and most other mathematical disciplines focused almost exclusively on solving specific algebraic equations, employing only real, and less frequently complex, numbers in theoretical as well as practical endeavors. One result of the several movements contributing to the so-called abstract turn in twentieth century algebra was not only the much-increased technical economy through introduction of symbolic operations but also a notable increase in generality and scope.

Although the axiomatic foundationalism of David Hilbert is rightly recognized as contributing the motivation and methods to this generalization by outlining how many specific algebraic operations could be reconstructed for greater applicability using new abstract definitions of elementary concepts, the other "constructivist" approaches—of Henri-Léon Lebesgue, Leopold Kronecker, Heinrich Weber, and especially Ernst Steinitz—had an equally concrete impact on the redevelopment and extensions of modern algebra.

KRONECKER'S CONTRIBUTIONS

Kronecker had unique convictions about how questions on the foundations of mathematics should be treated in practice. In contrast to Richard Dedekind, Georg Cantor, and especially Karl Weierstrass, Kronecker believed that every mathematical definition must be framed so as to be tested by mathematical constructional proofs involving a finite number of steps, whether or not the definitions or constructions could be seen to apply to any given quantity. In the older view, solving an algebraic equation more or less amounted only to determining its roots tangibly via some formula or numerical approximation. In Kronecker's view, the problem of finding an algebraic solution in general was much more problematic in principle since Évariste Galois's discoveries about (in)solvability of quartic and higher-order polynomials. For Kronecker, it required constructions of "algorithms," which would allow computation of the roots of an algebraic equation or show why this would not be possible in any given case.

Group and Field Theory

The question of finding algebraic roots in general had been of fundamental import since the prior work of Galois, Niels Henrick Abel, and Carl Friedrich Gauss. In particular, these efforts led Abel and Sophus Lie to formulate the first ideas of what is now known as the "theory of groups." Later, Dedekind introduced the concept of "field" in the context of determining the conditions under which algebraic roots can be found. Kronecker was the first to employ the idea of fields to prove one of the basic theorems of modern algebra, which guarantees the existence of solution roots for a wider class of polynomials than previously considered.

The novelty of the field approach is seen from the introduction to Weber's contemporaneous paper "Die allgemeinen Grundlagen der Galois'chen Gleichungstheorie" (the general foundations of Galois theory). Weber first proved an important theorem stated by Kronecker, which relates the field of rational numbers to so-called cyclotomic, or Abelian, groups, a subsequently important area of the development field theory. Weber also established the notion of a "form field," being the field of all rational functions over a given base field F, as well as the crucial notion of the extension of an algebraic field. Although the main part of Weber's paper interprets the group of an algebraic equation as a group of permutations of the field of its algebraic coefficients, Weber's exposition is complicated by many elaborate and incomplete definitions, as well as a premature attempt to encompass all of algebra, instead of only polynomials. In his noted 1893 textbook on algebra, Weber calls $F(a)$ an algebraic field when a is the root of an equation with coefficients in F, equivalent to the definition given by Kronecker in terms of the "basis" set for $F(a)$ over a.

A central concern of Weber and other algebraists was that of extending the idea of absolute value, or valuation, beyond its traditional usage. For example, if F is the field of rational numbers, the ordinary absolute value $|a|$ is the valuation. The theory of general algebraic valuations was originated by Kronecker's student Kurt Hensel when he introduced the concept of p-adic numbers. In his paper "Über eine neue Begründung der algebraischen Zählen" (1899; on a new foundation of the algebraic numbers), Weierstrass's method of power-series representations for normal algebraic functions led Hensel to seek an analogous concept for the newer theory of algebraic numbers. If p is a fixed rational prime number and a is a rational number not zero, then a can be expressed uniquely in the form $a = (r/s)\,p^n$, where r and s are prime to p. If $\phi(a) = p^{-n}$, for $a \neq 0$, $\phi(a)$ is a valuation for the field of rational numbers. For every prime number p, there corresponds a number field that Hensel called the p-adic field, where every p-adic number can be represented by a sequence.

At this time, the American mathematician Joseph Wedderburn was independently considering similar problems. In 1905, he published "A Theorem on Finite Algebra," which proved effectively that every algebra with finite division is a field and that every field with a finite number of elements is commutative under multiplication, thus further explicating the close interrelations between groups and fields.

Steinitz on Algebraic Fields

Two years after Hensel's paper, Steinitz published his major report, "Algebraische Theorie der Körper" (1909; theory of algebraic fields), which took the field concepts of Kronecker, Weber, and Hensel much further. Steinitz's paper explicitly notes that it was principally Hensel's discovery of p-adic numbers that motivated his research on algebraic fields. In the early twentieth century, Hensel's p-adic numbers were considered (by the few mathematicians aware of them) to be totally new and atypical mathematical entities, whose place and status with respect to then-existing mathematics was not known. Largely as a response to the desire for a general, axiomatic, and abstract field theory into which p-adic number fields would also fit, Steinitz developed the first steps in laying the foundations for a general theory of algebraic fields.

Steinitz constructed the roots of algebraic equations with coefficients from an arbitrary field, in much the same fashion as the rational numbers are constructable from the integers ($a\,X = b$), or the complex numbers from real numbers ($x^2 = -1$). In particular, Steinitz focused on the specific question of the structure of what are called inseparable extension fields, which Weber had proposed but not clarified. Many other innovative but highly technical concepts, such as perfect and imperfect fields, were also given. Perhaps most important, Steinitz's paper sought to give a constructive definition to all prior definitions of fields, therein including the first systematic study of algebraic fields solely as "models" of field axioms. Steinitz showed that an algebraically closed field can be characterized completely by two invariant quantities: its so-called characteristic number and its transcendence degree. One of the prior field concepts was also clarified.

IMPACT

Although Steinitz announced further investigations—including applications of algebraic field theory to geometry and the theory of functions—they were never published. Nevertheless, the import and implications of Steinitz's paper were grasped quickly. It was soon realized that generalized algebraic concepts such as ring, group, and field are not merely formally analogous to their better-known specific counterparts in traditional algebra. In particular, it can be shown that many specific problems of multiplication and division involving polynomials can be simplified greatly by what is essentially the polynomial equivalent of the unique-factorization-theorem of algebra, developed directly from field theory in subsequent studies.

In 1913, the concept of valuation was extended to include the field of complex numbers. An American algebraist, Leonard Dickson (1874-1957), further generalized these results to groups over arbitrary finite fields. Perhaps most notably, the French and German mathematicians Emil Artin and Otto Schreier in 1926 published a review paper, which in pointing out pathways in the future development of abstract algebra, proposed a program to include all of extant algebra in the abstract framework of Steinitz. In 1927, Artin introduced the notion of an ordered field, with the important if difficult conceptual result that mathematical order can be reduced operationally to mathematical computation. This paper also extended Steinitz's field theory into the area of mathematical analysis, which included the first proof for one of Hilbert's twenty-three famous problems, using the theory of real number fields.

As noted by historians of mathematics, further recognition and adoption of the growing body of work around Steinitz's original publication continued. Major texts on modern algebra, such as that by Bartel Leendert van der Waerden in 1932, already contained substantial treatment of Steinitz's key ideas. As later pointed out by the "structuralist" mathematicians of the French Nicolas Bourbaki group, the natural boundaries between algebra and other mathematical disciplines are not so much ones of substance or content, as of approach and method, resulting largely from the revolutionary efforts of Steinitz and others such as Emmy Noether. Thus, the theory of algebraic fields after the 1960's is most frequently presented together with the theory of rings and ideals in most textbooks.

The theory of algebraic fields is not only an abstract endeavor but also, since the late 1940's, has proven its utility in providing practical computational tools for many specific problems in geometry, number theory, the theory of codes, and data encryption and cryptology. In particular, the usefulness of algebraic field theory in the areas of polynomial factonization and combinatorics on digital computers has led directly to code-solving hardware and software such as maximal length shift registers and signature sequences, as well as error-correcting codes. Together with Noether's theory of rings and ideals, Steinitz's field theory is at once a major demarcation between traditional and modern theory of algebra and a strong link connecting diverse areas of contemporary pure and applied mathematics.

See also Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Gerardo G. Tango*

AIDS

THE SCIENCE: The AIDS epidemic began to gain attention in 1981, when the U.S. Centers for Disease Control first cited cases of pneumocystis pneumonia in various American cities.

THE SCIENTISTS:

James W. Curran (b. 1944), epidemiologist

Joel Weisman (b. 1928), physician who, with Dr. Michael Gottlieb, identified the first cases of AIDS

Grete Rask (d. 1977), Danish surgeon practicing in Zaire who became the first documented European to be infected with the AIDS virus

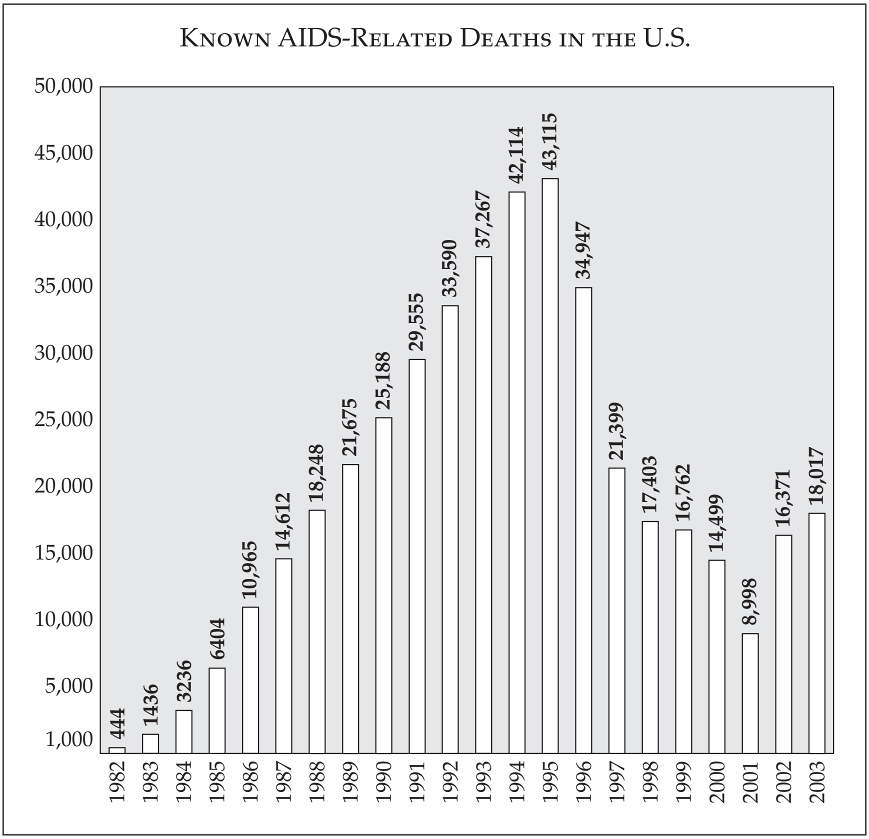
A Mysterious Affliction

In 1976, people in a village along the Ebola River on the border of the Sudan and Zaire (later renamed Congo) experienced a virulent and horrifying disease that came suddenly. A trader from the nearby village of Enzara, suffering from fever and profuse and uncontrollable bleeding, was admitted to the teaching hospitals in Moridi. Within days of his admission, 40 percent of the nurses and several doctors were stricken. By the time the World Health Organization officials and U.S. Centers for Disease Control (CDC) staff arrived, thirty-nine nurses and two physicians had died from what was being referred to as Ebola fever. Later that year, another insidious disease, manifested by malaise, unrelenting pneumonia, skin lesions, and weight loss, was making its rounds in the village of Abumombazi, Zaire, close to the Ebola River.

Notable among the first affected in Africa was a Danish surgeon, Grete Rask, who had devoted much of her professional life in medical service to the people of the former Belgian Congo. Sterile rubber gloves, disposable needles and syringes, and adequate blood banking systems were almost nonexistent in the village hospital. As the only surgeon in a Zairian village hospital, Rask often operated on her patients with her bare hands, using poorly sterilized equipment.

In 1976, Rask developed grotesquely swollen lymph glands, severe fatigue, and continuous weight loss and was suffering from diarrhea. Later, she labored for each breath and finally decided to return to her native Denmark to die. For months, doctors tested and examined the surgeon but were unable to explain what was making her sick. Doctors could not understand why several health problems were afflicting the frail woman. Her mouth was covered with yeast infections, staphylococcus bacteria had spread in her bloodstream, and her lungs were infected with unknown organisms. Serum tests showed her immune system as being almost nonfunctional. She died at the end of 1977.

The autopsy revealed that millions of organisms identified as *Pneumocystis carinii* had caused the rare pneumonia that had slowly ravaged and suffocated Rask. That particular protozoan became the landmark organism in the identification of the new disease. Questions were raised as to where and how she became infected, but answers were not forthcoming.



Source: Statistics are from the U.S. Centers for Disease Control, National Center for Health Statistics.

About all that was known of this strange new disease was that it depleted the patient's immune system, leaving the patient's body vulnerable to unusual and rare infections. It would soon become known universally as acquired immunodeficiency syndrome (AIDS).

Investigating the History of AIDS

Clinical epidemics of cryptococcal meningitis, progressive Kaposi's sarcoma, and esophageal candidiasis were recognized in Zaire, Zambia, Uganda, Rwanda, and Tanzania. This syndrome was termed "slim disease" in these countries because of the sudden unintentional weight loss of the affected individuals, resulting in a severely emaciated appearance. Kaposi's sarcoma, a kind of skin cancer, had become an especially common finding in the affected patients. During the same period, similar clinical manifestations were noted in the United States, primarily in homosexual males in New York City and San Francisco. These men had developed Kaposi's sarcoma of the skin, oral candidiasis, weight loss, fever, and pneumonia.

One of the first identified cases in North America was a Canadian flight attendant, Gaetan Dugas, who would later become known as "patient zero." In 1978, he developed purplish skin lesions and was informed that he had Kaposi's sarcoma and that it was nonmalignant. He went about his regular routines with no further concern. After hearing news of more cases of Kaposi's sarcoma in the homosexual population, he contacted doctors Alvin Friedman-Kien and Linda Laubenstein at New York University. His affliction then was rediagnosed as malignant cancer. In desperation, he went to bathhouses and engaged in anonymous sex.

In Europe, signs of the mysterious disease began to appear among homosexual men who had visited the United States or whose sexual partners had visited that country. The outbreak had also afflicted a number of immigrant Africans.

The CDC embarked on a major investigation to track patients and their sexual partners in an effort to determine the disease's causes, its origin, the way it was being spread, and why it was focused on homosexual men. European and African doctors, with assistance from major international agencies, were involved, likewise, in the search for answers and to determine why women in Africa were getting sick as fast as the men were.

Impact

The virus that causes AIDs would be called the human immunodeficiency virus, or HIV, because it attacked the body's ability to fight infections. It was found in the blood and was transmitted through blood transfusions. It would also be found in the umbilical cord and passed from mother to fetus. The virus could be passed through hypodermic needles, endangering the lives of intravenous drug abusers. The virus would also be found in semen and become a threat to the sexual partners of affected individuals, both men and women. In short, the virus with the opportunistic infections producing AIDS would become the most feared and dreaded epidemic of the twentieth century. AIDS came at a time when the priority of the U.S. government was to cut spending on domestic affairs.

After the first public report of AIDS in 1981, the number of affected individuals began to multiply rapidly. Added to the global estimates of persons diagnosed with AIDS are an unknown number of dead victims.

The virus has now well established itself in the general population, with young persons and heterosexual women particularly at risk. The estimates of HIV-positive cases worldwide are in the millions. Although the number of persons living longer with HIV in developed countries, where mitigating drugs are available, has risen, the death toll worldwide has increased, especially in Africa and Eastern Europe. The epidemic of infection and deaths in Africa—where in some nations it is estimated that a third or more of the population has been exposed to the disease—is a grim reminder of how AIDS can ravage those struggling with ignorance of the disease and lack of access to education and appropriate medical care. Even in the United States, where mortality from AIDS decreased in the late 1990's, the death toll is again on the rise—a grim reminder that there is no cure, that available therapies do not allow a "normal" lifestyle, and that vigilance is essential to avoid placing oneself, and others, at risk.

See also Human Immunodeficiency Virus; Immunology; Oncogenes; Viruses.

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—*Margaret I. Aguwa, updated by Christina J. Moose*

ALPHA DECAY

THE SCIENCE: George Gamow applied the newly developed quantum mechanics to the atomic nucleus to explain alpha decay and founded the field of nuclear physics.

THE SCIENTISTS:

George Gamow (1904-1968), Russian American physicist
Fritz Houtermans (1903-1966), Austrian physicist
Ernest Rutherford (1871-1937), British physicist

MYSTERIES OF THE ATOM

In 1911, Ernest Rutherford's experiments, in which he bounced alpha particles off the atoms of a very thin gold foil, showed that all the positive charge and more than 99 percent of the mass of atoms is concentrated in a tiny central region of the atom called the "nucleus." The diameter of the nucleus is one one-hundred-thousandth of the diameter of the atom. By 1913, Niels Bohr had developed a model of the atom in which the negatively charged electrons orbited the nucleus in specific allowed orbits. Bohr's model explained Rutherford's results and accurately predicted certain atomic spectra.

Bohr's theory left an unanswered question: Why are electrons allowed only in certain orbits? Answering this question showed that electrons must behave sometimes like waves and sometimes like particles. The laws of physics that govern objects that behave like waves and particles at the same time are called quantum mechanics.

In 1928, physicists had just developed mathematical techniques for doing calculations using the newly developed rules of quantum mechanics. In major European universities, young physicists eagerly applied quantum physics to the behavior of atoms in emitting light and in forming molecules. The university at Göttingen in Germany was the center of this activity. Waiters in local cafés had standing instructions not to send tablecloths to the laundry until someone had checked to see that no valuable equations were written on them. Study at Göttingen became essential to any student who hoped to become a theoretical physicist.

THE NUCLEAR VALLEY

George Gamow came to Göttingen with a quick mind and a formidable sense of humor. He already understood the basic principles of quantum mechanics and was fascinated by its power to predict atomic behavior. An individualist to his toes, however, Gamow disliked working in crowded, fashionable fields of physics. Since most of Göttingen was working on the application of quantum mechanics to atoms, he looked for a new problem.

Unlike the atom, the nucleus had been little studied. Physicists realized that it had positive charge and mass. Certain nuclei also spontaneously

George Gamow: Physicist, Cosmologist, Geneticist

Born March 4, 1904, in Odessa, Russia, George Gamow started his scientific career as a boy, when his father gave him a telescope for his thirteenth birthday. Little did his father know that his son would one day become one of the greatest scientists of the twentieth century.

After graduating from the University of Leningrad in 1926, Gamow went to Göttingen, a center for the study of the new quantum mechanics. At this time, natural radioactivity was the focus of research of many of the great physicists of the day, from the Curies to Lord Rutherford, and Gamow was particularly interested in its relationship to the atomic nucleus. In 1928, he made his first great contribution when he described quantum tunneling of alpha particles to explain the radioactive process of alpha decay. His investigation of the atomic nucleus would take him to Copenhagen, where he worked under Niels Bohr laying the theoretical groundwork for nuclear fusion and fission.

During the 1930's, Gamow taught at universities in Copenhagen, Leningrad, Cambridge, Paris, and the United States. In Washington, D.C., he and Edward Teller worked on the theory of beta decay. He also turned his attention to astrophysics and the origin of the elements. This work led to his 1948 proposal of the "big bang" theory of the universe, for which he is best known.

Gamow was more than a theoretical physicist, however: Known for his sense of humor and revered by his students, he was also devoted to education. His "Mr. Tompkins" series used science fiction to explain difficult science in a way that anyone—including Tompkins, whose attention span was notoriously short—could understand. In 1954, inspired by the Watson-Crick DNA model, he theorized that the order of the DNA molecules determined protein structure. The problem, as he saw it, was to determine how the four-letter "alphabet" of nucleic acid bases could be formed into "words." His "diamond code" paved the way for Marshall W. Nirenberg to crack the genetic code in 1961.

In 1956, Gamow settled in Boulder to teach at the University of Colorado. That year, he received UNESCO's Kalinga Prize for his popularization of science, and two years later he was married (a second time) to Barbara "Perky" Perkins, who initiated the George Gamow Lecture Series after his death, in 1968.

emitted nuclear radiation of various kinds. One kind of emission, alpha particles, had been extensively studied by Rutherford and his collaborators. They had shown that alpha particles are the nuclei of helium atoms and that they carry two units of positive charge. Although it is impossible to predict when any given nucleus will emit an alpha, the rate at which a sample of a particular kind of nucleus emits alphas is characteristic. All the alphas emitted from one type of nucleus have a unique energy. Furthermore, the rate at which alphas are emitted increases as the energy of the alpha particle increases.

Gamow recognized that the large positive charge of the nucleus means that an alpha particle is electrically repelled by the nucleus. The only way that alphas can stay inside a nucleus is if they are held in place by a very strong nuclear force that is not in effect beyond the edge of the nucleus. The situation is analogous to that of a ball trapped in a valley that rolls up one side of the hills that trap it. Unless it has enough energy to go over the top of the hill, the ball rolls up hillside and rolls back down. If, however, the ball could suddenly dig a tunnel through the hill, it would be free of the valley and would roll down the other side of the hill and out into the countryside. The alpha particle is the ball trapped in the nuclear valley by the hills of the nuclear force. The electrical repulsion is the other side of the hill down which the alpha coasts, gathering speed as it goes.

Alpha Tunneling

Quantum mechanics predicts that the wave nature of certain particles allows them to penetrate regions of space where an ordinary particle is extremely unlikely to go. In the case of an alpha particle bouncing back and forth inside a nuclear valley, Gamow realized, each time the alpha collided with the nuclear energy wall, there was a small probability that its wave nature would allow it to penetrate the nuclear energy wall and escape from the nucleus down the electrical hill. The probability of penetration increased as the energy of the alpha particle increased. Gamow put numbers into this quantum model of the nucleus and predicted the rate at which alphas were emitted and the way that rate should increase as the energy of the alpha increased. Like the atom, the nucleus obeyed the laws of quantum mechanics.

Impact

Gamow’s explanation of alpha decay triggered an idea in the mind of another Göttingen physics student, Fritz Houtermans. Houtermans asked himself the following question: If alphas can escape from nuclei by tunneling through the energy wall of the nucleus, cannot nuclei be built from lighter nuclei when alphas tunnel into heavy nuclei? He realized not only that the alpha could be absorbed into the nucleus but also that energy would be emitted in the process. At the very high temperatures inside stars, this process could provide a tremendous source of energy and literally make the stars shine. It also determined the types of elements that were formed from hydrogen and deuterium in stellar interiors. Thus, Gamow's mechanism helped to determine the overall structure of the universe.

Gamow's success in using quantum mechanics to explain alpha decay opened the field of nuclear physics because it showed that nuclei could be treated by the logic of quantum physics. The fact that one nucleus emitted a lighter nucleus indicated that there must be a complex inner structure to the nucleus. Modern physicists are still working to understand that structure.

See also Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Compton Effect; Cosmic Rays; Electron Tunneling; Electrons; Electroweak Theory; Exclusion Principle; Grand Unified Theory; Heisenberg's Uncertainty Principle; Isotopes; Neutrons; Nuclear Fission; Photoelectric Effect; Plutonium; Quantized Hall Effect; Quantum Chromodynamics; Quantum Mechanics; Quarks; Radioactive Elements; Wave-Particle Duality of Light; X Radiation; X-Ray Crystallography; X-Ray Fluorescence.

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—*Ruth H. Howes*

AMINO ACIDS

THE SCIENCE: The discovery of amino acids in rocks as old as 3.1 billion years changed scientists' understanding of chemical evolution and the fundamental nature of biological systems.

THE SCIENTISTS:

Elso Barghoorn (1915-1984), American paleontologist and member of the United States National Academy of Sciences
J. William Schopf (b. 1941), American paleontologist and consultant on extraterrestrial life to the U.S. space program
Keith Kvenvolden (b. 1930), American organic geochemist and geologist
Stanley Miller (b. 1930), American chemist

LIFE IN ANCIENT ROCKS

On November 16, 1967, J. William Schopf and Elso Barghoorn of Harvard University and Keith Kvenvolden of the U.S. Geological Survey presented a paper to the National Academy of Sciences summarizing their search for traces of amino acids (the proteins that form the basis of life) in the oldest known sedimentary rocks. This team of scientists had analyzed organic material leached from pulverized black chert (a type of rock) from three formations: the 1-billion-year-old Australian Bitter Springs formation, the 2-billion-year-old Canadian Gunflint chert, and the 3-billion-year-old Fig Tree chert from South Africa. The latter was the oldest undeformed Precambrian sedimentary rock known at the time. (The Precambrian era began about 4.6 billion years ago and ended about 570 million years ago.)

The Gunflint locality had already yielded abundant evidence of early life in the form of many examples of structurally preserved microorganisms. Gunflint was the subject of a classic 1954 paper in the journal *Science* by Barghoorn and Stanley Tyler, which announced the first indisputable reports of early Proterozoic microfossils. (The Proterozoic is the later of two divisions of Precambrian time.) Well-preserved microorganisms were reported in the Bitter Springs formation by Barghoorn and Schopf in 1965.

The fossil evidence for life in the Fig Tree chert was not as compelling, but Schopf and Barghoorn were in the process of examining this material and saw bacterial microfossils using an electron microscope; they reported these findings in 1966.

The types and quantities of amino acids present in the samples were determined by pulverizing carefully cleaned samples of hard, virtually impermeable chert and leaching any organic material present with various solvents. The nature of the organic material was determined by gas chromatography, a method of separating the individual elements in a chemical mixture. Twenty amino acids were identified in all the samples; a twenty-first occurred only in the Bitter Springs formation. Concentrations were extremely low and decreased with increasing geologic age. Barghoorn and his colleagues noted that the concentrations of various amino acids in all

PSEUDOFOSSILS?

In 2002, paleobiologists Martin D. Brasier and Owen R. Green of the University of Oxford published a paper in *Nature* in which they questioned the widely accepted view that the oldest microfossils—evidence for microorganisms capable of photosynthesis about 3.465 billion years ago—are located in the Apex chert in Western Australia's Warrawoona group. If this is true, as many paleobiologists believe, then oxygen-releasing life would have changed Earth's atmosphere during this period, setting the environmental conditions for life ever since.

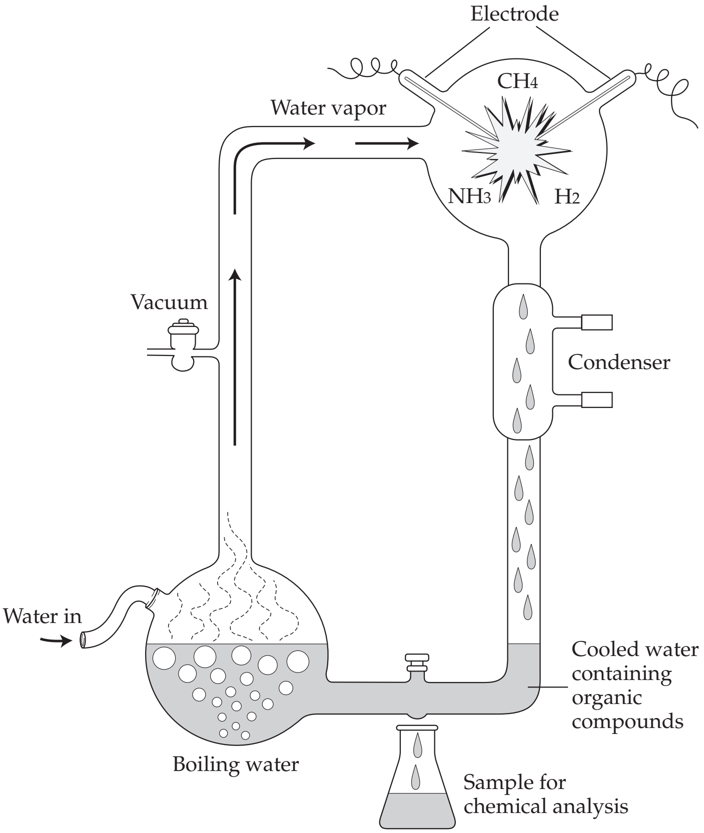
Brasier and Green described the use of new geochemical and other techniques that encouraged a reevaluation of previous assumptions. Brasier's group demonstrated that structures similar to microfossils can be formed through abiotic (inorganic) reactions involving amorphous carbon. They postulated that microfossils were actually "pseudofossils" and that J. William Schopf and his colleagues should reconsider their conclusions. According to Brasier, "The shapes are far too complicated to be bacteria. . . ." It is far more likely, he contends, that the squiggles thought to be microfossils were really caused when rocks formed from reactions between the carbon dioxide and monoxide released by hot, metal-rich hydrothermal vents. These reactions may even have jump-started the amino acids that are the basis of terrestrial life.

Schopf's group countered that, if Brasier were correct, the microfossils would have been found throughout the world. The two camps are still analyzing their data. New studies, on both sides, underscore that the mysteries of early life still remain to be revealed.

three samples corresponded to the distribution of amino acids in living organisms.

Because the amino acids occurred with microfossils in samples high in organic matter, the scientists concluded that microfossils developed at the same time that chemical evolution produced life, and that this proved the existence of life as early as 3 to 3.1 billion years ago. This also provided evidence that amino acids, the fundamental chemical building blocks of cells, had remained essentially unchanged throughout history.

THE MILLER-UREY EXPERIMENT



It has been shown many times that organic compounds, the beginnings of life, including amino acids, are produced readily within water in sealed flasks containing reducing gases such as carbon dioxide energized by electrical discharges, ultraviolet light, or even shock waves. The most famous of these experiments, shown here, was conducted in 1953 by Stanley L. Miller and Harold C. Urey.

Chemical Evolution

All life on Earth shares a unique carbon-based chemistry. The presence of deoxyribonucleic acid (DNA) and amino acids is a primary indicator of the presence of life. When examining meteorites and lunar samples, for example, scientists routinely look for these chemicals or the products left over when these chemicals decompose. By studying closely the chemistry of the microfossil samples, therefore, scientists learned much about the evolutionary history of life, especially life in its earliest stages.

The theory that a period of chemical evolution preceded the emergence of the earliest true life-forms was first suggested by the Soviet biochemist Aleksandr Ivanovich Oparin in the 1920′s and 1930′s. In the early 1950′s, the American chemists Harold C. and Stanley Miller expanded this theory for the early evolution of life, postulating a "soup" of organic chemicals that existed in bodies of water on the primordial Earth. Heat, electrical discharge, and cosmic rays acted upon this soup to produce a broad spectrum of organic compounds, including those that characterize living systems.

On a global scale, over millions of years of geologic time, chemical reactions led to increasingly complex molecules. These reactions eventually produced a prototype DNA molecule that was able to make copies of itself and to direct the synthesis of other complex compounds. Finally, the ability to create a membrane to enclose the replicating genetic material was a crucial step in the evolution of simple cells.

Impact

The discovery of amino acids in ancient Precambrian sediments attracted attention throughout the scientific community because it confirmed predictions about the nature of early evolutionary events. The validity of the discovery, however, was questioned almost immediately.

Since 1968, several sedimentary formations older than the Fig Tree chert have been identified, including the Onverwacht formation (which underlies it), the 3.5-billion-year-old Warrawoona group in Australia, and the 3.8-billion-year-old Isua formation in Greenland. The Warrawoona group contains stromatolites, simple filamentous microfossils that Schopf accepted as the oldest plausible microbial microfossils known. Information on the chemical composition of the microorganisms in this formation would be tremendously useful to scientists studying evolution. Had photosynthesis already evolved at this early date, or did these organisms rely on a chemical energy source? How did the basic building blocks of life 3.5 billion years ago compare to those today?

The origins of life on Earth and the age of the oldest microfossils remain unclear. The organic material in the Warrawoona group, it has been argued, may have formed through abiotic reactions under hydrothermal conditions. Scientists studying evolution continue to rely on the biochemistry of living forms, mathematical models of the life process, and laboratory experiments to unravel the story of the emergence of the unique chemical processes that characterize life on Earth.

See also Double-Helix Model of DNA; Fossils; Genetic Code; Geologic Change; Microfossils; Ribozymes.

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—*Martha Sherwood-Pike*

ANESTHESIA

THE SCIENCE: Anesthesia saved lives by making formerly painful surgical procedures possible.

THE SCIENTISTS:

Charles Thomas Jackson (1805-1880), eccentric Boston physician and scientist who claimed full credit for Wells's and Morton's work

Crawford Williamson Long (1815-1878), Georgia physician who first used ether in surgery

William Thomas Green Morton (1819-1868), Boston dentist who first demonstrated surgical anesthesia for the public

Horace Wells (1815-1848), Boston dentist who attempted to use nitrous oxide as an anesthetic

SURGERY BEFORE ANESTHETICS

On October 16, 1846, in the Massachusetts General Hospital, William Thomas Green Morton, a Boston dentist, gave the first public demonstration of the successful use of surgical anesthesia. Although surgery had made considerable progress during the previous two centuries as anatomists had gradually delineated the major outlines of gross anatomy, the surgical patient still faced excruciating pain and the virtual certainty of secondary infections. Without anesthetics, the agonies of the patients forced surgeons to operate as quickly as possible, and the shock and pain often proved disastrous. Dreaded diseases, such as hospital gangrene or blood poisoning, often hastened the patient's death. In the 1840's, U.S. ingenuity solved the problem of anesthesia. Control of infection, however, had to await the bacteriological revolution in the last half of the nineteenth century.

By 1840, the stage was set for the advent of anesthesia. Surgeons, as deeply troubled by the agonies of their patients as by the difficult logistics of operating on a screaming, writhing patient, were eager for help. A growing humanitarian spirit, with its acute sensitivity to human suffering, made the public more receptive to innovations. Yet, it was the rapid development of dentistry in America that created a strong demand for some sort of pain reliever. By this time, three anesthetic agents were available: nitrous oxide, sulfuric ether, and chloroform. The exhilarating effects of the first two gases were well known, and "ether frolics" and "laughing gas" parties had become common indoor pastimes. In the course of these parties, it had been observed that individuals under the influence of the gases appeared to feel no pain.

The first professional man to see the significance of these agents in relieving pain was Crawford W. Long, a Georgia physician. He had witnessed the effect of sulfuric ether during ether frolics and determined to try it as an aid to surgery. Between 1842 and 1846, Long performed eight oper-

THE ETHER DEBATE

In November, 1846, after his public demonstration of etherization as anesthesia, William Thomas Green Morton secured patent rights to his ether preparation as "Letheon." He hoped to control the anesthetic for two reasons: to prevent its misuse and to provide himself with an income. That hope was quickly dashed when physicians realized that ether was readily available in unpatented form. By year's end, etherization was being used in American, English, and French hospitals, and by 1848, anesthesia was a tool of dentistry, obstetrics, and therapeutics, as well as surgery.


(Library of Congress)

However, there was a debate over who, exactly, should take credit for the "discovery" of ether as an anesthetic: the dentist Morton; Morton's partner Horace Wells; the chemist Charles T. Jackson, who had informed Morton of how physicians used ether drops; or the surgeon through whom Morton had arranged his public demonstration, Henry Jacob Bigelow. This debate proved to be one of ugliest in medical history. Morton—considered a lower-class "tooth puller" in a time when dentistry was an occupation of questionable repute—suffered from attacks on his character and ability. Jackson took advantage of Morton's lack of medical education to make him out to be an unscrupulous profit-seeker. Morton soon lost his dental practice and was ruined financially.

Supporters petitioned Congress to give Morton adequate compensation for his discovery of anesthesia. In the 1850's, Congress introduced two bills appropriating $100,000, but active supporters of Jackson, Wells, and several other claimants prevented any appropriation. A direct appeal by Morton to President Franklin Pierce led to a promise of a reward, but the cause was lost with the advent of the Civil War (1861-1865). During that war, Morton served with distinction as an anesthetist in field hospitals.

In 1868, Morton went to New York in an agitated state over a pro-Jackson article in *The Atlantic Monthly*, determined to defend himself with a reply. While there, he suffered a fatal stroke. Following his interment, Boston citizens donated a monument bearing a moving tribute to him as the inventor of anesthetic inhalation. In 1873, Jackson visited the site and, still obsessed with Morton, began to scream and flail wildly. He had to be restrained, and he remained confined to a mental institution until his death in 1880.

ations using sulfuric ether on human patients. However, he made no effort to publish his work until after Morton's demonstration of the anesthetic properties of ether in 1846.

Ether vs. Chloroform

Among the many discoveries in the history of medicine, few have provoked so much controversy as that of anesthesia. No fewer than four American claimants to the honor of introducing this benevolent contribution to humanity vied with each other for recognition during their lifetimes. Subsequently, the controversy acquired an international flavor. Simultaneous events in England further blurred the claim to discovery. The argument quickly focused on the superiority of ether versus chloroform. The struggle has since been carried on by historians. The American contest, however, now rests largely between Crawford W. Long, who was the first to use surgical anesthesia, and William Thomas Green Morton, who first publicly demonstrated its use.

A Boston dentist, Horace Wells, also experimented with anesthesia. He had observed the results of nitrous oxide during laughing gas parties and decided to see if it could provide the basis for painless extraction of teeth. After several successes, he arranged for a public demonstration of his technique at the Harvard Medical School. Precisely what happened there is unclear. Apparently the nitrous oxide had not taken its full effect on the patient. When Wells began to pull a tooth, the patient let out a terrified yell, and the students began to laugh and hiss. Wells fled, leaving his instruments behind. After this humiliation, he arranged another demonstration, but this time he gave too large a dose and the patient nearly died. Wells retired in disgrace, giving up all attempts to use nitrous oxide as an anesthetic.

Meanwhile, William Morton, another Boston dentist, was investigating the problem of surgical anesthesia. At the suggestion of Charles Thomas Jackson, a well-known physician, geologist, and chemist, Morton experimented with ether. When he felt confident, Morton persuaded John Collins Warren to allow him to anesthetize one of the famous surgeon's patients. It was Morton's use of anesthesia during this operation in 1846 that introduced anesthesia to the world. Jackson later demanded credit for the discovery, but his claim was rejected by the public and the academic community.

Ironically, misery was the lot of the three persons chiefly responsible for the introduction of anesthesia: Wells committed suicide soon after his unhappy appearance before the Harvard students; Morton sacrificed his career while fighting for recognition as the rightful discoverer of ether as an anesthetic and died a frustrated and bitter man; and Jackson was ultimately committed to an insane asylum. Long escaped the litigation and public quarreling in which Jackson and Morton became embroiled. He survived the Civil War and died a respected and successful practitioner in Georgia. His failure to publish the results of his early experiments deprived him of credit for the discovery of anesthetic surgery, and had he not encountered the publicity given to Morton's successful demonstration in 1846, Long might never have made mention of his work.

Impact

News of Morton's demonstration of painless surgery spread rapidly throughout the world, and the use of anesthesia (a name suggested by Oliver Wendell Holmes) for surgical and obstetrical purposes quickly became general. In 1869, an acrimonious debate erupted between English obstetrician Sir James Young Simpson and Jacob Bigelow, a Boston physician. The controversy focused more on whether Simpson had taken more credit than he was due for the discovery of a safe anesthetic than on the superiority of ether over chloroform. As the number of surgical operations increased, so did the incidence of secondary hospital infections; it took another twenty years for the work of the Englishman Lord Joseph Lister in antiseptic, and later aseptic, techniques to alleviate this problem in American hospitals.

As a result of the use of anesthesia, surgery eventually became a healthier and relatively painless procedure for the patient. The successful use of anesthesia also permitted the development of better surgical techniques and a more sophisticated understanding of anatomy. Nevertheless, as knowledge of anesthesia and bacteriology steadily widened, the way was being prepared for making the twentieth century the age of the surgeon.

See also Antisepsis.

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—*John Duffy and Kathleen Carroll*

ANTISEPSIS

THE SCIENCE: Joseph L. Lister promoted antisepsis, challenging physicians and surgeons to adopt antiseptic procedures that saved lives after surgery.

THE SCIENTISTS:

Joseph L. Lister (1827-1912), English surgeon

Louis Pasteur (1822-1895), discoverer of the germ theory of disease

Ignaz Philipp Semmelweiss (1818-1865), Hungarian physician and early discoverer of the principle of antisepsis

Sir James Young Simpson (1811-1870), Scottish physician opposed to Lister's principles

PRE-LISTERIAN HOSPITALS

Surgery in the nineteenth century was a precarious undertaking. The problem of pain during operations had been solved by the introduction of anesthetics such as chloroform and ether. There remained, however, the dreaded hospital diseases, often fatal infections that commonly appeared in a very short period after successful surgery. Surgeons did not know what caused these diseases, but many assumed that death was inevitable. (Surgical texts often label this period pre-Listerian; the following period, after the acceptance of antiseptic procedures promoted by Lister, Louis Pasteur, and Ignaz Philipp Semmelweiss, is called Listerian.)

Not counting tetanus, the hospital diseases were gangrene, erysipelas, pyemia, and septicemia. All four often caused death or left the patient permanently debilitated or crippled. They were all epidemic. During the so-called erysipelas season in America, which lasted from January until March, no surgery was performed. In England, all surgery came to a complete halt when gangrene became epidemic in a hospital. In addition to these diseases that followed surgery, there was puerperal fever, which often affected women who gave birth to their children in hospitals; it was usually fatal.

Semmelweiss and Early Antisepsis

Semmelweiss, a doctor who joined the Lying-In Hospital in Vienna in 1846, concluded that puerperal fever came from within the ward rather than from outside. He further concluded that the fever was carried by doctors and medical students, who transmitted it to mothers during prenatal examinations. The answer was cleanliness and the disinfecting of the examiner's hands.

Semmelweiss was astute in his judgment. In 1847, he insisted that all who attended surgery wash their hands in chloride of lime. This procedure reduced deaths from 15 percent to 3 and then to 1 percent. Semmelweiss had made enemies, however, and although his mortality statistics showed that his antiseptic methods worked, these methods failed to gain acceptance. Lister apparently did not find out about the work of Semmelweiss until years after his own discovery.

Putting Pasteur into Practice

In 1864, a young doctor, Joseph L. Lister, was lecturing and practicing surgery in Glasgow when he first became acquainted with Pasteur's work on putrefaction. He believed that some of his own research might be advanced by a study of Pasteur's works.

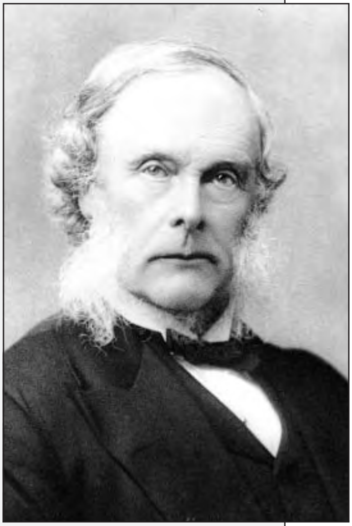
Lister replicated for his own satisfaction the Pasteur experiments and realized that Pasteur's germ theory applied to hospital diseases. What Lister now needed was an agent that would kill microbes before they had a chance to penetrate deeply into body tissues. The word "microbe" was not formally introduced to the medical community until February 26, 1878, by Dr. Sedillot, a military surgeon, in a treatise on the treatment of purulent infection, a very common problem in military surgery. In this same paper Sedillot says,

> We shall have seen the conception and birth of a new surgery, a daughter of Science and of Art, which will be one of the greatest wonders of our century and with which the names of Pasteur and Lister will remain gloriously connected.

Lister obtained some carbolic acid, which he knew had been used successfully to treat garbage in the city of Carlisle. One of its remarkable ef-

LISTER AND THE LONG ROAD TO CLEANLINESS

A combination of Joseph Lister's humble personality, the conservatism of the medical profession, and occupational jealousy made the adoption of his antiseptic methods much slower than that of other medical advancements of the day, such as anesthesia. In 1867, *The Lancet* carried reports of Lister's success in treating compound fractures aseptically, but because of Lister's modest claims and the profession's skepticism about innovation, antiseptic surgery was initially perceived as a method for the specific treatment of compound fractures rather than a general principle.


(Library of Congress)

Over the next twenty years, Lister struggled to convince his skeptical and sometimes self-serving colleagues to adopt antisepsis. By the early 1870's, he was using a spray made with carbolic acid to keep the air clean any time a wound was exposed, and by the 1880's he was using gauze impregnated with cyanide of mercury and zinc as an antiseptic dressing. Lister's wards were the healthiest in Edinburgh, and he successfully applied his methods to cases that would not even have been accepted a few years before.

Nevertheless, his fame spread on the European continent long before his British colleagues took his techniques seriously. One of his opponents at home was Dr. James Simpson, respected for his introduction of anesthesia into the British Isles. Instead of antisepsis, Simpson advocated quickly built wooden hospitals that could be abandoned when infections became rampant, and he not only pushed his own ideas but also deprecated those of Lister. Other physicians investigated the use of antiseptics but failed to conduct their experiments correctly, and it appeared that antisepsis would not work. The annoyed Lister then resisted publication of much of his work lest it lead to more harm than good.

Lister's students, however, personally began to spread the correct antiseptic technique, and the tide began to turn. In 1877, Lister was invited to become professor of clinical surgery at King's College in London. He was reluctant to leave Edinburgh, but he felt duty-bound to go: If he succeeded in London, his antiseptic techniques would gain a wide audience. He accepted the position, and within a decade he was a dominant figure in British medicine. The reserved and strictly honest physician whose students had dubbed him "the Chief" had finally persuaded the medical world of the importance of antisepsis.

fects had been to stop the sickening of cattle who grazed in fields near the city's garbage dumps. In 1865, he used it on his first patient, but the man died. The next four cases were all very serious surgical problems, but they all survived because they did not develop any of the hospital diseases. Lister continued to treat surgical cases with carbolic acid solutions and bandages. Lister soaked his bandages and cotton wool in carbolic acid, and a carbolic vapor was blown over the surgeon's hands and the wound during surgery. The wound was surrounded by carbolic-soaked towels and the instruments kept in a carbolic solution. He presented the evidence in 1867 in an article published in *The Lancet*, the journal of British medicine: "On a New Method of Treating Compound Fracture, Abcess, Etc."

A considerable opposition was mobilized against Lister, particularly by Dr. James Y. Simpson. As more and more physicians adopted his methods, however, the opposition collapsed, and antiseptic surgery gained general acceptance. The work of Louis Pasteur from 1844 to 1895 was to affect the medical field in England, Germany, and France. In the United States, the Mayo clinic used the surgical and antiseptic techniques developed by Pasteur and refined by Lister.

Impact

After centuries of losing casualties to infection, Listerian methods made it possible to save lives and limbs. Much was to be learned from analysis of wounds received on the battlefields of the day. Pre-Listerian surgeons had to learn different methods of wound treatment to suit the site of war. Researchers noticed that bacteria flourished in damp conditions but diminished in arid lands. Methods were argued, and as bacteria were identified, the doctors who were persuaded that bacteria caused infection used antiseptic methods that eventually prevailed.

See also Antisepsis; Contagion; Galen's Medicine; Germ Theory; Immunology; Microscopic Life; Penicillin; Streptomycin; Viruses.

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—*Robert F. Erickson and Norma Crews*

ARTIFICIAL INTELLIGENCE

THE SCIENCE: Alan Turing developed the basic principles governing the design of programmable computers and proposed that a programmable computer could simulate human thinking.

THE SCIENTISTS:
George Boole (1815-1864), English logician and mathematician
David Hilbert (1862-1943), German mathematician
Alan M. Turing (1912-1954), English mathematician
John von Neumann (1903-1957), Hungarian American mathematician

MECHANIZING MATHEMATICS

At one level, mathematics can be viewed as a method of rearranging symbols according to a set of rules to obtain true statements about the things represented by the symbols. In elementary algebra, for example, one learns how to separate the unknown terms from the known terms in an equation to find values for those unknown terms. In a book titled *An Investigation of the Laws of Thought*, published in 1854, George Boole showed that conclusions about the truth or falsity of a combination of statements could be determined by using similar methods. Boole had opened up the field of mathematical logic. By the end of the nineteenth century, mathematicians were excited by the possibility that all mathematical ideas could be translated into a system of symbols in such a way that the truth of any idea could be determined by the manipulation of the symbols in which it was expressed.

In 1928, the German mathematician David Hilbert posed what most mathematicians considered to be the major questions about such a symbolic system for mathematics. One of these was the issue of decidability: Could the truth of any statement be determined by the mechanical manipulation of symbols in a finite number of steps?

TURING'S BRILLIANT CAREER

Alan Mathison Turing's brilliant career was not restricted to mathematics and computation, although he is now known as one of the fathers of modern computer science.

During World War II, he volunteered his services to the Government Code and Cypher School in Bletchley, a small town between Oxford and London, where a massive effort was under way to construct calculating machines capable of decoding machine-encrypted German diplomatic and military messages. Turing played a crucial role in the design of this equipment and in the development of procedures for breaking the codes: The work at Bletchley was critical to the Allied successes in Europe, and Turing was highly decorated for his contributions.

(Smithsonian Institution)

This wartime experience gave Turing a familiarity with electronics that complemented his mathematical training. In 1945, he moved to the National Physical Laboratory in Teddington, where he was given the responsibility for designing an electronic, stored-program computer for use in government work. What Turing designed was a physical embodiment of his universal Turing machine. The plans he drew up called for an ambitious modern computer using vacuum tubes for logical switching and mercury delay lines for storing information. A scaled-down version, known as Pilot Automatic Computing Engine (ACE), was completed in 1950—one of the first modern computers placed in operation—and was used for important government and industrial research, including aircraft design. From there Turing went to Cambridge and then Manchester University as the chief programmer for a powerful new computer, the Mark I, where he did the work for which he became most famous.

Turing's life came to a sudden end in 1954 as the result of a fatal dose of cyanide poisoning. He was not yet thirty-two years old. A few months earlier, he had been convicted of homosexual activity, a felony in Great Britain at that time. He had been sentenced to mandatory estrogen treatments, which caused strong physiological and psychological changes in him. These changes severely depressed Turing, and many people believe they caused him to take his life. At the time of his death, Turing had begun an ambitious investigation of the chemical basis of morphogenesis, the process in living organisms that determines why and how single cells grow into differentiated organs with specific functions. Such cells are today known as stem cells. This line of research was simply one more in an extraordinarily creative and productive scientific career.

THE TYPEWRITER PROVIDES A KEY

As a young boy, Alan Turing thought a lot about machines, and he developed several designs of his own—none of which was very good—for a typewriter. In 1936, when he was a research student in mathematics at Cambridge University, it was perhaps natural that he would see the important part of Hilbert's question as the need to identify exactly what is meant by a mechanical procedure as performed by a human mathematician. In a paper published in 1936 in the *Proceedings of the London Mathematical Society*, Turing described the simplest type of machine that could perform the same manipulation of symbols that mathematicians do.

Turing's device, which is now referred to as a "Turing machine," was similar to a typewriter in that it could print out a string of symbols, but different in that it could also read symbols and erase them; in addition, its behavior would be controlled by the symbols read by it rather than by a human operator. For simplicity, Turing envisioned the machine as acting not on a sheet of paper but on an endless paper tape that could be read only one symbol at a time. The internal workings of the Turing machine involved a memory register that could exist in only a limited number of states and a set of rules that determined, on the basis of any symbol that could be read and the state of the internal memory, what symbol would be printed to replace it on tape, what the new state of the internal memory would be, and whether the tape would be moved a space to the right or left or not at all.

In this same important paper, Turing also showed that one could build a programmable calculating machine that could first read in, from the tape, a description of the rules of any other Turing machine and then behave as if it were that machine in manipulating the symbols that followed on the tape. Using the properties of such a programmable, or "universal," Turing machine, Turing was able to prove that the answer to Hilbert's "decision problem" was a definite no. There was no mechanical procedure that would directly demonstrate the truth or falsity of a mathematical statement.

The most important consequence of Turing's paper, however, may be his reduction of the manipulations and mental processes of a human mathematician to operations that could be performed by a machine that could be built. If the thinking involved in solving mathematical problems was not very different from that used by humans in planning and in the other types of problem-solving behavior that constituted human intelligence, there was no fundamental reason that a large enough, suitably programmed machine could not be programmed to display intelligence.

Impact

Although mechanical aids to computation such as the abacus and the slide rule existed long before Turing's work, the first large programmable computer was built during World War II to meet military needs. The first machine, the Electronic Numerical Integrator and Calculator (ENIAC), was built at the University of Pennsylvania under the direction of another great mathematician: John von Neumann. Turing, whose own contribution to the war effort involved creating machines for breaking secret codes, rejoined the machine intelligence debate in 1950 when he proposed what has become known as the Turing test, in the simplest form of which a human is restricted to typewritten communication with both a human and a computing machine. If the human cannot determine which correspondent is the computer, then Turing felt that the computer could be considered to possess intelligence. It should be noted that intelligence, in this sense, does not necessarily imply that the computer is conscious, is alive, or experiences feelings and emotions.

The term "artificial intelligence" was not used until 1956, when John McCarthy, a young mathematics professor at Dartmouth College, along with three other scientists, arranged the first official conference on the subject. Interest in artificial intelligence has grown as computers have become smaller, faster, and much more reliable. Today computers can be programmed to read stories and answer questions about them, to assist medical doctors in diagnoses, to play chess at the expert level, and to assist humans in numerous other information-processing tasks that have become commonplace in modern society.

See also Internet; Personal Computers.

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—*Donald R. Franceschetti*

ASPIRIN

THE SCIENCE: In 1897, while researching therapeutics that might relieve the pain of arthritis, Felix Hoffman, a chemist with Friedrich Bayer and Company, "rediscovered" Charles Gerhardt's earlier work with acetylsalicylic acid. Hoffman developed a method to efficiently synthesize a less irritating, more stable form of the drug.

THE SCIENTISTS:

Edward Stone (1702-1768), British clergyman who reported the ability to treat various ailments using willow extracts

Charles Frederick von Gerhardt (1816-1856), French chemist who synthesized the earliest formulation of what would become aspirin

Felix Hoffman (1868-1946), German chemist who modified Gergardt's formula to produce a stable form of aspirin

Hermann Kolbe (1818-1884), German chemist noted for demonstrating that organic molecules could be derived from inorganic sources

John Robert Vane (1927-2004), British pharmacologist who discovered the pharmacological basis for the activity of aspirin

EARLY ANALGESICS

The earliest "medical text" known to exist can be traced to the Sumerian city-states during the period around 3000 B.C.E. Among the extant "prescriptions" discovered from this period is a transcribed stone, known as the Ur III tablet, listing plants such as myrtle or willow for the treatment of illness. On a contemporary Middle Eastern papyrus discovered in the 1860's by George Ebers, the Ebers Papyrus, is an additional reference to the use of willow in the treatment of ear infections as well as its use in a salve for allowing muscles to become more supple.

While the precise meaning of the writings is unclear, the general interpretation is that it describes the use of willow for treatment of pain. Since willow is among the plants that contain salicylates, the active ingredient of aspirin, the assumption is this represents the earliest description of the chemical to treat inflammation. The relationship between the Ur III tablet and the Ebers Papyrus, other than apparently originating during the same period, is unknown. Both economic trade and exchange of knowledge among the states of the Middle East was common, but it is certainly possible the palliative effects of willow could have been discovered independently.

Hippocrates (c. 450 B.C.E.), in his cornucopia of medical treatments, also included willow tree bark for relief of headaches and even the pain of childbirth. Willow bark continued to be used by the Romans around 100 B.C.E.-100 C.E. for treatment of various forms of pain, including muscle pain, joint aches, and ear infections. Most of these remedies included diverse mixtures of various agents, but clearly there existed a strong and persistent belief in the analgesic (pain-relieving) properties of plant extracts.

Much of the knowledge associated with plant or herbal medicine remained anecdotal until the mid-seventeenth and eighteenth centuries. In 1633, a Spanish monk in Central America described a "fever tree," a cinchona, the bark of which, when made into a powder, would relieve the symptoms of malaria. The extract, named quina or quinine after the Peruvian name *kina*, represented the first remedy that could actually be studied.

Others followed. In the mid-1750's, Edward Stone, a British religious clergyman as well as an amateur naturalist, observed that the bitter taste of the willow bark was similar to that of the cinchona. He also noticed that by chewing ground powder from the willow, one could relieve the pain associated with ague, a general condition often marked by headache or muscle pain. Stone reported his findings to the British Royal Society, a collection of naturalists and mathematicians. While Stone's work was acknowledged, the true significance of his discovery was overlooked.

SALICYLIC ACID

Isolation of the active ingredient from willow, salicylic acid, would not occur until the 1820's. In 1826, the Italian scientist Luigi Brugnatelli partially purified what he called salicin, a highly impure form of salicylic acid. Several years later, the Frenchman Henri Leoux was able to prepare several grams of a crystalline form of the chemical. In 1838, Raffaele Piria named the crystal salicylic acid. The purified form was found to contain pain-relieving benefits and joined the list of treatments available in some European apothecary shops.

Salicylic acid, because it was an acid, had a number of unpleasant side effects, chief among them that it was often irritating to the stomach. Aware that it was a possible therapeutic agent and an organic one as well, French chemist Charles Gerhardt began to study its molecular structure. Techniques in chemistry during the mid-nineteenth century were crude, and Gerhardt's initial interest was first to classify the molecule. He observed that the basis for salicylic acid's irritating properties was in the hydroxyl (–OH) group attached to the side of a ring. Gerhardt modified the structure by replacing the hydrogen with an acetyl group, thereby creating acetylsalicyclic acid, tantalizingly close to the structure found in today's aspirin. Gerhardt's primary challenge was to accomplish the process in a timely and relatively simple procedure, something he never was able to achieve. After several largely unsuccessful attempts, Gerhardt moved on to other endeavors.

Others attempted to continue Gerhardt's work in developing more efficient means of synthesizing modified forms of salicylic acid. In part, the impetus for the work was the belief that the compound could serve as a food preservative, despite its taste. Among the more successful chemists was Hermann Kolbe. Best known for his research on structural theory related to inorganic and organic molecules, Kolbe found he could efficiently synthesize various forms of salicylic acid from relatively simple molecules. The ability to synthesize large quantities of acetylsalicylic acid was applied by one of Kolbe's students, Friedrich von Heyden, whose chemical factory, Heyden Chemical, was founded in 1874, in part specifically to produce the molecule. The production of salicylic acid by the company represented the first artificially produced pharmaceutical substance; ironically, its application was in part based on assumed antiseptic properties—properties it did not possess.

HOFFMAN AND BAYER

In 1894, Felix Hoffman was hired by Friedrich Bayer and Company. Born in 1868, Hoffman had shown an early interest in science and had been trained as a pharmaceutical chemist. Anecdotal evidence suggests that Hoffman began looking into the development of pain relievers as a means to relieve the arthritis suffered by his father. While his father in all likelihood did suffer from arthritis, the reality of Hoffman's work suggests other reasons for his research.

By the 1890's, it was clear that salicylic acid provided benefits as an analgesic. What was needed was a more efficient method of production, as well as a means to modify the chemical structure to increase its stability and eliminate the side effects, all in keeping with the role of Bayer as a pharmaceutical company.

Hoffman was assigned the task. While researching the background of the chemical, Hoffman came upon Gerhardt's original paper. By treating the acid with various chemicals, Hoffman found a method to neutralize the acidic properties without inhibiting its analgesic properties; ironically, using the same modification procedure on a different chemical, Hoffman also discovered morphine at the same time.

The product, acetylsalicylic acid (ASA), quickly underwent simple field trials. Given to dentists, ASA was found to relieve the pain of toothaches. In 1899, it was time to introduce a trade name for the drug, which would soon be marketed. Because ASA could also be obtained from the meadowsweet plant, genus *Spiraea*, it was named a-spirin (for acetylation-spirin), or aspirin. The following year, it was marketed in tablet form. Aspirin was the first such drug to be sold in such a manner.

Impact

Aspirin can rightly be considered one of the earliest "wonder drugs," certainly the first to be artificially synthesized in large quantities. Initially manufactured by Bayer as an analgesic, acetylsalicylic acid is more commonly known by the trade name, registered by Bayer: aspirin. It has been utilized for its anti-inflammatory activity, as a means to treat or help prevent heart attacks or certain forms of stroke due to its anticlotting ability, and more recently as a potential preventive for certain forms of colon cancer.

A variety of companies today market generic forms of the drug under several trade names. However, the firm Bayer AG remains the most prominent drug manufacturer of aspirin: Approximately 50,000 tons of acetylsalicylic acid are produced each year. Estimates are that 137 million tablets are consumed in the world every day.

Ironically, the pharmacological basis for the function of ASA was determined only in the 1970's. John Vane at the University of London observed that the active ingredients in aspirin could prevent the action of prostaglandins, molecules released in the body during inflammatory activity. With the determination of the role played by prostaglandins in actions as diverse as inflammation and blood clotting, it finally became possible to understand how aspirin plays an inhibitory role in a variety of functions in the human body.

See also Diphtheria Vaccine; Penicillin; Polio Vaccine: Sabin; Polio Vaccine: Salk; Smallpox Vaccination; Streptomycin; Yellow Fever Vaccine.

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—*Richard Adler*

ATMOSPHERIC CIRCULATION

THE SCIENCE: George Hadley observed that global atmospheric circulation is driven by solar heating and the rotation of Earth. He was the first person to explain the patterns of atmospheric circulation seen in the tropics and subtropics.

THE SCIENTISTS:

George Hadley (1685-1768), English lawyer and amateur scientist

Vilhelm Bjerknes (1862-1951), Norwegian meteorologist and founder of the Bergen Geophysical Institute

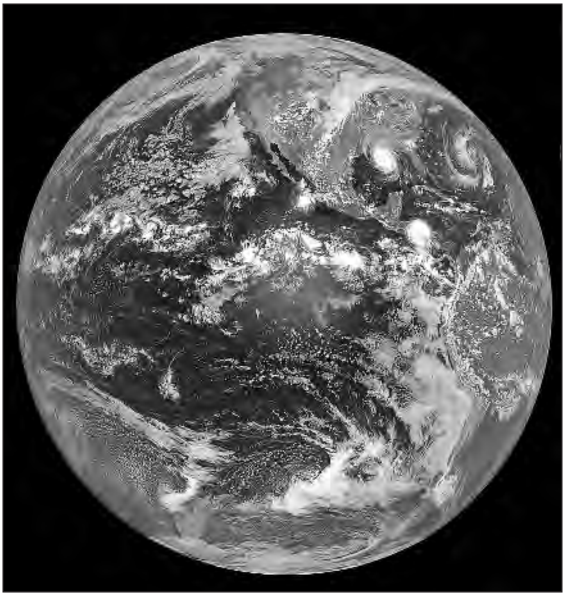
Gustave-Gaspard de Coriolis (1792-1843), French mathematician and physicist

Edmond Halley (1656-1742), second Astronomer Royal of England, 1722-1742, who published the first weather map

Carl-Gustav Arvid Rossby (1898-1957), Swedish meteorologist and a student of Bjerknes

THE TRADE WINDS

Many astute fifteenth century European navigators were familiar with the overall westerly winds of the midlatitudes, the easterly winds of the lower latitudes, and the doldrums of the equatorial regions. Christopher Columbus first demonstrated the importance of these zonal winds in transoceanic travel. Instead of sailing west from the Iberian Peninsula, he first sailed the three Spanish ships under his command south to the Canary



A weather satellite image of the Earth showing atmospheric circulation and weather fronts. (NASA/GSFC)

Islands before crossing the Atlantic in 1492. Then he made use of a brisk tailwind to sail from the Canary Islands to the Bahamas in thirty-six days. This southerly route allowed Columbus to cross the Atlantic sailing within the low-latitude easterlies, and he is thus frequently credited with having "discovered" the trade winds. Columbus returned to Europe at higher latitude, stopping at the Azores as he sailed in the favorable westerlies.

In the sixteenth century, the easterly trade winds in the low latitudes north and south of the equator became the preferred engine between Europe and the Western Hemisphere. There was a consensus that these winds arose as the Earth rotated from west to east, but many mathematicians and astronomers realized that the Earth's rotation was insufficient to power the trade winds. British scientists became interested in providing a solid scientific explanation for these winds, and in 1686 Edmond Halley published a study of the trade winds in the Royal Society's *Philosophical Transactions*. He stated that solar heating was responsible for atmospheric circulation and, in the first weather map published, showed average winds over the oceans.

SYMMETRICAL CIRCULATION

George Hadley, a barrister by training and brother of the astronomer John Hadley, became interested in weather phenomena and in providing a scientific explanation of the midlatitude westerlies and the easterly low-latitude trade winds. Hadley realized that the trade winds could be explained only using a rotating coordinate system under the influence of solar heating. Hadley used Halley's work on trade winds as a starting point and concluded that solar heating of the atmosphere is at its maximum at the equator, causing warm equatorial air to rise at low latitudes and move poleward aloft. Upward air movement occurs in the doldrums, and cooler surface air is constantly moved eastward toward the equator to be warmed. (This explanation only roughly conserves angular momentum.) Hadley envisioned this atmospheric circulation system as zonally symmetric, with the Northern and Southern Hemispheres having mirror-image latitudinal wind systems.

Hadley's explanation of the trade winds was generally accepted when he presented his work to the Royal Society in London in 1735. About fifty years later, Hadley's explanation had been forgotten, and John Dalton and Immanuel Kant independently proposed explanations similar to Hadley's. Eventually meteorologists determined that Hadley's assumption of conservation of velocity instead of conservation of angular momentum was incorrect.

The Coriolis Effect

A century after Hadley advanced his explanation for the trade winds, Gustave-Gaspard de Coriolis explained mathematically the apparent deflection (commonly referred to as the Coriolis effect) of winds to the right in the Northern Hemisphere and the left in the Southern Hemisphere. The amount of deflection is a function of wind speed and latitude; the Coriolis effect is zero at the equator.

Impact

Sailing ships gave way to steam-powered vessels, lessening the importance of the trade winds to commerce. By the mid-1850's, American meteorologists William Ferrel and Matthew Maury and the British mathematician James Thomson all independently proposed a three-cell meridional circulation structure in each hemisphere. This concept maintained the low-latitude Hadley cell, with the midlatitude cell being called a Ferrel cell. The Ferrel cell was envisioned to have a rising motion at about 60° latitude. The Hadley cell was still credited with supplying a westerly momentum to the midlatitudes. This structure (even when known to be scientifically inaccurate) continued to be used as a simplistic illustration of the global atmospheric circulation through most of the twentieth century.

With the proliferation of meteorological observations in the centuries following Hadley's work, atmospheric circulation was determined not to be zonally symmetric. Even though it was obvious that the trade winds were adequately described by zonal averages, observations had clearly established that large departures from zonal means were common. These departures were called "eddies" by scientists. In 1937, the Norwegian meteorologist Vilhelm Bjerknes suggested that a Ferrel-Thomson three-cell circulation was feasible only if the atmosphere had no eddies. Subsequent research into the general circulation of the atmosphere has concentrated on how eddies arise and propagate.

With the growth of observational meteorology in the late nineteenth century and satellite meteorology in the twentieth century, scientific understanding of the atmospheric circulation patterns grew. Investigation of atmospheric instabilities using data from upper-air observations collected by radiosondes ("weather balloons") and aircraft revealed the existence of large waves in the atmosphere arising from a wide variety of causes, including thermal and gravitational forcing.

Satellite imagery clearly defines the region where the trade winds converge. Viewed from space over the oceans, this convergence is visible as a band of clouds caused by thunderstorm activity. This band of cloudiness arises in the region where Hadley concluded that warm, moist air ascends and is now known as the Intertropical Convergence Zone, or ITCZ. The northern and southern borders of the trade winds, where air descends from aloft, are found roughly at 30° north and 30° south of the equator and are seen in satellite imagery as cloud-free areas.

By the late twentieth century, zonally averaged atmospheric circulation was accepted as a convenient "subset" of the total atmospheric circulation. The term Hadley cell continues to be commonly used to refer to the zonally averaged low-latitude winds. With increased mathematical knowledge and the development of high-speed computers in the late twentieth century, numerical modeling of atmospheric dynamical processes became possible. A student of Bjerknes, Carl-Gustav Rossby, was among the first to work on numerical models of the general circulation soon after computers were invented.

See also Atmospheric Pressure; Chaotic Systems; Weather Fronts.

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—*Anita Baker-Blocker*

ATMOSPHERIC PRESSURE

THE SCIENCE: Evangelista Torricelli was first to offer a clear definition of the fundamental concept of "atmospheric pressure," confirming that air has weight. His work supported Galileo's idea that the Earth could move through space without losing its atmosphere, and he also noted the day-to-day variation in the height of mercury in a column, thus initiating the scientific study of meteorology.

THE SCIENTISTS:

Evangelista Torricelli (1608-1647), Italian mathematician and physicist
Galileo Galilei (1564-1642), Italian physicist and astronomer
Benedetto Castelli (1577/1578-1643), student of Galileo and teacher of Torricelli
Blaise Pascal (1623-1662), French philosopher, mathematician, and physicist
Otto von Guericke (1602-1686), German engineer
Robert Boyle (1627-1691), Irish physicist
Robert Hooke (1635-1703), English experimenter and associate of Boyle

HEIR TO GALILEO

Evangelista Torricelli studied the work of Galileo in Rome as a student of Benedetto Castelli, Galileo's favorite student, who recommended him to Galileo. Torricelli invented the mercury barometer two years after serving as Galileo's secretary and assistant for the last three months of his long life. After Galileo died, Grand Duke Ferdinand II de' Medici of Tuscany appointed Torricelli to succeed Galileo as court mathematician at the Florentine Academy.

The invention of the mercury barometer followed a question raised by Galileo, who was curious why the grand duke's pump makers could raise water by suction to a height of only 34 feet. Ironically, Galileo had appealed to the Scholastic idea that "nature abhors a vacuum" to suggest that the "horror" extends to only about 34 feet. It occurred to Torricelli that Galileo's concept of gravity—applied to air—was the true explanation, suggesting that the weight of the air raises the water being pumped. He proposed that humans live at the bottom of a "sea of air," which extends up some 50 miles.

To test this idea, Torricelli sealed one end of a 40-inch glass tube and filled it with mercury. When he inverted the tube with the open end in a bowl of mercury, the column did not empty completely, but instead fell to a height of only about 30 inches. Torricelli maintained that this 30-inch column of mercury, weighing about the same as 34 feet of water in a column of the same diameter, is held up by the weight of the air.

Torricelli expected this result because he knew that mercury is 13.6 times heavier than water and, thus, 34 feet of water divided by 13.6 matches the 30 inches of mercury needed to counterbalance the weight of the air. Since a 30-inch column of mercury with one square inch of cross-sectional area weighs about 15 pounds, the air pressure is about 15 pounds per square inch, or 2,100 pounds per square foot at sea level. Torricelli also observed that the height of the mercury column varied from day to day because of changes in atmospheric pressure. These ideas later became important in the development of meteorology and of the steam engine.

Torricelli maintained that the space above the mercury column is a vacuum, contrary to the Scholastic opinion of the day, which held to Aristotle's argument that a void is logically impossible. The "Torricellian vacuum" was the first sustained vacuum. Torricelli's demonstration of two concepts—that a vacuum can exist and that the sea of air is held to the Earth by provided critical support to the idea that the Earth moves through the vacuum of space.

The first description of the mercury barometer was in a letter that Torricelli wrote on June 11, 1644, to his friend Michelangelo Ricci in Rome, a fellow student of Castelli. (Torricelli's letters on atmospheric pressure are translated into English in a volume of his *Collected Works*.) Later in 1644, he published in Florence his *Opera geometrica* (geometric works), which included original geometric theorems on the cycloid, his studies on projectile motion, and his work on fluids that led to his equation, known as Torricelli's law, to determine the speed of fluid flow from an opening in a vessel.

Torricelli died of typhoid fever on October 25, 1647, at the young age of thirty-nine. He is honored in low-pressure research by the unit for pressure called the torr, equivalent to the pressure of one millimeter of mercury. Standard atmospheric pressure is defined as 760 torrs (76 cm of mercury).

PASCAL'S EXPERIMENT

Torricelli's ideas on atmospheric pressure and the vacuum were quickly confirmed and extended by other experimenters. In France, Blaise Pascal recognized that if air has weight, it should diminish with altitude. In 1646, he engaged his brother-in-law to climb the Puy-de-Dôme with a mercury barometer, finding that the mercury level dropped from its sea-level value of 76 centimeters to about 70 centimeters at a height of about one mile. In addition to inventing this altimeter concept, he suggested using the barometer to predict weather after noting that stormy conditions were usually preceded by falling air pressure.

In a famous experiment, Pascal refuted the idea that the mercury column is held up by vapor at the top of the column, thereby preventing a vacuum. He repeated Torricelli's experiment with red wine in a 14-meter tube. If the gap at the top of the column indeed were made of vapor instead of being a vacuum, then the volatile wine should fall lower than water; but if it were a vacuum, the lower-density wine should fall less than water to balance the weight of the air, as was observed. Pascal is honored by the International System of Units and the meter-kilogram-second (MKS) system for pressure called the Pascal.

IMPACT

Torricelli's invention of the mercury barometer introduced the concept of "air pressure" and demonstrated the existence of a vacuum. His ideas solved one of the problems raised by the Copernican theory and Galileo's emphasis on a moving Earth: If the Earth is in motion, it must carry its "sea of air" with it. Gravity acting on the air and producing air pressure holds the air in its place around the Earth, and the surrounding space must be a vacuum if the atmosphere is not to be stripped away.

The ideas of "air pressure" and "the vacuum" led to the invention of the air pump in 1650 by the German engineer Otto von Guericke, the burgomaster of Magdeburg. He showed that a close-fitting piston in an evacuated cylinder could not be removed by the effort of twenty men. In 1654, he gave a public demonstration of the power of a vacuum by evacuating two large metal hemispheres fitted together along a greased flange. Air pressure held these "Magdeburg hemispheres" together so tightly that even a team of sixteen horses could not pull them apart.

At Oxford University in England, Robert Boyle engaged Robert Hooke in 1657 to build an improved version of the air pump, and together they began to experiment with reduced air pressures. They showed that a ringing bell produced no sound in a vacuum and that a feather and lead ball fall at the same rate in an evacuated jar. In his first scientific work, *New Experiments Physico-Mechanicall, Touching the Spring of the Air and Its Effects* (1660), Boyle described his experiments in both physics and the physiology of respiration. By gradually exhausting the air in a jar containing a mouse and a candle, he observed the resulting expiration of the candle at about the same time as the mouse.

In 1662, Boyle found the pressure-volume law now known by his name. He showed that the volume of a gas is inversely proportional to the applied pressure. The same law was discovered independently several years later by the French physicist Edmé Mariotte, who, in his *Discours de la nature de l'air* (1676; discourse on the nature of air), was the first to coin the word "barometer."

See also Atmospheric Circulation; Chaotic Systems; Weather Fronts.

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—*Joseph L. Spradley*

ATOMIC NUCLEUS

THE SCIENCE: Ernest Rutherford discovered the nucleus of the atom during experiments with radioactive elements. In the process, he deduced the true, divisible nature of the atom.

THE SCIENTISTS:

Ernest Rutherford (1871-1937), English physicist who won the 1908 Nobel Prize in Chemistry

Sir Joseph John Thomson (1856-1940), English physicist who won the 1906 Nobel Prize in Physics

Hans Geiger (1882-1945), German physicist

Ernest Marsden (1888-1970), Rutherford's assistant

Niels Bohr (1885-1962), Danish physicist who won the 1922 Nobel Prize in Physics

FROM PHILOSOPHY TO SCIENCE

Until the beginning of the twentieth century, nearly all atomic theory had come straight from philosophers. The early Greeks assumed that one could divide matter no farther than into tiny particles they called *atomos*, meaning indivisible. In English, *atomos* became "atom." Atomic theory was made more or less respectable by the British physicist and chemist Robert Boyle in the seventeenth century, but from a modern perspective it was still philosophy without hard scientific evidence.

On April 29, 1897, atomic science was transformed from philosophy to hard science. That evening, Sir Joseph John Thomson announced that he had discovered tiny subatomic particles, which he called "corpuscles," that were much smaller than the atom. They were later renamed "electrons." Thomson's discovery confirmed not only that atoms existed but also that they were probably made up of even smaller particles. According to Thomson's theory, the atom comprised a positively charged, fluidized interior of great volume and tiny, negatively charged electrons enclosed in the fluid. Thomson described the aggregate as similar to "plum pudding."

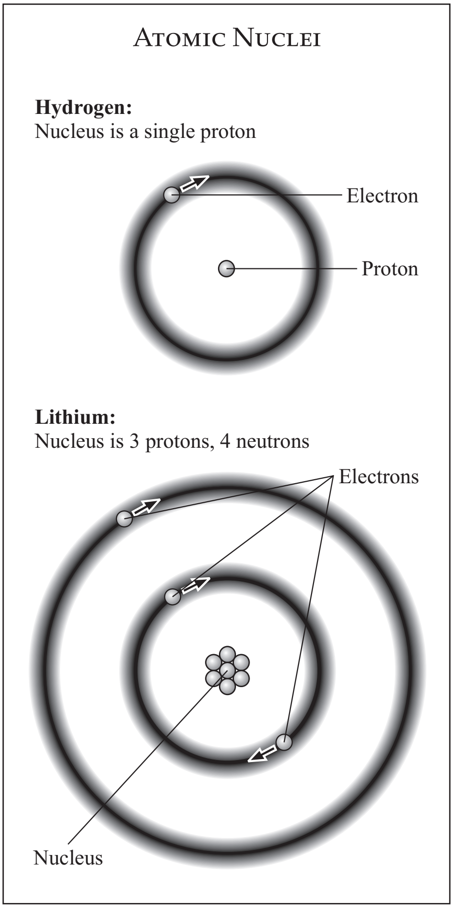
In 1907, Ernest Rutherford accepted a position at Manchester, England. He had been experimenting with the particles that appeared to emanate from the radioactive atom. These efforts had been narrowed to a series of experiments that he hoped would finally identify these particles and their nature. Assisting him were Hans Geiger and an undergraduate student named Ernest Marsden.

Enough data from Thomson's work had filtered in that Rutherford and his assistants knew that the electron was a piece of the atom and that it was both lighter and smaller than the whole atom. They also knew its charge was negative; whatever was left of the atom had to be much heavier and have a net positive charge. Yet the particles that were emitted by the radioactive material Rutherford was examining—called alpha particles—were much heavier than electrons but still smaller than a whole atom. The question that perplexed Rutherford was whether, like the electron, these were also a part of the atom.

Throwing Out the "Plum Pudding"

The experimental apparatus that Rutherford set up was quite simple compared with the multimillion-dollar devices used by physicists a century later. It consisted of a glass tube that held an alpha particle emitter at one end. At the other end was a target of gold foil and beyond that a fluorescent screen that acted as the detector.

The theory behind Rutherford's experiments was that the alpha particle from the radioactive element would race down the tube from its source and strike the atoms in the gold foil. If the atoms were made up of Thomson's "plum pudding," then as the massive alpha particle struck the electrons, they would be deflected only slightly or not at all. By measuring where the tiny blips of light struck the gold foil, Rutherford could calculate the angle of deflection and indirectly determine the mass of whatever the alpha particle had struck on its way down the tube. He reasoned that the deflections of the more massive alpha particles striking tiny electrons would be minimal, but that if, by the most bizarre of circumstances, one of these particles should encounter a series of electrons on its way through an atom, the deflection might register as much as 45°.


Atomic Nuclei

The experiments began in 1910 with Geiger assisting Marsden, counting the almost invisible flashes of light on the fluorescent screen through a magnifying lens in a completely blackened laboratory. They immediately found an astonishing effect. One out of about eight thousand alpha par-

Ernest Rutherford, Modern Alchemist

Born to a rural New Zealand family with twelve children, Ernest Rutherford depended on scholarships to pay for his education. He won many, finally reaching the prestigious Cavendish Laboratory in Cambridge, England, in 1895. There he worked alongside such eminent scientists as James Clerk Maxwell, John William Rayleigh, and his mentor J. J. Thomson.

It was the era when X rays were discovered, a scientific development that was to point the way to Rutherford's future work. His discovery of a curious "emanation" from thorium (radioactivity) was overshadowed by the discovery of radium by Irène and Frédéric Joliot-Curie, who were credited with the discovery of radioactivity. However, Rutherford and chemist Frederick Soddy recognized that radiation arose from the transformation of one element into another—an outrageous suggestion, with overtones of alchemy, but soon accepted by the scientific community. In 1908, Rutherford was awarded the Nobel Prize in Chemistry for his work on radioactivity.

By 1914 Rutherford had achieved international standing and was honored at home by a knighthood. He next began to use radioactivity to determine the nature of the atom itself. Max Planck and Neils Bohr separately pushed out the theoretical boundaries of atomic physics into quantum mechanics; Rutherford and his colleagues supplied the experimental verifications. When Rutherford smashed the atom in 1917 and the predicted particles were emitted, Bohr's theory was demonstrated beyond doubt. During this period World War I was raging, and Rutherford was called to discover ways of detecting submarines under water, concentrating on sonic methods. His talent for diplomacy was engaged to construct a team of scientists and naval officers to work together under difficult and sometimes hostile circumstances. In 1919, Thomson resigned as head of the Cavendish Laboratory and Rutherford was asked to take his place. Under his direction, the Cavendish led the world in atomic physics, and in 1925 he was elected president of the Royal Society.

Perhaps the greatest tribute to Rutherford's character and convictions can be seen in his efforts on behalf of those living under totalitarian regimes. In the 1930's, when many Jewish scientists had to flee from Nazi Germany, Rutherford became their champion. He enabled the Nobel Prize winner Max Born to work at the Cavendish, and he worked tirelessly on behalf of the brilliant Soviet physicist Peter Kapitsa when he was detained in Leningrad. For Rutherford, science was an international pursuit without geographical boundaries.

ticles was deflected at an angle, varying from greater than 45° to 180°.

It was obvious to Rutherford that plum pudding could never account for such wild deflections. He considered that perhaps the nucleus held a charge vastly greater than any hypothesized and that the alpha particle was being whipped around the interior of the atom like a comet tossed back into the deep solar system by the Sun.

The only other plausible explanation, which Rutherford eventually accepted, was that the atom contained a tiny, pinpoint nucleus that occupied only a minuscule portion of the total volume of the atom but, at the same time, itself contained nearly all the atom's mass. The electrons, he supposed, orbited like tiny, flyweight particles at huge distances from the densely packed core. On March 7, 1912, Rutherford presented his theory at the Manchester Literary and Philosophical Society.

Rutherford had the correct idea of the nucleus. Electrons do not "orbit" in the classical sense, however; they "exist" in a quantum state, as Niels Bohr would later prove. In the process, Bohr would change the face of physics. Rutherford's discovery would be the last major finding of classical physics. By 1913, Rutherford's vision would be replaced by Bohr's quantum view.

Impact

From the time of classical Greece, people had viewed matter as made up of tiny, indivisible particles. The notion was nothing more than an educated guess. It held through thousands of years not because of its inherent accuracy but because it was a useful paradigm and because of the lack of technology to prove otherwise. This idea became so firmly implanted that it became a kind of theology of reason without implicit cause. When Rutherford proved the notion of the indivisible atom wrong, he was met with immediate disbelief. At least Thomson's atom had substance; according to Rutherford, atoms were made up mostly of space.

Bohr would soon redefine the atom in new and innovative terms. Bohr described everything equal in size or smaller than the atom in terms of quantum mechanics, which deals with the interaction of matter and radiation, atomic structure, and so forth. Rutherford explored as deeply inside the atom as one could go within the framework of knowledge current at that time. A new science had to be developed to go even deeper. Quantum mechanics would join with Albert Einstein's work on relativity to reorder physics and redefine the nature of all matter and energy.

See also Atomic Structure; Atomic Theory of Matter; Compton Effect; Electrons; Isotopes; Neutrons; Nuclear Fission; Quarks.

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—*Dennis Chamberland*

ATOMIC STRUCTURE

THE SCIENCE: Niels Bohr applied Max Planck's quantum theory to Ernest Rutherford's nuclear model of the atom, providing a theoretical explanation for a large number of atomic phenomena.

THE SCIENTISTS:
Niels Bohr (1885-1962), Danish physicist
Ernest Rutherford (1871-1937), founder of nuclear physics
Sir Joseph John Thomson (1856-1940), discoverer of the electron

EARLY MODELS OF THE ATOM

At the beginning of the twentieth century, physicists were learning about the structure of the atom. In 1897, Sir Joseph John Thomson had discovered the part of the atom that became known as the electron, and he developed a model of the atom. It consisted of a central sphere, or "nucleus," that carried a positive electrical charge; around this sphere orbited the electrons, which carried a negative charge. All the electrons traveled in the same planar "shell"; moreover, the electrons accounted for a large portion of the atom's mass. At the time, this model was accepted by most scientists.

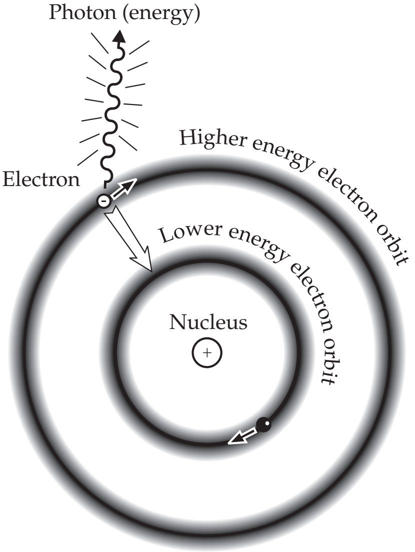
In 1911, both Niels Bohr and Thomson were at Cambridge University, where Bohr was completing his doctoral dissertation on the electron theory of metals. Bohr then went to Manchester, where he joined Ernest Rutherford, who had recently proposed a different model of the atom—one in which the positively charged nucleus was much smaller than the atom as a whole. At the same time, even though the size of this nucleus was very small, its mass was very great. There appeared to be a problem with Rutherford's model, however: It was not stable according to the laws of physics that were known at that time, which were governed by Sir Isaac Newton's laws of mechanics.

BOHR'S MODEL: STATIONARY ORBITS

Bohr became interested in this problem after reading a paper by Charles Galton Darwin and noticing some errors in it. Because classical mechanics could not explain how the atom could remain stable, Bohr decided to turn to Max Planck's quantum theory. He assumed that an electron must have a certain, exact amount of energy in order to maintain a stable orbit around a nucleus. This amount of energy, which was defined by a ratio discovered by Planck, is called Planck's constant. Bohr called such stable orbits "stationary states."

This theory allowed Bohr to explain the relationship of many different chemical elements to one another and to position them on the periodic table of elements. He suggested that the radioactive properties of an element (which determine how unstable it is) depend on the atom's nucleus, and the chemical properties of an element (which determine how it combines with other elements to form molecules, for example) depend on the number of electrons in the atom. Bohr also considered how atoms would act in different

BOHR'S MODEL OF THE ATOM



In Bohr's model of the atom, electrons orbit the nucleus in discrete energy states. When an electron moves from a higher-energy orbit to a lower-energy orbit, the extra energy is released as a photon of light.

Niels Bohr. (The Nobel Foundation)

energy states and explained some of the phenomena that had been observed concerning the spectral lines emitted by atoms.

Bohr discovered that electrons could travel in various stable orbits, or stationary states, around an atomic nucleus, not only in a single stable orbit, as Thomson had thought. It was possible for an electron to move from a higher-energy orbit farther from the nucleus to a lower-energy orbit closer to the nucleus, or vice versa. The electron could move to a higher-energy orbit if it received energy from outside the atom, and it could move to a lower-energy orbit if it gave off energy. The energy given off or received by the electron could be seen as a "spectral line," a light or dark line in the spectrum of light given off by the atom. Such a line would be either an "absorption line" (if the electron received the energy) or an "emission line" (if the electron gave off the energy).

Bohr presented his ideas about the atom in a trilogy of papers published over the course of the year 1913. Reactions were mixed, because most physicists at the time still doubted that Planck's quantum theory could have any effects on observed physical phenomena. This changed, however, when Bohr's theory began to explain the details of the spectra emitted by atoms, which had not been satisfactorily explained before. More physicists began to accept the new atomic model.

Impact

One part of Bohr's theory, called the "correspondence principle," became especially important in the overall development of quantum theory, which in turn shaped all of modern physics. According to the correspondence principle, the results of quantum mechanics do not conflict with those of classical mechanics in the realm of physical phenomena, where classical laws are valid. Bohr's original theory was therefore extended to other areas of physics.

Bohr's theory was able to make remarkably accurate predictions for atoms with a single electron; it was less reliable, however, when it was applied to atoms with more than one electron. In 1920, Bohr focused on this problem and presented an improved and consistent theory.

Bohr's groundbreaking trilogy of 1913, although flawed, paved the way for quantum mechanics, which would ultimately dominate twentieth century physics. Bohr himself not only continued to contribute to physics but also educated a new generation of physicists who went on to develop quantum mechanics. Although he never became as famous as Albert Einstein, his work is among the most important in the history of physics.

See also Atomic Nucleus; Atomic Theory of Matter; Compton Effect; Electrons; Isotopes; Neutrons; Nuclear Fission; Quarks.

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—*Roger Sensenbaugh*

ATOMIC THEORY OF MATTER

THE SCIENCE: The formulation of the atomic theory of matter and the first tabulation of atomic weights by John Dalton had a profound effect on the development of chemistry and established the basis for quantitative chemistry.

THE SCIENTISTS:

John Dalton (1766-1844), English chemist and meteorologist

Thomas Thomson (1773-1852), Scottish chemist and medical doctor
Antoine-Laurent Lavoisier (1743-1794), French chemist
Joseph-Louis Proust (1755-1826), French chemist
Jons Jakob Berzelius (1779-1848), Swedish chemist
Joseph Louis Gay-Lussac (1778-1850), French chemist and physicist

Atomic Mass

In 1803, John Dalton wrote a classic paper titled "The Absorption of Gases by Water and Other Liquids," which was published in 1805. Near the end of the paper, he proposed an atomic theory of matter that also included the first published tabulation of atomic weights. His concept of atoms was directly related to the measurable property of mass. He had determined the relative weights of a number of atoms from chemical analyses that were available for water, ammonia, carbon dioxide, and a few other substances.

Dalton assumed that chemical combination always occurred in the simplest way possible with the smallest number of atoms. This insight led him to the principle that particles of different mass can combine chemically. It also led him to assume, incorrectly, that only one atom of hydrogen combines with oxygen to form water. As a result, he concluded that oxygen atoms weighed eight times as much as hydrogen atoms.

Experiments conducted later by Joseph Gay-Lussac showed that two atoms of hydrogen combine with oxygen to form water, which required a change in Dalton's table of atomic weights. Since Dalton was a very independent scientist who feared that others might misguide him in his research, he was reluctant to accept the findings of Gay-Lussac.

Dalton continued the development of his atomic theory of matter in a series of lectures that he presented in London in 1803, in Manchester, England, in 1805, and in Edinburgh, Scotland, in 1807. The motivation that led Dalton to his atomic theory was discovered by chemist Henry Roscoe after Dalton's death. Roscoe carefully studied Dalton's notebooks and concluded that Dalton had formulated his atomic theory of matter from his observations that gases with different densities mix together instead of separating into layers. It was also motivated by an idea proposed by Joseph Proust in 1800 that elements combine in definite proportions to form compounds.

Proust's concept enabled Dalton to associate the idea of an atom with the concept of an element. Although Dalton's scientific experiments were carried out with crude, homemade experimental equipment that produced rather imprecise data, they were of high enough quality to provide the necessary clues that Dalton's creative mind needed to formulate the explanation for the observed data. However, because of the many revisions that

Dalton made in his lab notebooks, as well as the lack of dates on many of the pages, it is almost impossible to determine the exact time when he formulated the atomic theory of matter.

Five Basic Principles

In 1808, Dalton published the details of his atomic theory in *New System of Chemical Philosophy*. His atomic theory can be summarized by five basic statements:

(1) All matter is composed of small particles called atoms.
(2) Atoms are the smallest entities that make up matter. They cannot be subdivided, created, or destroyed.
(3) The atoms of a specific element are identical in size, mass, and all other properties. The atoms that make up different elements differ in size, mass, and other properties.
(4) The atoms of different elements can combine in simple, whole-number ratios to form chemical compounds.
(5) Atoms are combined, separated, or rearranged in chemical reactions.

Dalton defined an element to be a substance composed of only one kind of atom. His theory provided a natural way to represent chemical compounds. After inventing a set of elemental symbols, he used them to combine different elements to provide schematic representations of what he believed were the molecular structures of a variety of compounds.

Dalton constructed the first periodic table of elements. He used letters and symbols arranged inside of circles for his scheme. Later, Jons Jakob Berzelius pointed out that the circles were not needed and recommended the one- or two-letter symbols currently used in the periodic table of elements.

Impact

Although Dalton's atomic theory did not initially attract much attention from other scientists, his publication of *New System of Chemical Philosophy* (1808), along with Thomas Thomson's *A System of Chemistry* (1807), stirred great interest in Dalton's theory. The atomic theory of matter allowed Dalton and others to explain many principles of chemistry with simplicity. Dalton's theory explained the fact that mass can be neither be created nor destroyed in chemical or physical reactions. This is known as the law of conservation of mass, a principle first discovered by Antoine-

Laurent Lavoisier around 1789. Dalton's theory also explained the law of definite proportions, which states that every chemical compound has a definite composition by mass. The amounts of products and reactants in any particular chemical reaction always occur in the same definite proportions by volume of gases or by numbers of molecules.

John Dalton: From Atmosphere to Atom

From the time that he was a young boy, John Dalton showed a keen interest in scientific observations. A poor, mostly self-taught individual, Dalton developed an intuitive ability to formulate a theory that could explain a collection of data. Between 1787 and 1844, he kept a daily record of the weather, recording more than two hundred thousand meteorological observations in his notebooks. This interest led him to investigate the composition and properties of gases in the atmosphere. He realized that water could exist as a gas that mixed with air and occupied the same space as air.

(Library of Congress)

Dalton was deeply influenced by the British tradition of popular Newtonianism, a way of visualizing the world through the internal makeup of matter and the operation of short-range forces. Sir Isaac Newton had shown that these forces could be described mathematically. Dalton was also interested in scientific applications: barometers, thermometers, rain gauges, and hygrometers. He wrote essays on trade winds, proposed a theory of the aurora borealis, and advanced a theory of rain. His meteorological investigations caused him to wonder how the gases in the air were held together: Were they chemically united, or were they physically mixed together just as sand and stones were in the earth? He concluded that gases, composed of particles, were physically mixed together, and this led him to deduce that in a mixture of gases at the same temperature, every gas acts independently (Dalton's law of partial pressures).

It is ironic that in trying to provide a proof for his physical ideas, Dalton discovered the chemical atomic theory. What started as an interest in meteorology ended up as a new approach to chemistry. When he published his table of atomic weights in a Manchester journal, his theory initially provoked little reaction, and Humphry Davy at the Royal Institution rejected Dalton's ideas as mere trivial speculations. Dalton persevered, and in 1804 he worked out the formulas for different hydrocarbons. By 1808, he had published the first part of his system of "chemical philosophy." With this publication, the chemical atomic theory was launched.

In the latter part of 1808, Dalton once again concentrated his efforts on meteorological research and associated investigations. He also frequently defended his atomic theory of matter in private conversations and in scientific meetings. Since he pictured atoms as hard, indivisible spheres, his theory provided no insight into the structure of atom or its components; consequently, the theory cast no light on the way atoms of different elements can bond together. Dalton's theory, however, laid the foundation for other scientists to pursue and eventually explain these phenomena.

John Dalton is referred to as the father of modern atomic theory. Until Dalton proposed the atomic theory of matter, the concept of atoms that was originally stated by Leucippus and Democritus in the fourth century B.C.E. remained a very simplistic idea. Dalton's atomic theory provided chemists with a new, enormously fruitful model of reality. It led to two fundamental laws of nature—the law of conservation of mass and the law of definite composition—which eventually led to the periodic table of elements. In addition, his theory of the existence of atoms led to the explanation of many confirmed experimental results.

Nevertheless, Dalton's theory is still used to explain the properties of many chemicals and compounds today. His theory has been expanded to explain new observations, including the existence of elementary particles that make up the internal structure of atoms and the existence of isotopes of atoms. A variety of isotopes can be used to trace the various steps in chemical reactions and metabolic processes in the human body. Tracer techniques have proven invaluable in the clinical diagnosis of many disorders in the body.

Because Dalton's theory formed the foundation for the science of chemistry, Dalton is also considered to be the father of modern chemistry (although Lavoisier also vies for that distinction). Dalton's atomic theory has led to many significant applications, including the development of the best model of the atom, the description of different phases of matter, the harnessing of atomic energy, the development of atomic weapons, the quantitative explanation of chemical reactions, and the chemistry of life. Dalton's theory established the framework for the development of biochemistry and the understanding of the bonding of carbon atoms to form chains and branching structures that are essential in the formation of sugars, fatty acids, nucleic acids, carbohydrates, proteins, and other molecular structures on which life is based.

See also Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Compton Effect; Electrons; Isotopes; Neutrons; Nuclear Fission; Quarks.

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—*Alvin K. Benson*

Australopithecus

THE SCIENCE: Raymond Dart discovered the first australopithecine, or link between ape and human, cast in limestone recovered from a quarry in Taung, South Africa.

THE SCIENTISTS:

Raymond Arthur Dart (1893-1988), anatomist who discovered the first "missing link" between apes and humankind

Robert Broom (1866-1951), Scottish physician

EARLY HOMINID FINDS

In 1871, Charles Darwin suggested in *The Descent of Man and Selection in Relation to Sex* that it was quite likely that Africa would prove to be the continent where humankind first appeared. Darwin's suggestion was to become the center of a debate that greatly influenced the field of paleoanthropology. He made his suggestion despite the fact that the only human fossils known at the time had been found in Europe; for example, the first paleontological human remains were those of Neanderthal man, found in Germany in 1856. Indeed, the first hominid remains discovered outside Europe were those from Java found in 1891 by Eugène Dubois, which prompted Western scientists to believe that humans first appeared in Asia, not Africa. Dubois's find, better known as Java man, has since been reclassified into the genus and species *Homo erectus*.

In 1907, a fossil known as the Heidelberg man was discovered in Germany. The next hominid remains believed to be of major significance were those found by Charles Dawson in 1911 in Sussex in southern England. This fossil was placed into a new genus and species known as *Eoanthropus dawsoni*, meaning "Dawson's dawn man." The fossil is perhaps best known as Piltdown man. While most fossil discoveries that are given a new name create controversy, this was not true of Dawson's find, because it looked the way most anthropologists of the time thought it should. In other words, the cranium was large and modern-looking, and the face was primitive and apelike. At the time, it was widely believed that intellect was an important step in the evolution between humans and apes, an idea supported by the large cranium. Additionally, since a human ancestor would need to possess some primitive traits, these might be found in the face and lower jaw.

Taung Baby

In 1924, Raymond Arthur Dart was a young professor of anatomy in his second year of teaching in the Medical School at the University of Witwatersrand in Johannesburg, South Africa. Early during that summer, a fossil was brought to him from the Taung quarry by a student, Josephine Salmons. While Dart determined that the fossil was that of a previously found extinct form of baboon, it prompted his interest in the limestone quarry at Taung. He made arrangements to receive any other fossils the workers might find in the quarry, and he later received some boxes from Taung that contained more fossils. In one box was an unusual endocast, or fossilized cast, representing the interior of a cranium, notable for its size and unique structure. Dart recognized the anatomy as that of a higher primate, but unlike that of any living ape by virtue of its increased size. Also included was a single large fragment of a fossilized facial skeleton. The endocast and face were portions of the same animal. To Dart, the remains revealed a never-before-seen combination of traits, suggesting an anthropoid halfway between man and ape.

In February, 1925, Dart introduced his find to the scientific community with a brief article in the British journal *Nature*. He described the fossil as a juvenile member of a new genus, *Australopithecus*, and new species, *africanus*. *Australo* means "of the Southern Hemisphere," *pithecus* means "simian" or "apelike," and *africanus* means "of Africa." Thus, *Australopithecus africanus* literally means "the South African ape."

Except for Robert Broom, a Scottish physician who had become a well-known paleontologist as a result of his South African discoveries bridging the gap between reptiles and mammals, the scientific community immediately opposed the acceptance of Dart's discovery. A major criticism was re-

A Gift Before the Wedding

On a Saturday afternoon in 1924, Raymond Dart was dressing for a wedding reception when he received a shipment of fossils from Taung and decided to take a peek before leaving:

. . . a thrill of excitement shot through me. On the very top of the rock heap was what was undoubtedly an endocranial cast or mold of the interior of the skull. Had it been only the fossilised brain cast of any species of ape it would have ranked as a great discovery, for such a thing had never before been reported. But I knew at a glance that what lay in my hands was no ordinary anthropoidal brain. Here in lime-consolidated sand was the replica of a brain three times as large as that of a baboon and considerably bigger than that of an adult chimpanzee. The startling image of the convolutions and furrows of the brain and the blood vessels of the skull were plainly visible.

It was not big enough for primitive man, but even for an ape it was a big bulging brain and, most important, the forebrain was so big and had grown so far backward that it completely covered the hindbrain.

But was there anywhere among this pile of rocks, a face to fit the brain? I ransacked feverishly through the boxes. My search was rewarded, for I found a large stone with a depression into which the cast fitted perfectly.

I stood in the shade holding the brain as greedily as any miser hugs his gold, my mind racing ahead. Here I was certain was one of the most significant finds ever made in the history of anthropology.

Source: Raymond A. Dart, *Adventures with the Missing Link* (New York: Harper and Brothers, 1959).

lated to Dart's introduction of the new name based on a juvenile specimen. There was no question that the fossil was that of a juvenile, since the specimen retained some of its deciduous, or baby, teeth. As a result, Dart's discovery has frequently been called Taung child, Taung baby, or Taung boy.

Some critics seized this issue and argued that new names should not be based on juvenile specimens because dramatic differences between juveniles and adults of the same species might exist. Some argued that Dart may have simply found a juvenile member of an already documented fossil primate. Criticisms also were based on the fact that the discovery was made in South Africa and not Asia, where the world's attention had become focused since Dubois's discovery in 1891. Additionally, Dart's discovery possessed a small brain and a relatively modern-looking face and dentition, unlike Dawson's Piltdown man.

A New Species

By the mid-1950's, however, the discoveries of adult forms of *Australopithecus* and other intermediate forms in the same area compelled many of Dart's critics to accept his 1924 discovery. Many critics were converted to Dart's ideas as a result of the 1947 Pan-African Congress of Prehistory held in Nairobi, Kenya. The congress, organized by Louis S. B. Leakey, allowed several widely respected physical anthropologists to examine some of the early African hominids firsthand.

The last barrier to acceptance was torn down in the early 1950's. In 1953, Kenneth Page Oakley and others began a reexamination of *Eoanthropus dawsoni*. A new dating technique, fluorine dating, revealed that the cranium was from the late Pleistocene epoch, while the mandible belonged to a modern orangutan. Both portions had been modified and stained in order to appear as though they had come from the same animal. Piltdown man was thus exposed as a fraud, and its existence could no longer hinder the acceptance of the South African australopithecines as the link between modern *Homo sapiens* and living apes.

Impact

While the limestone and sedimentary contexts from which the South African fossils were recovered did not lend themselves to accurate geological dating, one could suggest that the fossils were from the lower Pleistocene epoch, approximately 1 million years ago. Moreover, the South African discoveries led paleoanthropologists to conclude that early hominids first appeared in a grassland or savannah environment, as opposed to the tropical forests others were suggesting. In addition, *Australopithecus africanus* and the remaining australopithecines provided clear evidence that human ancestors possessed more or less modern jaws and were walking upright before the expansion of the brain. This idea contradicted the previous notions about the significance of increased cranial capacity during human evolution.

Some have called Dart's discovery of the first *Australopithecus* one of the most significant scientific events of the twentieth century. Though such claims are debatable, there can be little question that the discovery must rank near the top of any list of important events in the fields of anthropology, paleontology, and prehistory.

See also Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Turhon A. Murad*

AXIOM OF CHOICE

THE SCIENCE: Beppo Levi acknowledged and criticized the axiom of choice in set theory and attempted to justify and carry out infinite choices.

THE SCIENTISTS:

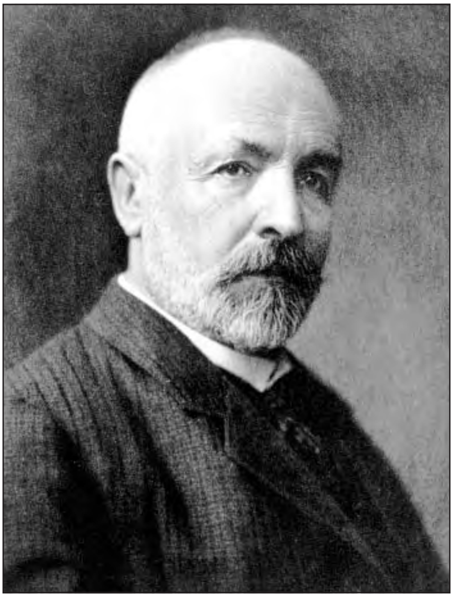
Beppo Levi (1875-1961), Italian mathematician
Giuseppe Peano (1858-1932), Italian mathematician and logician
Felix Bernstein (1878-1956), German mathematician
Georg Cantor (1845-1918), German mathematician

ACTUAL AND POTENTIAL INFINITIES

The notion of infinity has been a perennial problem in both mathematics and philosophy. A major question in (meta) mathematics has been whether and in what form infinities should be admitted. The debate of Gottfried Wilhelm Leibniz and Sir Isaac Newton on the use of the "infinitesimal" in seventeenth century differential calculus is only one of many possible examples of this problem. In most pre-twentieth century mathematics, infinities occur only in what might be called a "potential" (inactual, implicit) form.

Potential infinity can be illustrated readily by considering a simple example from limit theory. There is no question of an actually infinitely great or infinitesimally small quantity to be computed or otherwise arrived at. As set theoretician Abraham A. Fraenkel remarked in *Set Theory and Logic* (1966), many nineteenth century mathematicians—such as Carl Friedrich Gauss and Augustin-Louis Cauchy—considered infinity in mathematics to be largely a conventional expression showing the limits of ordinary language when pressed into trying to express pure mathematical concepts.

In addition to the less problematic notion of potential infinity, an equally old problem of "actual" infinity had long been faced in speculative philosophy and theology, including that of Saint Augustine, Saint Thomas Aquinas, René Descartes, and Immanuel Kant, among many others. A major thematic front throughout nineteenth century mathematics and logic was precise clarification of the boundary and relations between actual and potential infinities, in foundational as well as applied mathematics. One of the earliest such efforts was that of Bernhard Bolzano, whose *Paradoxien des Unendlichen* (1851; *Paradoxes of the Infinite*, 1950) cataloged a large number of extant and novel conundrums, as well as unclear and unusual properties of actual infinities in mathematics. A particular emphasis, to recur repeatedly in later set theory and logic, was the apparent paradox of the equivalence of an infinite set to a proper part or subset of itself—which counterintuitively implies different levels or kinds of infinity where previously only one infinity was supposed. The term "set" was first employed in Bolzano's text as an important mathematical concept.



Georg Cantor. (Library of Congress)

Cantor's Set Theory

The first major developments in forming a consistent and comprehensive theory of actual infinities in mathematics were primarily the work of Georg Cantor. Between 1873 and 1899, Cantor sought to lay systematically the foundations for a new branch of mathematics—called the theory of aggregates or sets—which would not only formalize the mathematically acceptable concepts of infinity but also serve as the foundation for every other mathematical theory and discipline employing infinities. Cantor's set theory did not begin with philosophical speculations about infinity but with the problem of actually distinguishing finitely and infinitely many "specified" points—for example, the points of discontinuity in the theory of functions. Yet, despite many strenuous efforts, Cantor, as well as Richard Dedekind, Giuseppe Peano, and many other mathematicians, blurred (or passed over unawares) the distinction of choices implicitly or explicitly made by some kind of a rule or algorithm, from which a given denumerable or indenumerable (uncountable) point set was defined.

In particular, although the first *n* members of a subset were seen clearly as selected specifically by a selection- or generative-rule, neither Cantor nor anyone else explained how such a rule could actually be extended to define likewise the entire (actually infinite) subset. This problem was complicated by the fact that many mathematicians of the era frequently made an infinity of arbitrary selections, not only independently but also where each given choice depended on the choices previously made. These questions not only undercut the proof method of using "one to one" mappings or correspondences between different sets but also underscored the then-formulating foundational questions of whether "in the last analysis" mathematical entities such as sets are discovered or are defined/created.

BEYOND INFINITY

In 1882, particularly, Cantor argued to Dedekind and others that his means of extending the (infinite) sequence of positive numbers by introducing symbols for infinity (such as ∞, $\infty + 1$, $\infty + 2$, and the like) was not merely conventional but a legitimate number choice.

Perhaps the simplest example of Cantor's transfinite numbers is the model suggested by Zeno's paradoxes of motion. Here, a runner uniformly traverses a road divided into intervals. Although the number of intervals is ∞, the time taken to traverse them is finite (hence, the paradox). If the first interval is designated the $\omega -$ th interval, the subsequent intervals will be the $\omega + 1 -$ th, $\omega + 2 -$ th, and so on. These numbers ω, $\omega + 1$, $\omega + 2$, and so on, are the transfinite ordinal numbers first designated by Cantor.

Also called into question was Cantor's related continuum hypothesis, which asserts that every infinite subset of the real numbers either is denumerable (countable via a finite procedure) or has the degree of infinity of the continuum. In Cantor's sense, the continuum is defined by the assumption that, for every transfinite number t, 2^t is the next highest number. Equivalently, the continuum hypothesis proposes that there is no (transfinite) cardinal number between the cardinal of the set of positive integers and the cardinal of the set of real numbers.

These developments, and other related developments, left early twentieth century set theory with a network of fundamental, interlinked, and unsolved problems, all of which somehow involved the notions of selection or choice, linking well-known finite mathematics with the newer mathematics of actual infinities. Nevertheless, very few, if any, mathematicians explicitly considered all these questions from this viewpoint.

Justifying Infinite Choices

Peano, an Italian mathematician responsible for the first symbolization of the natural number system of arithmetic, was coming up against similar inconsistencies in his investigations of the conditions for existence and continuity of implicit functions. In 1892, one of Peano's colleagues, Rodolfo Bettazzi, investigated conditions under which a limit-point was also the limit-point of a sequence. Bettazzi underscored the same underlying issue as Peano. The third mathematician to consider this problem of how to justify or actually carry out infinitely many choices was Peano and Bettazzi's colleague, Beppo Levi.

Levi was completing his dissertation research, inspired by René Baire's work in set theory. Baire had developed the novel notion of "semi-continuity" for point sets. In 1900, Levi published a paper extending Baire's investigations of fundamental properties satisfied by every real function on any subset of the real numbers. Without proof, Levi proposed that every subset 1 is equal to the union of subsets 2 and 3 minus subset 4, where 2 is any closed set, and 3 and 4 are "nowhere-dense" sets. Levi also asserted that every uncountable subset of the real numbers has the power of the continuum, essentially Cantor's continuum hypothesis.

In another dissertation of 1901, a student of Cantor and David Hilbert, Felix Bernstein, sought to establish that the set of all closed subsets of the real number system has the power of the continuum. In 1897, Bernstein had given the first proof of what is known as the equivalence theorem for sets: If each of two sets is equivalent to a subset of the other, then both sets are mutually equivalent. In his 1901 work, Bernstein remarked that Levi's 1900 results were mistaken. As a response, in 1902 Levi published a careful analysis of Bernstein's dissertation, in which his use of choices in defining sets came into sharp and explicit critical focus.

In Levi's broad analysis of then extant set theory, he questioned Cantor's assertion that any set can be well-ordered. Well-orderedness is the property whereby a set can be put systematically into a one-to-one correspondence with elements of another set. Levi pointed out that even though Bernstein had openly abandoned the well-ordering principle, Bernstein had, nevertheless, employed an assumption that appeared to be derived essentially from the same postulate of well-orderedness. This questionable assumption was Bernstein's so-called partition principle; that is, if a set R is divided or partitioned into a family of disjoint (nonintersecting) nonempty sets S, then S is less than or equal to R. Following Levi's proof that Bernstein's partition principle was valid only whenever R was finite, Levi critically remarked that the example was applicable without change to any other case where all the elements s of S are well-ordered, or where a unique element in each s can be distinguished. This statement is, essentially, a summary of what would be explicitly termed the axiom of choice.

Impact

Although Levi's axiom of choice proved to be a catalyst for subsequent work by Bernstein, Hilbert, Ernst Zermelo, and many other mathematicians, the direct response to and recognition of Levi's 1902 paper was limited. Basically, although Levi explicitly recognized the axiom of choice embodied in the work of Cantor and Bernstein, he rejected its use in its then current form. This led ultimately to Zermelo's 1904 publication, proving the well-ordering principle by use of the axiom of choice.

In his 1910 seminal paper on field theory foundations in algebra, Ernst Steinitz summarized the widespread attitude toward the axiom of choice in algebra, topology, and other disciplines. Thus, although explicit examination of the axiom of choice was largely ignored for some time, beginning in 1916 the Polish mathematician Vacυaw Sierpiński issued many studies of implicit as well as open applications of the axiom of choice. Although Levi in 1918 offered what he called a "quasi-constructivist" improved alternative to the axiom, his effort was considered too limited and unwieldy by most mathematicians. In 1927, American logician Alonzo Church sought unsuccessfully to derive a logical contradiction from the axiom. No alternative was developed until 1962, when two Polish mathematicians, J. Mycielski and H. Steinhaus, proposed their axiom of determinateness. Since then, it has been shown that a number of other propositions are equivalent to varyingly weaker or stronger forms of the axiom of choice, as originally recognized by Levi and positively employed as such by Zermelo.

See also Abstract Algebra; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Gerardo G. Tango*

BALLISTICS

THE SCIENCE: Sixteenth century theories on bodies in motion gave rise to a generation of scientific investigation into the science that came to be known as ballistics. Niccolò Tartaglia's observation-based theories helped pry sixteenth century physics away from Aristotelian thinking, which was entrenched in the Church-supported schools and universities, and toward an empirical, experimentally based physics approaching the modern scientific method.

THE SCIENTISTS:

Niccolò Fontana Tartaglia (c. 1500-1557), Italian mathematician

Gerolamo Cardano (Jerome Cardan; 1501-1576), Italian mathematician and astrologer

Giovanni Battista Benedetti (1530-1590), Italian mathematician and physicist

ARISTOTELIAN MOTION

The influence of the Greek philosopher Aristotle's theory of motion and other scientific concepts, left over from the study of the physical world in classical Greece, was pervasive throughout the Middle Ages. Attempts to devise new theories of motion took the form of commentaries on the works of Aristotle rather than observation and description of the physical world. The mathematics used in these descriptions could be found in the geometry of Euclid's *Stoicheia* (compiled c. 300 B.C.E.; *Elements*, 1570). Then, work in Italy in the middle of the sixteenth century led to a reevaluation of the basis for mathematical models of motion in the physical world.

FROM ARISTOTLE TO TARTAGLIA

Aristotle (384-322 B.C.E.) had devoted a certain number of the works that circulated under his name to questions having to do with physics, although they were usually addressed from the standpoint of what might be called philosophy instead of mathematics or science. His concern was primarily to understand how motion and change were possible, in resisting the arguments of many of his contemporaries, who denied that possibility. By contrast, the tradition associated with the Greek mathematician Archimedes (c. 287-212 B.C.E.) started from the reality of certain physical processes and then tried to analyze them in terms of the mathematics known at the time, especially the geometry of Euclid. Both approaches to the study of motion continued through the Middle Ages, although the Aristotelian ideas received a larger share of attention and blessing from the Church. Those who studied questions of motion in the universities of Western Europe could be guaranteed a fair dose of Aristotelian doctrine.

It is therefore not surprising that the originator of the most lasting revolution in the study of motion outside the tradition of Aristotle was not the product of a university. Niccolò Tartaglia came from a family unable to bear the cost of formal education, so he was largely self-educated. That did not mean that he was unfamiliar with the extensive classical literature surrounding issues of motion, but he had no particular predisposition in favor of the Aristotelian view. Throughout the early part of the sixteenth century, various treatises, from both classical and medieval times, appeared in Italy, and Tartaglia was involved in bringing the work of Archimedes before the public. Tartaglia's approach to the science of mechanics, which included the laws of motion, was based partly on his independence from tradition and partly on the need to try to resolve questions of pressing interest to those who had resources with which to support scholars.

Projectiles in Motion

Tartaglia's *La nova scientia* (1537; *The New Science*, partial translation in *Mechanics in Sixteenth-Century Italy: Selections from Tartaglia*, 1969) first appeared in Latin in 1537 and then appeared in the vernacular within fifteen years afterward. In it, Tartaglia addressed one of the most compelling practical problems of the time: the study of the behavior of projectiles in motion, which came to be known as ballistics. These questions were key to understanding the operations of siege weapons, cannon, and firearms, or guns.

There had been plenty of practical discussion of gunnery previously, but not much of it had aspired to the dignity of a science. Tartaglia did not see any reason that the methods of mathematics could not be used to find solutions for the problems of gunnery, of which the most notable was the relationship between the angle at which a projectile was launched and the trajectory it followed. This was not an idle matter, with city walls to be bombarded in sieges, but it also could be fit into a mathematical framework. In Aristotelian accounts of motion, the fundamental curves were the straight line and the circle, so it had been assumed that the motion of a projectile could be analyzed as a mixture of those two. Just as the Aristotelian version of mechanics had been built into the system for planetary motion developed by the Greek astronomer Ptolemy (c. 100-c. 178 C.E.), only to be replaced in 1543 by the system developed by the Polish astronomer Nicolaus Copernicus, so the Aristotelian theory of motion as applied to projectiles was rejected by Tartaglia, who recognized that circles and straight lines were not the best constructs for analyzing motion.

Tartaglia's mathematical treatment of the path of a projectile arose from empirical observation. He observed that, even if the projectile started off in a straight line, it began to curve and followed that curve for the rest of its flight. The curve was clearly not a circular arc, which left Tartaglia with the problem of determining what angle would produce the maximum range. Even though there was an error in Tartaglia's mathematical analysis, he did obtain the correct value, namely, 45° as the angle of inclination. Tartaglia did not have a theoretical model that explained the deviations from a straight line, but his empirical approach allowed the application of mathematics to this practical problem.

Gerolamo Cardano, a professor of mathematics in Milan and a rival of Tartaglia, held views on motion that were similar to those of Tartaglia. Unlike Tartaglia, however, Cardano was the product of the Italian university system and did not express his ideas as explicit deviations from Aristotle. Cardano asserted that if two spheres of different sizes were released at the same time, they would reach the ground at the same time. His mathemati-

THE SECRET OF CUBIC EQUATIONS

In addition to establishing the field of ballistics, Niccolò Tartaglia was a great mathematician who succeeding in solving cubic equations. Tartaglia was not the first to approach the problem. Ancient mathematicians tried to extract cube roots, and so even the Greeks considered the issue of whether they could handle such calculations with Euclidean methods. In medieval Islamic mathematics, trigonometry afforded a new set of techniques for looking at algebraic equations. It was not clear how much Islamic material was brought back to Europe, along with the text of Euclid used by mathematicians in the Near East.

The mathematician Scipione del Ferro had devised a method for solving cubic equations in which there was no quadratic term. Del Ferro passed his along to a student, Antonio Fiore, who challenged Tartaglia to a mathematical duel. Tartaglia had managed to go beyond the technique of del Ferro and could solve cubic equations even when they included a quadratic term. As a result, he emerged victorious, becoming the "star" among mathematicians of the time.

(Library of Congress)

Tartaglia was reluctant to let the details of his method enter the public realm. He had, however, discussed them with mathematician Gerolamo Cardano, whom he swore to secrecy. Cardano subsequently claimed to have found a way to solve a quartic equation (solving with a fourth power of the variable) but went beyond the cubic equation of Tartaglia and so felt that he was released from his vow of secrecy. The heated controversy that resulted when Cardano published Tartaglia's method—even though he gave Tartaglia credit by name—is an indication of the extent to which intellectual property was an important issue in the Italy of the Renaissance. Tartaglia had no shortage of strong language to use when he was indulging in acrimonious debate, and he was not always able to make the same impression in public confrontations as he had done with Fiore. This probably contributed to his relative isolation later in life. He died with relatively little to show for his success in solving cubic equations.

cal argument for this theory was unconvincing, however, and Tartaglia—incensed over Cardano's intellectual theft—impugned both his character and his mathematical competence. History, however, has recognized Tartaglia's achievement and credits him as the father of ballistics.

The third member of the school of northern Italians who created the new science of ballistics was Giovanni Battista Benedetti, who claimed to have been a student of Tartaglia. He shared with Tartaglia the lack of a university education and in 1553 published a work on mechanics, *De resolutione*, that included a letter of dedication in which he asserted the "law of equal times of fall" that had been presented less clearly and argued for less effectively by Cardano. This law asserts that the time of descent for a body depends on the vertical distance traveled rather than the distance covered in other directions. The fact that the letter of dedication was to a priest is typical of the extent to which Tartaglia and Benedetti managed to stay on good terms with the Church in presenting notions contrary to the teachings of Aristotle. It is interesting to note that Cardano, by contrast, did spend some time in prison at the behest of the Inquisition. Perhaps his efforts to give an Aristotelian flavor to his novelties in the theory of motion were regarded with more alarm by the Church than the more practical speculations of Tartaglia and Benedetti.

Impact

The appearance of Tartaglia's work and its influence on the school that included Cardano and Benedetti indicates a change from the intellectual and mathematical traditions of the past. Even though Tartaglia was familiar with the works of Euclid, he had a stronger interest in trying to predict the motion of projectiles than in trying to fit his observations into the geometry that Euclid presents. In particular, the idea that motion requires more than lines and circles for its analysis helped to remove the Aristotelian qualitative discussions from the center of the stage in favor of mathematical models.

As for the influence of Tartaglia's work on the generations ahead, the outstanding example is certainly Galileo. In fact, Galileo in many ways was trying to perfect the ideas roughly sketched out by Tartaglia, Cardano, and Benedetti, by fitting them into a full world system. It was perhaps the attempt to make a world system out of his calculations that caused Galileo to follow Cardano into the clutches of an Inquisition reluctant to allow quite so much of Aristotelian physics to be abandoned. It is also clear that political protection was an important consideration for research into the motion of projectiles, with safety coming to those whose mathematical models helped their patrons to remain the victors.

See also D'Alembert's Axioms of Motion; Falling Bodies; Gravitation: Newton; Medieval Physics.

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—*Thomas Drucker*

BELL CURVE

THE SCIENCE: Abraham de Moivre was the first person to describe the so-called normal curve, a symmetrical bell-shaped graph that symbolizes probability distribution. This graph of the average distribution of events resolved a serious issue that had been left hanging by the previous generation of mathematicians.

THE SCIENTISTS:

Abraham de Moivre (1667-1754), French-born English mathematician

Jakob I Bernoulli (1655-1705), Swiss mathematician

Nikolaus Bernoulli (1687-1759), Swiss mathematician, lawyer, and editor of Jakob's posthumous text

GAMES OF CHANCE

The earliest mathematical work on probability involved problems with dice. Throws of the dice could be described by a function called the binomial distribution, which provided the probability of any given result coming up a set number of times given a set number of tosses of the dice. For example, given thirty-six tosses, 7 is most likely to come up six times; the next most likely outcomes are five times or seven times, then four times or eight times, and so on. The binomial distribution provides the exact probability of each result.

Problems relating to the binomial distribution proved difficult to answer until the mathematician Abraham de Moivre found a graphical way to approximate the function. The approximation had the shape of a bell—so, to continue the example of the dice, rolling six 7's would form the highest point on the bell, which would then slope downward to either side. This approximation enabled de Moivre to answer important questions about games of dice and other situations in which probability could be represented by the binomial distribution.

De Moivre developed an interest in probability by reading some of the earliest treatments of the subject, which had acquired mathematical respectability only in the middle of the seventeenth century with the work of Blaise Pascal and Pierre de Fermat. He probably first read a treatise on probability by the Dutch mathematician Christiaan Huygens and shortly thereafter wrote one of the first English accounts of the subject, "De Mensura Sortis" (1711; on the measurement of chance), published in the *Philosophical Transactions of the Royal Society*. The progress of de Moivre's subsequent work on probability can be measured by the later editions of this text, which appeared in English as the textbook *The Doctrine of Chances: Or, A Method of Calculating the Probability of Events in Play* (1718, 1738, 1756). De Moivre also had a strong philosophical interest in the application of probability, which led him to draw philosophical conclusions from his mathematical results.

Bernoulli and the Law of Large Numbers

After the appearance of de Moivre's Latin text in the Royal Society's *Philosophical Transactions*, the foundations of probability theory were transformed by the posthumous appearance of Jakob I Bernoulli's *Ars Conjectandi* (1713; the conjectural arts). The work was prepared for the press by Bernoulli's nephew, Nikolaus Bernoulli. Nikolaus himself had used his uncle's theories in a dissertation he submitted to the Faculty of Law at the University of Basel. The work was intended to illustrate the applications of probability to law, although it seems to have been of more interest to mathematicians than to lawyers.

One of the advances in Jakob I Bernoulli's treatment of probability was his formulation of the binomial distribution. The distribution was pro-

ABOUT ABRAHAM DE MOIVRE

Abraham de Moivre was born in France to a Protestant family. He received his education in France but then left the country at the time of the revocation of the Edict of Nantes (1685)—which since 1598 had provided French Protestants with a measure of religious freedom—in view of the prospective danger to Protestants represented by Louis XIV's abandonment of the policy of tolerance.

De Moivre's mathematical work was all done in England. Although he was a distinguished mathematician, however, he never fit into the English mathematical world. Most of his life he had to eke out a living by tutoring students and answering questions about the practical applications of probability.

Nevertheless, de Moivre was highly esteemed by his contemporaries, including Sir Isaac Newton, the most eminent mathematician of the period. Newton is said to have told students with questions to ask de Moivre on the grounds that de Moivre knew the material better than Newton did. There is no evidence that Newton was being ironical in making such a strong claim, and de Moivre's name is still attached to an important theorem about powers of complex numbers.

duced by looking at a sequence of identical experiments, where each had one possible target outcome (called a success) and one or more other outcomes (which would be collected together and called a failure). For example, if one throws a die a number of times, one could call a 6 a success and any other number a failure.

Bernoulli showed that the relative frequency of an event with probability p in n independent trials converges to p as n gets bigger. In other words, the odds of rolling a 6 are one in six: One could easily roll a die six times and not roll a 6; however, if one were to roll the same die one thousand times, it would be surprising if 6 did not come up about one-sixth of the time (approximately 167 times), and if one were to roll the die 1 million times, it would be extremely surprising if roughly one-sixth of the rolls did not result in 6's. The more times the die is rolled, the closer to the average or ideal theoretical results one's actual results will be. This is known as the law of large numbers, and it furnished a basis for the application of probability theory to practical situations in the physical world.

STIRLING'S FORMULA

Despite demonstrating the law of large numbers theoretically, Bernoulli was unable to find a manageable way to perform the necessary arithmetic calculations to determine the probability of specific ranges of outcomes when the number of trials became large. For example, it was easy to calculate what the probability was of two successes in six trials, but it was much harder to figure out the arithmetic in the case of two hundred successes in six hundred trials. (In both cases, the probability is close to one in three, but it is actually slightly smaller. One needs to crunch the numbers to find the exact probability.) The difficulty of performing extended arithmetical calculations made it difficult in turn to extend the general results Bernoulli had obtained to any specific situation. The algebra of dealing with the sum of many terms of a polynomial did not have an obvious solution.

De Moivre recognized both the importance of Bernoulli's problem in this regard and the most fruitful direction to explore in order to find a solution. Earlier in his career, de Moivre had found a way to approximate factorials of large numbers. (Factorials are products of all the positive integers from 1 up to a certain number, so that 5 factorial, written 5!, is equal to 5 × 4 × 3 × 2 × 1). De Moivre had given credit for his method to the Scottish mathematician James Stirling, even though de Moivre had figured it out before Stirling did. The use to which de Moivre put the so-called Stirling's formula altered the course of probability theory thereafter. Indeed, de Moivre felt that the work was of such importance that he published it at his own expense.

The Normal Distribution

De Moivre's application of Stirling's formula was published first in Latin as a pamphlet supplementing his *Miscellanea Analytica* (1730), *Approximation ad summam terminorum binomii (a + b) in seriem expansi: Supplement to "Miscellanea Analytica"* (1733; approximation to the sum of the terms of a binomial [a + b] expanded in a series). It was later incorporated in English into subsequent editions of *The Doctrine of Chances*. What de Moivre accomplished in this pamphlet was the introduction of a curve known to mathematicians as the normal distribution and more popularly as the "bell-shaped curve," or simply the "bell curve." This curve would have been impossible to conceive without calculus, but de Moivre was able to use the techniques of the calculus to make a number of statements about what the curve was like. He did not actually write down what mathematicians now regard as the strict mathematical definition of the curve, but his results indicated that he understood it well enough to use it.

The bell-shaped curve enabled de Moivre to come up with a good approximation of the probability of ranges of outcomes in the binomial distribution, thereby solving the problem that had plagued Bernoulli. One of the major consequences of the curve was that it made it possible accurately to determine the rough probability of a range of outcomes clustered around the center of the distribution for large numbers of trials. For example, if one flipped a coin 600 times, one could use de Moivre's technique to determine the likelihood of getting a number of heads between 250 and 350. Even more important, de Moivre's curve enabled the work of Bernoulli to be expressed in a more concrete, quantitative form. In evaluating the series that he obtained at values that were multiples of the square root of the number of trials, de Moivre concluded that the natural unit for measuring the deviation from the center would be that square root.

IMPACT

The appearance of the normal distribution in the work of de Moivre permanently altered the emerging science of probability theory and its applications. One of the difficulties that Jakob Bernoulli had encountered is his work was in trying to apply his results to statistical inference. The binomial distribution was the easiest distribution to describe mathematically, making it the best suited for creating a mathematical theory of statistical inference. De Moivre's curve was a necessary stepping stone to such a theory, which was created in the next generation by Pierre-Simon Laplace. Laplace also added a few details that de Moivre had omitted (such as a formal proof of his main result).

The bell-shaped curve has made its appearance in all sorts of investigations and has been liable to misuse as much as to use. The conditions underlying the proper application of the curve have been studied at length and just as studiously ignored by those who saw it as the one necessary ingredient for a probabilistic analysis. The normal distribution has probably been cursed by students who are under the impression that it was responsible for "grading on a curve." Nevertheless, the language for measuring errors and deviations from a set standard has depended for many years on the normal distribution.

See also Abstract Algebra; Axiom of Choice; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Thomas Drucker*

BIG BANG

THE SCIENCE: George Gamow proposed that the observable universe resulted from the explosion of a hot, dense primordial fireball, which later expanded and condensed into galaxies and then suns.

THE SCIENTISTS:

George Gamow (1904-1968), Russian-born American nuclear physicist and cosmologist who developed the big bang theory

Ralph Asher Alpher (b. 1921), American physicist and collaborator with Gamow who calculated the formation of heavy elements during the big bang

Robert C. Herman (b. 1914), American physicist who worked with Alpher on the calculations of heavy element formation

Georges Lemaître (1894-1966), Belgian Jesuit priest, astronomer, and cosmologist who proposed the concept that the universe expanded from an original "cosmic egg" of super dense matter

Fred Hoyle (1915-2001), English astronomer who proposed a "steady-state" model of the universe, which was the chief cosmological competitor of the big bang during the 1950's and 1960's

Robert H. Dicke (1916-1997), experimental physicist at Princeton University

An Expanding Universe

In the late 1920's and early 1930's, Edwin Powell Hubble and others had established that the universe was expanding. After World War II (1939-1945), George Gamow, a professor at George Washington University in Washington, D.C., began a series of calculations demonstrating that reversing the galactic expansion pointed to a time when all the matter was confined to an extremely small space (perhaps thirty times the Sun's diameter) at a temperature of thousands of trillions of degrees. He presumed that the density of the radiation was greater than the density of the matter, a condition that caused the explosion leading to the formation of the present universe, known as the big bang theory.

Gamow's big bang theory was based on the cosmological implications of Hubble's discovery in 1929 of the directly proportional relationship of distance and velocity of recession for the distant galaxies. This relationship implied that the universe was expanding, which had an immediate effect upon Albert Einstein's preferred static cosmological model, which had dominated thought since his publication of the general theory of relativity in 1916. Einstein had been forced to introduce a "constant of repulsion" to counteract the force of gravity in a static universe. Willem de Sitter found a second static solution that implied near zero density and also that the light of distant stars would be redshifted. In Russia, Aleksandr A. Friedmann discovered a dynamic solution that implied an expanding universe. Georges Lemaître, unaware of Friedmann's solution, proposed in 1927 that a homogeneous and isotropic universe originated from a "cosmic egg." Lemaître unfortunately had to retain Einstein's constant of repulsion to explain the expansion in his model since he did not envision an initial explosion.

Formation of the Heavy Elements

The primary motive for Gamow's proposal was not to resolve the issue of a static versus a dynamic universe but to explain how the heavier elements could be formed in their observed relative abundances. Hydrogen and helium were presumed to constitute approximately 99 percent of the matter in the universe. The other 1 percent consisted of the heavier elements, which decline in abundance through the periodic table until zinc is reached. At this point, roughly halfway down the periodic table, the abundance flattens out and approximately the same amount of all the remaining elements occur.

Gamow, in these early days, reasoned that this pattern could not be the result of the stellar formation of the heavy elements. He proposed that they were formed in the first thirty minutes of the initial explosion, before the temperature had cooled too much. He believed he could explain how deuterium (heavy hydrogen) could be formed in the big bang, while he was convinced that it would be destroyed only in stellar interiors. He also believed that helium was too abundant to be formed in the stars and had to result from the initial explosion. Finally, the uniform distribution of the helium implied that it was not the consequence of stellar activity. This portion of his initial ideas has stood the test of time. Gamow also devoted extensive attention to stellar dynamics in his 1940 book *The Birth and Death of the Sun*. At this time, however, he still did not have an adequate explanation for how the heavy elements could be formed during stellar evolution, so he proposed the big bang as a means of resolving that problem.

Gamow enlisted the aid of two physicists to calculate the mathematics involved in heavy element formation: Ralph Asher Alpher, a Ph.D. candidate at The Johns Hopkins University, and Robert Herman, enlisted because of his skills with the early computers in use by the Bureau of Standards. A major element of their theory came from a surprising source. During World War II, Donald Hughes at Brookhaven National Laboratory had measured the neutron-capture characteristics for several atoms and found that capture increased during the first half of the periodic table and then flattened out, the inverse of the pattern of abundance of the elements. On this basis, Alpher proposed that neutron capture explained Gamow's element formation during the first thirty minutes of the big bang.

Although Alpher and Herman devoted extensive efforts to demonstrating how the elementary particles could combine under extreme conditions, serious problems remained with the formation of the heavy elements if the temperature dropped below a billion degrees, which implied that all the heavy elements had to form during the first thirty minutes of the big bang. There were no stable elements with atomic number 5 or 8, which meant that there would be a gap in the buildup of atoms of the heavier elements between helium and lithium. Other astronomers regarded the gap as evidence that the buildup would result only in the formation of hydrogen and helium in the initial big bang, a position that has become generally accepted. While Gamow devised a theoretical means of bridging the gap, the low probability of his proposed sequence of events led to a severe time constraint in the cooling state of the early universe. He conceded eventually that the heavy elements were not created in the initial big bang.

REACTION: HOYLE AND "STEADY STATE"

While assumption that the dynamics of self-gravitating gaseous clouds caused condensation of the cooling gases into galaxies and stars presented difficulties, Gamow believed that the outline of the theory was firm enough to present it publicly in 1948. It was popularly presented in 1952 in the book entitled *The Creation of the Universe*.

Many astronomers were troubled by Gamow's proposal, especially the implications of a beginning and an ending to the universe. By 1950, Fred Hoyle of the University of Cambridge proposed what came to be called the "steady-state" universe, in which hydrogen was continuously originating in intergalactic space and then coalescing into gaseous clouds that eventually gave birth to new stars. In such a universe, there need be no beginning,

FRED HOYLE AND THE STEADY-STATE THEORY

Troubled by the problems presented by George Gamow's early theory of the big bang, Fred Hoyle and the University of Cambridge developed an alternative and well-respected proposal: the "steady-state" theory.

Ironically, the term "big bang" had been coined by its main adversary—Hoyle himself—during one of his series of BBC radio talks. Hoyle used the term to belittle Gamow's theory. Hoyle favored a different view: that the universe, although currently expanding, was infinitely old and in the long term existed in a steady state. Galaxies were not receding from each other as the aftermath of a primordial explosion (which defenders of the big bang held). Rather, space was being created between galaxies at a constant rate, and hydrogen was being created to fill that space, coalescing into nebular clouds that then formed young stars and galaxies among the old.

The problem with this theory was that it contradicted the law of the conservation of matter: namely, that matter could neither be created nor be destroyed without being converted into energy. In the 1950's, the discovery of radio galaxies by Sir Martin Ryle revealed that galaxies had evolved billions of years ago, supporting the big bang theory.

Once Arno Penzias and Robert Wilson discovered the cosmic microwave background radiation, Hoyle's steady-state theory was largely abandoned in favor of the theory he himself had named: the big bang. Although Hoyle revised his theory to account for the background radiation, his once dominant view of the universe was out of favor. Hoyle, however, remained philosophical to the end: "The Universe eventually has its way over the prejudices of men, and I optimistically think it will do so again."

but it contradicted the physical concept of the conservation of matter—namely, that matter could neither originate nor be destroyed without being converted into energy.

MICROWAVE BACKGROUND RADIATION

While Gamow's presentation of the big bang was accepted by many astronomers as a proper interpretation of the astronomical evidence, the specific proof of the theory was slower in coming. Alpher and Herman pointed out in 1948 that the level of radiation had steadily declined since the big bang to a level that they estimated to be 5 Kelvins (above absolute zero). They thought that it might still be detectable not as light but perhaps as a low-level microwave radiation.

In 1965, Robert Henry Dicke, unaware of Alpher's and Herman's work, calculated that the residual radiation should be apparent at about 5 Kelvins and would emanate from all parts of the sky. He believed so firmly in his prediction that he began to construct equipment large enough and sophisticated enough to detect the radiation. Unknown to him, Arno Penzias and Robert Wilson of the Bell Laboratories had already discovered the microwave radiation in their efforts to study sources of background radiation causing static in radio transmission. A friend who heard a lecture about Dicke's prediction mentioned it to them, whereupon they realized they had detected the radiation and contacted Dicke for verification.

The discovery of this background radiation—corrected to 3 (instead of 5) Kelvins—provided major confirmation of the hot big bang. The big bang more aptly explained the expansion of the universe than other theories and has gradually become the accepted understanding of the origin of the universe.

IMPACT

The expansion of the universe, combined with a reasonable explanation of the manner in which it has evolved, changed conceptions of a static universe that prevailed in the 1920's. The big bang cosmology has been successful as a means of stimulating cosmological theory and research. As a means of explaining the relative abundance of the elements as Gamow originally proposed it, however, the theory was only partially successful. The formation of the heavier elements is now presumed to take place in the stars themselves, rather than during the big bang, where hydrogen and helium are assumed to have been the result.

Because of the problem of the heavy elements, there was some early neglect of the success of the theory in explaining the buildup of helium and the abundance of hydrogen and helium compared with the rest of the elements. Gamow's team was also successful in identifying the process of heavy element formation through neutron capture. They merely had the wrong location—the big bang—instead of in the interiors of massive stars.

One attractive feature of Gamow's theory was that the original explosion was of such force that he did not have to hypothesize a "constant of repulsion," as Einstein had done in his gravitational field equations in order to counterbalance gravitation to maintain a static universe.

The clear implication of the big bang is that the universe had a beginning and that it will die a cold and isolated death as the galaxies become farther apart, with the individual stars eventually burning out as a result of an insufficient rate of birth of new stars. Some cosmologists have proposed a coming collapse of the universe (an idea Gamow described in 1952), with perhaps an oscillation of big bangs and collapses.

Gamow's general outline has become the standard cosmology, although the level of sophistication of the theory and its mathematical foundations have dramatically changed. The principal difficulty of his theory eventually forced Gamow to accept Fred Hoyle's explanation of heavy element formation in the interiors of stars. The success of this portion of Hoyle's theory explained why the rest of his steady-state cosmology enjoyed some temporary success in opposition to Gamow's proposal. Heavy element building from fundamental particles during the radiative life of massive stars, and dispersal into space through supernova explosions, is now the widely accepted view.

See also Black Holes; Cosmic Microwave Background Radiation; Expanding Universe; Galaxies; Inflationary Model of the Universe; Quarks; String Theory; Wilkinson Microwave Anisotropy Probe.

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—*Ivan L. Zabilka*

BINOMIAL CLASSIFICATION

THE SCIENCE: Carolus Linnaeus designed a hierarchical taxonomic system for naming and classifying plants and animals. His system gave each organism a two-term name that was derived from its unique defining characteristics and its position within the hierarchical system. Linnaeus's classification system brought an intellectual order to biology that persists to this day.

THE SCIENTISTS:

Carolus Linnaeus (Carl von Linné; 1707-1778), Swedish physician and botanist
Joseph Pitton de Tournefort (1656-1708), French physician and botanist
John Ray (1627-1705), English Protestant cleric and naturalist
Andrea Cesalpino (1525-1603), Italian physician, philosopher, and botanist

THE NEED FOR A SYSTEM

In the fourth century B.C.E., the Greek philosopher Aristotle (384-322 B.C.E.) formulated the earliest known system of biological classification by grouping organisms according to their habitat or means of transportation—air, land, or water. Classical Greek and Roman botanical works by Theophrastus (c. 372-287 B.C.E.) and Pedanius Dioscorides (c. 40-c. 90 C.E.) served as foundational references for medieval herbalists, who expanded the lists of medically useful plants but offered few systematic means to distinguish them other than descriptions or portraits of their specimens. Ordering plants according to their purported medicinal value was common; a few reference books listed animals in alphabetical order.

During the Renaissance, explorers to distant lands introduced naturalists to a flood of new plants and animals, and this new material provided the impetus for classifying plants and animals according to their relationships to one another rather than their usefulness to humans. Italian physician and botanist Andrea Cesalpino utilized the Aristotelian criteria ofessential characteristics (such as reproductive organs) and accidental characteristics (such as taste, smell, or color) to specify features important to plant classification. This approach deeply influenced later naturalists. English Protestant cleric John Ray and French botanist Joseph Pitton de Tournefort helped define the concept of "species" as the most fundamental unit of biological classification, and Tournefort was the first to recognize the "genus" as a basic category of classification, falling between species and families.

However, the discipline of biological classification, otherwise known as taxonomy, suffered from a lack of standardization. The names given to organisms varied from one naturalist to another. To make matters worse, the classification system of Tournefort squeezed the approximately 10,000 known species of plants into 698 genera that botanists had to memorize. Such classification systems were impractical, difficult to use, and detrimental to the effective analysis of the exotic material being supplied by explorers.

Flexibility and Standardization

Although trained as a physician, Carolus Linnaeus spent the vast majority of his scientific energy on taxonomy. Linnaeus greatly simplified the conventions that governed the naming of plants and animals by using a standardized binomial nomenclature in his seminal work, *Systema naturae* (1735; *A General System of Nature: Through the Three Grand Kingdoms of Animals, Vegetables, and Minerals*, 1800-1801). Gaspard Bauhin (1560-1624) had developed binomial nomenclature almost two hundred years earlier, and Linnaeus used this naming technique to replace the cumbersome descriptions of his day with a double name in Latin called a *binomen*.

The first half of the *binomen* consisted of a capitalized *genus* name, designating a group composed of several species. The second part, a *specific epithet*, designated the species name. Linnaeus used Latin *binomens* to replace the long, unwieldy descriptions in Latin used by naturalists at this time. For example, the wild briar rose was known as *Rosa sylvestris inordora seu canina* (odorless woodland dog rose) or *Rosa sylvestris alba cum rubore, folio glabro* (pinkish white woodland rose with smooth leaves). Linnaeus simplified these rambling descriptions to *Rosa canina*. In the tenth edition of *A General System of Nature* (1758), Linnaeus became the first person to employ binomial nomenclature consistently and without exception to name plants and animals. Because of the simplicity of this naming system, naturalists not only could remember names but also could agree on them.

In *A General System of Nature*, Linnaeus also described a simple hierarchical system of plant classification anyone could use. He arranged plants into twenty-four "classes" according to the number and relative positions of their male reproductive organs, or stamens. He further divided these classes into sixty-five "orders," based on the number and position of the female reproductive organs, or pistils. The orders were then divided into genera, or sets of species that shared similar characteristics.

Because of the ease of using Linnaeus's taxonomic scheme, amateurs, travelers, or gardeners could employ the Linnaean system for themselves and arrive at the same conclusions. Linnaeus also demonstrated the utility

LINNAEUS'S SEXUAL SYSTEM

Carolus Linnaeus was interested in a wide range of topics in natural history, but his primary interest was classification. His goal was to produce a system by which one could correctly identify organisms, and his method was to use the common Aristotelian technique of downward classification.

This method involved taking a class of objects, dividing it into two groups (for example, the class of living organisms can be divided into animals and nonanimals), and continuing the process of dichotomous divisions until there was only the lowest set, the species, which could not be further divided. Such a system was highly artificial, since the basis for many of the divisions was arbitrary. However, based on his philosophical and theological commitment to the argument from the Creator's design, Linnaeus believed that if the correct characteristic was chosen as the basis of division, natural relationships would be revealed. In his typically arrogant manner, he claimed to have discovered that trait and built his system around it. He called it his "sexual system."


(Library of Congress)

Linnaeus's system was more adapted to botany than to zoology. With his system, he was personally able to classify more than eighteen thousand species of plants, but his attempts to classify animals created duplications and confusion, primarily because he could not find a characteristic that would work for animals the way reproductive structures did for plants. His inclination to classify everything can also be seen in his attempts to classify diseases, humans, and even botanists.

Linnaeus should not, however, be regarded as merely a taxonomist. His essays and lectures provide evidence that he was exploring ideas that would now be considered basic to ecology and biogeography. He sought to develop, within both a theological and biological context, a concept of the harmony of nature. Finally, he tried not to allow his philosophical or theological positions to blind him to his data. As a result of his evidence, he revised his views on fixity of species to allow for a kind of evolution—formation of new species by hybridization—below the genus level.

of his sexual classification system in a botanical account of his 1732 expedition to Lapland, *Flora Lapponica* (1737; *The Flora of Lapland*, 1811), and in his catalog of the plants from the garden of the wealthy amateur horticulturist George Clifford, *Hortus Cliffortianus* (1738; Clifford's garden). His later work *Species plantarum* (1753; *Plant Species*, 1775) cataloged all known species of plants and expanded his taxonomic principles. These books helped his sexual classification system gain widespread acceptance and use in Europe, despite opposition from some naturalists who thought that it was too sexually explicit.

Nested Hierarchies

The Linnaean classification system provided a rigorously nested hierarchy of plant and animal categories in which small groups were nested within successively larger and larger groups. A species, the smallest denomination into which organisms could be classified, was embedded in a larger group, the genus; one or more genera composed a family; and several families were grouped into classes, etc. Such a classification scheme easily accommodated new organisms or even new groups of organisms.

Linnaeus's nested hierarchical system received wider use and acceptance than the non-hierarchical schemes proposed by his competitors. For example Georges-Louis Leclerc, comte de Buffon (1707-1788), Linnaeus's principal competitor, thought that the entire morphology of the organism should be considered when deciding relatedness and not just a few "essential" structures, like the reproductive organs. To encapsulate his approach to classification, Buffon proposed a classification system that joined some organisms by means of physiology and others via anatomy and still others by means of ecology. The system of Buffon did not endear itself to others because of its almost overwhelming complexity and inability to accommodate new material without substantial changes. By 1799, fifty different classification systems existed, and of these only the taxonomic system created by Linnaeus ultimately survived.

Impact

It is difficult to overestimate Carolus Linnaeus's contribution to biology, since he single-handedly made biological classification a rigorous scientific endeavor. Linnaeus once and for all simplified the naming system and developed a classification scheme that people with a wide range of training could successfully use. His system of taxonomy also easily accommodated the deluge of new biological material from foreign lands, and since its structure did not depend upon the criteria used to distinguish one group from another, the structure of the Linnaean classification system has survived to modern times, even though his sexual classification scheme was abandoned before the end of the eighteenth century.

Linnaeus's taxonomic scheme, which he viewed as a way of defining the initial species originally placed on earth by God, ironically paved the way for Charles Darwin's theory of evolution, because it could also accommodate a theory of evolution by common descent. Darwin's in-depth study of barnacle classification convinced him that evolutionary relatedness was the best criterion for classifying organisms in the same group. Linnaeus's nested hierarchical taxonomic system lent itself to Darwin's theory, since grouping organisms into ever-larger categories also allowed scientists to assemble organisms according to more recently or distantly shared common ancestors.

See also Evolution; Human Evolution; Mendelian Genetics; Population Genetics.

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—*Michael A. Buratovich*

BLACK HOLES

THE SCIENCE: In 1916, Karl Schwarzschild developed a solution to Albert Einstein's equations of general relativity that describes a gravitational black hole.

THE SCIENTISTS:

Karl Schwarzschild (1873-1916), German physicist
Albert Einstein (1879-1955), German American physicist
Sir Isaac Newton (1642-1727), English scientist and philosopher

GENERAL RELATIVITY

In 1915, Albert Einstein published his general theory of relativity, in which he discussed his theory of a "space-time continuum" that included four dimensions: length, width, height, and time. He believed that physical events could be located precisely on this continuum. This revolutionary new concept of space-time, which included the idea that space-time itself is curved, stood in opposition to the universal law of gravitation, which had been developed by Sir Isaac Newton in 1665. According to Newton, gravity is an attractive force acting between all particles of matter in the universe. Einstein, however, believed that gravity is a consequence of the shape of space-time. Local space-time, according to the general theory of relativity, is distorted by the presence of a large mass such as a star or a planet. Objects traveling close to a massive body would therefore travel in a curved path, causing the appearance of a gravitational field.

When the general theory of relativity was first proposed, the mathematics of its equations were thought to be beyond comprehension. In fact, it was frequently stated that only twelve or so scientists in the world completely understood the theory. Even today, many of its implications remain unexplained. The first person to find an exact solution to the equations of the general theory of relativity was the German physicist Karl Schwarzschild. Prior to the work of Schwarzschild, the only solutions to the equations had been approximations.

In 1916, when Schwarzschild was working on his solution, Germany was at war. The patriotic Schwarzschild insisted on serving in the German armed forces. Various campaigns took him to Belgium, France, and finally Russia. While serving in Russia he contracted the fatal disease pemphigus. Although he became too ill to continue in military service, he continued to work on the equations. Shortly after his return to Germany, he completed his work and sent a copy to Einstein. Within a few months, Schwarzschild died.

Schwarzschild had sought to determine what would happen if gravity around a spherical body became infinitely powerful. He also wanted to find the least complex explanation for the phenomenon. The result, the Schwarzschild solution, describes a "black hole," an object so dense that light itself cannot escape from its surface. Difficulties in interpreting the

THE SCHWARZSCHILD RADIUS

At the start of World War I in 1914, Karl Schwarzschild, a young professor at the University of Göttingen, volunteered for military service. Craving action, he eventually managed to get transferred to Russia, where he heard of Albert Einstein's new general theory of relativity. Schwarzschild wrote two papers on that theory, both published that year. He provided a solution—the first to be found—to the complex partial differential equations fundamental to the theory's mathematical basis. Schwarzschild solved the Einstein equation for the exterior space-time of a spherical nonrotating body. This solution showed that there is an enormous, virtually infinite, redshift when a body of large mass contracts to that certain radius—a size now known as the Schwarzschild radius.

The value of that size is easily calculated by a simple astrophysical formula Schwarzschild derived, relating the radius to the universal gravitational constant, the star's mass, and the speed of light: $R = 2GM/c(2)$. Surprisingly, he showed that the general theory of relativity gave basically the same results as Isaac Newton's more common theory of gravitation, but for different reasons. When the mass of the object is measured in units of the Sun's mass, the Schwarzschild radius is neatly given by three times the ratio of the mass to the Sun's mass, the answer expressed in kilometers: $R = 3 \times M/M$(Sun). If the Sun were contracted to a radius of 3 kilometers, it would be of the right size to be labeled a "black hole." A body becomes a black hole when it shrinks to a radius of less than the critical radius; at that point, nothing, including light, will have enough energy ever to escape from the body—hence the name "black hole," since no light escapes and anything falling in remains. Earth would have to contract to a radius of approximately one centimeter to become a black hole.

While in Russia, Schwarzschild contracted pemphigus, an incurable metabolic disease of the skin. He was an invalid at home in 1916 when he died. He was forty-two years old. For his service in the war effort, he was awarded an Iron Cross. In 1960, he was honored by the Berlin Academy, which named him the greatest German astronomer of the preceding century.

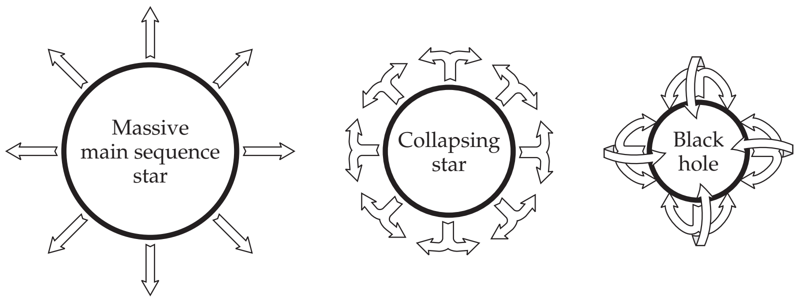

(AIP Neils Bohr Library)

Schwarzschild solution, however, cast some doubt upon its validity until the 1960's, when its true significance was recognized.

THE DEATH OF A MASSIVE STAR

The formation of a black hole is believed to be the final stage in the decay of a massive star, when nuclear fuel is exhausted in the star's core. The exact sequence of events depends entirely on the mass of the star. Toward the end of its life, a massive star will go through the supernova stage, in which much of its outer material is blasted into space. The core then begins to collapse. If the star's mass is 1.4 solar masses or smaller, it will end up as a "white dwarf." At this stage, the pressure exerted by the electrons of the atoms is enough to prevent total collapse. This hot carbon mass will eventually cool to become a "black dwarf." If the mass of the decayed star is between 1.4 and 3.1 times the mass of the Sun, gravity will cause a much more extensive collapse. At this point, gravity is so intense that electrons and protons combine to form neutrons, resulting in the formation of a "neutron star."

If the mass is greater than 3.1 solar masses, not even neutrons will be able to counteract the force of gravity, and the star will continue to collapse. As the star collapses, its surface gravity will become greater and greater. As a result, the velocity needed to escape this gravitational body increases. After the escape velocity has reached the velocity of light, further collapse results in the formation of a black hole. The distance at which the escape velocity is equal to the velocity of light is the distance calculated


THE MAKING OF A BLACK HOLE

A massive star may end its life as a black hole: During its main sequence (left), radiation emits outward. As the core burns (center), the star begins to collapse in on itself. Finally (right), the increasing mass at the core is so great that gravity is extremely strong, preventing any radiation (including light) from escaping.

by Schwarzschild in his solution to Einstein's equations; it is known as the "Schwarzschild radius" or the "event horizon." Beyond this point, there is no way of determining events. It is an area that is totally disconnected from normal space and time.

In theory, any object could become a black hole if it were compressed enough. If the Earth were shrunk to a volume slightly less than a centimeter in radius, it would become a black hole. If the Sun were compressed to a radius of less than three kilometers, it would become a black hole.

The diameter of the Schwarzschild radius of a black hole depends on the mass of the decayed stellar core. For example, a decayed core with a mass five times greater than that of the Sun would have an event horizon with a radius of 30 kilometers. A stellar remnant of 20 solar masses would have an event horizon with a 60-kilometer radius. Within this boundary, however, the remains of the star continue to collapse to a point of infinite pressure, infinite density, and infinite curvature of space-time. This point is known as the "Schwarzschild singularity."

Impact

The true significance of Schwarzschild's work was not recognized until more study was done on stellar structure and evolution. An important step was taken in 1931 when the astronomer Subrahmanyan Chandrasekhar completed calculations that described the interior of a white dwarf star. At that time, he did not consider the fate of very massive stars, but English astronomer Arthur Stanley Eddington proposed that massive stars in their death stages continue to radiate energy as they become smaller and smaller. At some point, they reach equilibrium. In 1939, the American physicist J. Robert Oppenheimer and his student Hartland Snyder showed that a star that possesses enough mass will collapse indefinitely.

By the end of the twentieth century, it was fully recognized that what the Schwarzschild solution describes is a black hole. However, the type of black hole described by the Schwarzschild equations is essentially static. Static black holes do not rotate and have no electric charges. The only property possessed by such bodies is mass. Later variations on Schwarzschild's work have led to theories about other kinds of objects, such as rotating black holes, black holes with electrical charges, and black holes that both rotate and have electrical charges.

Black holes, by their nature, cannot be seen, so evidence for their existence must necessarily be circumstantial. Nevertheless, proof that they actually exist has grown increasingly strong. In the last three decades of the twentieth century astrophysicists identified two dozen possible black holes—including one at the center of the Milky Way galaxy. In 2000 alone, the discovery of eight supermassive black holes was reported to the American Astronomical Association. With the development of new optical X-ray, infrared, and radio telescopes, more discoveries were anticipated, and astrophysicists were hypothesizing that black holes are not rare, but common, throughout the universe.

See also Black Holes; Gamma-Ray Bursts; Neutron Stars; Quasars; Relativity; Stellar Evolution; Very Long Baseline Interferometry; X-Ray Astronomy.

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—*David W. Maguire*

Blood Circulation

The Science: William Harvey's discovery of the circulation of the blood was one of most important discoveries in the history of medicine. Quickly accepted by the medical community, it led doctors and scientists to rethink the blood and heart's physiology, as well as general therapeutic strategies.

The Scientists:
William Harvey (1578-1657), English physician
Hieronumus Fabricius ab Aquapendente (1537-1619), Paduan professor whose lectures Harvey attended
René Descartes (1596-1650), French philosopher
Jean Riolan (1580-1657), French physician

TURNING GALEN UPSIDE DOWN

William Harvey's discovery of the circulation of the blood was not a punctual event. Rather, it was the product of a decade of observations, reflections, speculations, and writings, beginning in 1617 and ending in 1628, when Harvey published *Exercitatio anatomica de motu cordis et sanguinis in animalibus* (1628; *Anatomical Exercise on the Motion of the Heart and Blood in Animals*, 1653; commonly known as *De motu cordis*). This slim book, published in Frankfurt, formally announced the discovery, which turned accepted notions about the heart and blood upside down. These accepted notions sprang from the ideas of Galen (129-c. 199 C.E.), a second century Greek physician whose work was influential throughout the Middle Ages and Renaissance.

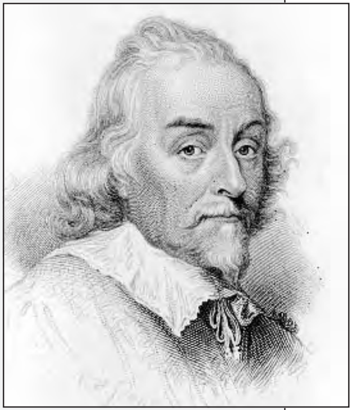
The dissections Harvey performed while lecturing on surgery at the Royal College of Physicians gave him the opportunity to study the heart, although he originally intended to focus his research on the heartbeat, and convinced him that the Galenic understanding of the function and motion of the heart and blood needed to be revised. In fact, while Renaissance dissections had considerably expanded the knowledge of human anatomy—epitomized by Andreas Vesalius's *De humani corporis fabrica* (1543; *On the Fabric of the Human Body*, books I-IV, 1998; better known as *De fabrica*)—they had neither revealed how or why the heart moves nor elucidated the circulation of the blood. Indeed, the cardiovascular system and cardiac movements are very complex phenomena that cannot be easily observed.

Although the Renaissance physician Realdo Colombo (1516?-1559) had already raised doubts about Galen's description of the heart's function, when Harvey first considered the anatomical evidence, he was a convinced Galenist, like most of his colleagues. In Galenic medicine, blood was considered to be one of the four humors whose balance determined the health of an individual. It was thought of, not as circulating in a closed system, but rather as being continuously produced and destroyed. Galen believed that the liver produced blood to provide nourishment to the body; therefore, blood was consumed and had to be regenerated. This nourishing plasma was identified with the darker, venous blood.

Red, arterial blood, according to Galen, had instead the function of carrying *pneuma*, the vital spirit that was infused when the blood mixed with air in the lungs. A minimal exchange between the two blood types was believed to occur only in the heart's septum. The lack of a circulatory process in this model demanded that blood flow very slowly, allowing time for its generation and destruction. Similarly, the heart was not seen as responsible for the motion of blood, which was instead thought to be attracted by the various organs and passageways, each at its own rate.

William Harvey: Question Authority

Like Galileo, William Harvey had little respect for authority. He believed anatomy should be taught by dissection and observation, not by books or ancient theories—no matter how venerable and respected. Scientists, he said, should test every hypothesis with their own eyes, trusting authorities only if their conclusions could be corroborated by firsthand observation and experiment.


(Library of Congress)

After the publication of his treatise on the circulation of blood, Harvey's life entered a public and political phase as he became physician to King Charles I and the royal household. He continued his experiments and observations of many species of animals, insects, and plants, making several trips, at the king's request, to Europe, Scotland, and even the Holy Roman Empire. Harvey's connection with the royal court gave him unusual opportunities for observation. Asked to examine seven Scottish women accused of witchcraft, he determined that they had no unusual anatomical characteristics and cleared them of the charge. Performing an autopsy on Thomas Parr, reputed to be 152 years old when he died, Harvey concluded that the cause of death was his move from Shropshire, where he had worked outdoors in cool, clean air, to London, where he sat, ate, and got little exercise while breathing unclean, sooty air.

Seventeenth century London, desperately overcrowded and growing fast, was in the midst of a medical crisis. Several recurrences of the plague motivated medical research on the disease's causes and treatment. In the 1630's, England was also moving closer to a civil war between Royalist and Parliamentary interests. As the king's physician, Harvey was directly touched by these two national crises. When London and Parliament turned against the king, Harvey was dismissed as chief physician of Saint Bartholomew's Hospital. The hostility of his former London colleagues was less disturbing to Harvey than was the plundering of his house and the destruction of his files, which included valuable observations on the generation of insects. To Harvey, politics was insignificant compared with the excitement of scientific investigation.

In 1646, at age sixty-eight, Harvey resigned his position as royal physician and was fined two thousand pounds for assisting the Royalist army. He spent the rest of his life making scientific observations and performing experiments.

One reason Galen’s model had endured so long was that oxygen-rich arterial blood in fact transforms into depleted venous blood in the capillaries, which are so small that they are visible only under a microscope. Since this process was beyond contemporary observational abilities, it neither required explanation nor stood as a recognizable contradiction to Galen’s system. The capillaries would not be observed until Marcello Malpighi discovered them in 1660.

Venous Valves

The chain of ideas and observations that led Harvey to challenge and undo the Galenic system remains a matter of speculation, because his notes and papers were lost during the Great Fire of London (1666). Any reconstruction of the exact history of Harvey’s discovery must therefore rely primarily on circumstantial evidence. Harvey wrote the crucial chapters of *De motu cordis* between 1617 and 1619, and in the 1628 work’s introduction, he claims to have discovered the circulation of the blood nine years earlier.

Harvey’s introduction also indicates that it was thinking about the properties of venous valves that originally compelled him to doubt Galenic notions, study the heart’s function and movement, and hypothesize that blood circulates through the body. Discovered by Hieronumus Fabricius ab Aquapendente and illustrated, albeit without understanding their true function, in his *De venarum ostiolis* (1603; on the veins’ little doors), venous valves prevent the blood from flowing away from the heart, forcing it toward the heart. Recognizing this action of the valves in the veins and realizing that arteries lack such valves, Harvey concluded that the blood must somehow pass from the arteries to the veins and therefore circulate in the body.

Harvey’s book uses metaphoric language and relies repeatedly on analogies of microcosm to microcosm and of the meteorological cycle of water. Beyond such abstract reasoning, however, Harvey devised a series of clever experiments to support his daring claim that blood circulates and is somehow transferred from the arteries to the veins. For example, by ligating an arm and regulating the blood flux in veins and arteries with a finger, he presented a visual demonstrations that valves prevent the blood from flowing away from the heart. These experiments are the only ones illustrated in *De motu cordis*, a book that includes only two plates.

Harvey also calculated the amount of blood that is expelled by the heart per hour: Even with conservative estimates for the average heartbeat and for the ventricles’ size and volume, he concluded that about 1,000 fluid ounces, or almost 8 gallons (about 30 liters), of blood emerge from the heart each hour. Since it seemed impossible for the body to produce and consume fluid at that rate, this figure seemed to prove that the same blood must pass through the heart repeatedly. Harvey's combined rhetorical arguments, experimental evidence, and quantitative observations ultimately proved convincing.

The Heart as Pump

The fact of the blood's circulation correlates with the notion that the heart must function as a pump. Harvey therefore studied the heart's motion and function, although he never actually used that often repeated comparison between the organ and the machine. Human cardiac movements remain unclear when observed in a heart beating at a normal rate, so Harvey performed vivisections of cold-blooded animals, whose hearts beat more slowly. He also examined dying mammals' hearts as they slowly stopped beating. These experiments allowed him to understand systolic and diastolic movements and thus to revise Galenic notions about cardiac anatomy and the function of the heart's four valves.

Harvey's claims and ideas were bold and challenged the status quo of medicine. Not surprisingly, they gave rise to heated debates in which he himself took part, as did prominent intellectuals of the seventeenth century, including Robert Fludd, Kenelm Digby, Thomas Hobbes, and René Descartes. The two most interesting opposing views were presented by Jean Riolan, a famous French physician and anatomist, and by Descartes. Riolan ingeniously attempted to reconcile Harvey's circulation of the blood with the Galenic model, allowing for the blood to circulate in a smaller circuit of the heart and lungs, though at a much slower rate of one complete cycle per day.

Conversely, Descartes fully supported circulation, but he disputed Harvey's account of the relationship of the blood to the heart. Following his belief that the body is a machine, Descartes tried to theorize the cardiovascular system and cardiac motions in mechanical terms, with the heart powered by the passage of the blood. Although significant, Riolan's hybrid system and Descartes's mechanical reinterpretation did not have a lasting impact; they were quickly disproved by experimental evidence.

Impact

Harvey's discovery of the circulation of the blood is often compared in tenor and importance to Galileo's discoveries and to Sir Isaac Newton's theories. Although it was certainly revolutionary, however, it is important to underscore that Harvey's discovery did not reflect or incorporate the basic tenets of the Scientific Revolution. In fact, Harvey remained a convinced Aristotelian; his explanations are generally qualitative rather than quantitative, and they all embody the causal scheme proper in Aristotelian natural philosophy. In fact, he conceived his research to be part of a program, which he shared with many of his colleagues, aimed at reviving Aristotelian medical theories. It is within this framework that his attitude toward dissection and experimentation should be viewed.

Despite many authoritative attempts to disprove it, Harvey's discovery became mainstream medical knowledge within four decades of its publication. His discovery had both theoretical and practical implications. Accepting that the blood circulates not only demanded that physicians rethink their notions of blood and cardiac physiology, but it also proved a death blow to Galenic medicine. Therapeutic strategies were also affected. For instance, the practice of bloodletting, previously meant to rid the body of a presumed excess of blood and to reestablish the balance among the four humors, lost meaning.

See also Blood Groups; Galen's Medicine; Germ Theory; Greek Medicine; Human Anatomy; Pulmonary Circulation.

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—*Renzo Baldasso*

BLOOD GROUPS

THE SCIENCE: Karl Landsteiner investigated the chemistry of the immune system and discovered the A-B-O blood groups, the most significant advance toward safe blood transfusions.

THE SCIENTISTS:

Karl Landsteiner (1868-1943), Austrian pathologist, immunologist, and winner of the 1930 Nobel Prize in Physiology or Medicine

Philip Levine (1900-1987), physician, immunoserologist, and Landsteiner's student

Alexander S. Weiner (1907-1976), immunoserologist who, with Landsteiner, discovered the rhesus blood system

ANTIBODIES AND BLOOD TYPES

In the late 1800's, immunology was developing rapidly as scientists examined the various physiological changes associated with bacterial infection. Some pathologists studied the ways in which cells helped the body to fight disease; others studied the roles of noncellular factors. In 1886, for example, the British biologist George Nuttall showed how substances in blood serum (the part of the blood that becomes separated when a clot forms) fight bacteria and other microorganisms that enter the human body.

During this time terms such as "antibody" and and "antigen" were introduced. Once a disease-producing organism invades the body, the body reacts by producing helpful substances, or antibodies. These are produced in the blood or tissues and weaken or destroy bacteria and other organic poisons. Antigens are any substances that, after entering the body, stimulate the production of antibodies. The latter then go about their work of fighting these potentially harmful invaders.

Another researcher, Max von Gruber, a bacteriologist at the Hygiene Institute in Vienna, was particularly interested in how the serum of one individual initiates the clumping, or agglutination, of foreign cells that it encounters. He and a student, Herbert Edward Durham, discovered that antibodies are what cause the agglutination of disease organisms in the blood.

Making Transfusion Safe

All this research was applied by scientists trying to figure out a way of making blood transfusions safer. It is now known that before transfusing blood from one person to another, the blood types of each person must be determined. For a transfusion to work, the donor and the recipient must have compatible blood types; otherwise, the recipient's immune system will reject the new blood. If it does, agglutination will occur, and clots will form in the recipient's blood; the result can be fatal for the recipient.

The discovery of the existence of blood groups was a necessary first step in understanding the mechanics of transfusion. Samuel Shattock, an English pathologist, first came close to discovering human blood groups. In 1899 and 1900, he described the clumping of red cells in serum taken from patients with acute pneumonia and certain other diseases. Because he could not find the clumping in the serums of healthy persons, he concluded that his results reflected a disease process.

What Causes Clumping?

In 1900 and 1901, Karl Landsteiner synthesized the results of such earlier experiments and provided a simple but correct explanation. He took blood samples from his colleagues, separated the red blood cells from the serum, and suspended the samples in a saline solution. He then mixed each person's serum with a sample from every cell suspension. Agglutination (clumping) occurred in some cases; there was no reaction in others. From the pattern he observed, he hypothesized that there were two types of red blood cell, A and B, whose serum would agglutinate the other type of red cell. There was another group, C (in later papers, group O), whose serum agglutinated red blood cells of both types A and B, but whose red blood cells were not agglutinated by serum from individuals with either A or B. He concluded that there were two types of antibodies, now called "anti-A" and "anti-B," found in persons of blood types B and A, respectively, and together in persons with blood type C. Successful transfusing was thus understood as dependent upon accurate blood-type matching.

In 1902, two students of Landsteiner, Alfred von Decastello and Adriano Sturli, working at Medical Clinic II in Vienna with more subjects, tested blood with the three kinds of cells. Four out of 155 individuals had no antibodies in their serum (2.5 percent), but their cells were clumped by

BLOOD TYPES, GENES, AND POSSIBLE OFFSPRING

Mating Number	*Genes of Parents*		*Blood Type of Parents*		*Possible Children*	
	Father	*Mother*	*Father*	*Mother*	*Genes*	*Blood Type*
1	AA	AA	A	A	AA	A
2	AA	AB	A	AB	AA or AB	A or AB
3	AA	BB	A	B	AB	AB
4	AB	AA	AB	A	AA or AB	A or AB
5	AB	AB	AB	AB	AA, AB, or BB	A, AB, or B
6	AB	BB	AB	B	AB or BB	AB or B
7	BB	AA	B	A	AB	AB
8	BB	AB	B	AB	AB or BB	AB or B
9	BB	BB	B	B	BB	B

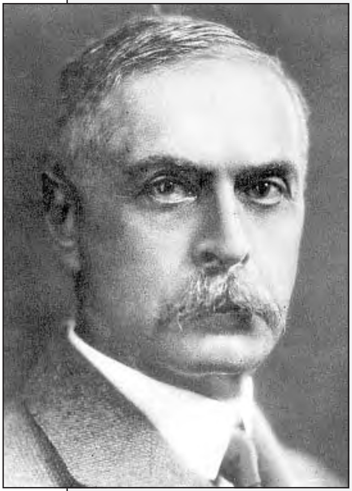
the other types of serums. This fourth, rare kind of blood was type AB, because both A and B substances are present on red cells. Decastello and Sturli proved also that the red cell substances were not part of a disease process when they found the markers equally distributed in 121 patients and 34 healthy subjects.

BLOOD TYPING

Landsteiner anticipated forensic uses of the blood by observing that serum extracted from fourteen-day-old blood that had dried on cloth would still cause agglutination. He suggested that the reaction could be used to identify blood. He noted also that his results could explain the devastating reactions that occurred after some blood transfusions. Human-to-human transfusions had replaced animal-to-human transfusions, but cell agglutination and hemolysis (dissolution of red blood cells) still resulted after some transfusions using human donors. In a brief paper, Landsteiner interpreted agglutination as a normal process rather than the result of disease. He thus laid the basis for safe transfusions and the science of forensic serology; he became known as the father of blood groups.

Landsteiner's experiments were performed at room temperature in dilute saline suspensions. These made possible the agglutination reaction of anti-A and anti-B antibodies to antigens on red blood cells but hid the reaction of warm "incomplete antibodies" (small antibodies that coat the antigen but require a third substance before agglutination occurs) to other, yet

LANDSTEINER'S FAMOUS FOOTNOTE



(The Nobel Foundation)

Karl Landsteiner studied medicine at the University of Vienna from 1885 to 1891, during a time frequently described as the golden age of microbiology. This period—from about 1876 to 1906—saw a great number of significant discoveries concerning the causes of disease and the functions of the immune system. Shortly after his graduation in 1891, the twenty-three-year-old physician left Vienna to begin work in biochemistry under the direction of Emil Fischer.

Landsteiner returned to Vienna in 1896 to work at Vienna's Hygienic Institute under Max von Gruber, one of the discoverers of agglutination. There he developed his interest in immunity and the nature of antibodies, worked in morbid physiology, and in 1900 discovered the human blood groups. In his paper announcing this discovery is one of the most famous footnotes in the history of medicine:

> The serum of healthy humans not only has an aging effect on animal blood corpuscles, but also on human blood corpuscles from different individuals. It remains to be decided whether this phenomenon is due to original individual differences or to the influence of injuries and possible bacterial infections.

Landsteiner's subsequent experiments proved that the differences were not the result of some pathology, as previously thought, but were quite normal individual differences, which he was able to categorize into the three basic blood groups A, B, and O.

undetected antigens such as the rhesus antigens, which are important for understanding hemolytic disease of the newborn.

IMPACT

The most important practical outcome of the discovery of blood groups was the increased safety of blood transfusions. In 1907, Ottenberg was the first to apply Landsteiner's discovery by matching blood types for a transfusion. A New York pathologist, Richard Weil, argued for testing blood to ensure compatibility.

Subgroups of blood type A were discovered in 1911, but it was not until 1927 that Landsteiner, now working at the Rockefeller Institute in New York, and his student, Philip Levine, discovered additional blood group systems. They injected different red blood cells into rabbits and eventually obtained antibodies that could distinguish human blood independently from A-B-O differences. The new M, N, and P factors were not important for blood transfusion but were used for resolving cases of disputed parentage. More scientists eventually became aware of the multiple applications of Landsteiner's blood group research, and in 1930, he was awarded the Nobel Prize in Physiology or Medicine.

See also Blood Circulation; Galen's Medicine; Greek Medicine; Human Anatomy; Hybridomas; Immunology; Pulmonary Circulation; Stem Cells.

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—*Joan C. Stevenson*

BLUE BABY SURGERY

THE SCIENCE: Alfred Blalock and Helen Taussig developed the first surgical method of correcting cyanosis, which is caused by congenital defects in the heart.

THE SCIENTISTS:

Alfred Blalock (1899-1964), American surgeon and physiologist
Helen Brooke Taussig (1898-1986), American physician
Vivien Thomas (1910-1985), surgical laboratory technician
Sanford Edgar Levy (b. 1909), American physician

ANOXEMIA

Anoxemia, often called the "blue baby" syndrome, is usually caused by congenital defects in the heart or blood vessels. In a "blue baby," blood does not circulate properly, and the blood does not carry enough oxygen. Symptoms include cyanosis (including blue lips and fingertips), shortness of breath, fainting, poor physical growth, skin problems, and deformities in the fingers and toes. Before the 1940's, children born with these problems often died at an early age; if they did survive, they suffered much pain. About seven out of every thousand babies are born with some kind of congenital heart disease.

Alfred Blalock was a skillful surgeon who studied the circulatory system. At Vanderbilt University, Blalock conducted experiments on dogs. Wanting to understand the effects of high blood pressure, his team of researchers linked the left subclavian artery (a major branch of the aorta) to the left pulmonary artery (which is connected to the lungs). They found that this did not increase blood pressure in the lungs very much. Five years later, Blalock would use a similar technique to correct blue baby disease.

Blalock did another surgical experiment on dogs, connecting the aorta to the left subclavian artery to correct blockage in the aorta. This operation was also successful, but Blalock did not feel ready to try it on human beings. He was afraid that clamping major blood vessels during surgery would cut off circulation to the brain and other organs for too long. In 1942, however, a Swedish surgeon, Clarence Crafoord, reported that clamping the aorta for twenty-eight minutes during surgery did not cause damage. This was reassuring to Blalock.

THE "BLUE BABY" OPERATION

During a conference on children's medicine at The Johns Hopkins University, the cardiologist Helen Brooke Taussig asked whether Blalock's procedure could be used to improve lung circulation in children with congenital heart defects. Taussig believed that children suffering from a condition known as "tetralogy of Fallot" had a narrowed pulmonary valve and artery and that this caused poor pulmonary circulation, so that not enough oxygen passed through the body.

DR. HELEN TAUSSIG: THE RIGHT TOUCH

Born in 1898 in Cambridge, Massachusetts, to Harvard economist Frank W. Taussig and Edith Guild, Helen Taussig would become one of the greatest physicians of her generation. Her mother died when she was only eleven, and Helen struggled to conquer dyslexia in order to follow in her mother's footsteps and become a Radcliffe student, where she also excelled as a champion tennis player.

In 1917, she moved to the University of California at Berkeley, earning her bachelor's degree from that institution in 1921. She next studied at Boston University and then—denied entry to Harvard because she was a woman—enrolled at The Johns Hopkins University School of Medicine, from which she graduated in 1927. By now, deafness had joined dyslexia as the disabilities she would overcome to pursue a medical career; discrimination would next deny her an internship in medicine, so she pursued pediatrics. However, she turned these obstacles into advantages: In the absence of hearing, her heightened sense of touch allowed her to sense abnormal heart rhythms, and her work with infants would lead to her greatest medical achievements. By 1930 Taussig was head of the Children's Heart Clinic at the Harriet Lane Home, Johns Hopkins Hospital's pediatric unit. She would remain there until 1963.

The first to question why some "blue babies" died quickly while others lived months and sometimes years, Taussig identified the condition causing the problem and developed the idea for the operation to correct it. After the brilliant surgical technician Vivien Thomas helped develop the procedure, surgeon Alfred Blalock, under Taussig's guidance, performed the new operation on November 9, 1944. Their technique soon spread around the world, saving thousands of lives. Taussig initially received little credit, however, and later recalled: "Over the years I've gotten recognition for what I did, but I didn't at the time. It hurt for a while."

Nevertheless, Taussig continued making valuable contributions: In 1947, she published *Congenital Malformations of the Heart*; in 1954, she received the prestigious Lasker Award; in 1959, she finally was advanced to full professor at Johns Hopkins; in 1962, she testified before the Food and Drug Administration on birth defects caused by the sleeping pill thalidomide, thus helping to stop its use in the United States; in 1964, President Lyndon Johnson awarded her the Medal of Freedom; and in 1965, she became the first woman elected president of the American Heart Association.

(Maryland Historical Society)

Blalock and Taussig began working together to design a way to join the left subclavian artery to the pulmonary artery in children so that more blood would flow to the lungs. With the help of surgical technician Vivien Thomas, they performed more experiments on dogs to test the procedure.

On November 29, 1944, Blalock performed the first blue baby operation on a fifteen-month-old girl who suffered from tetralogy of Fallot. Taussig and Vivien Thomas assisted him, along with resident surgeon William P. Longmire and anesthesiologist Merel Harmel. The surgery lasted three hours. Blalock clamped the left subclavian artery, cut through it several centimeters away from where it branched off the aorta, and tied off the useless upper end. He pulled the now-open end down toward the left pulmonary artery, which had also been clamped, and made an opening in the wall of the left pulmonary artery so the two could be stitched together. When the clamps were released, blood flowed out of the aorta through the left subclavian artery and into the left pulmonary artery. The lungs quickly began receiving a greater flow of blood.

The child soon was much healthier than she had been before. Sadly, she died nine months later. Yet Blalock and Taussig were encouraged to find that their surgical treatment could work, and within two months after the first blue baby surgery, they performed two more. By December, 1945, Blalock had performed sixty-five of these operations, with a success rate of 80 percent. Doctors came from all around the world to learn how to perform the new surgery. Blalock was praised as a hero, and newspapers published reports of how he had saved children who otherwise might have died.

Impact

The Blalock-Taussig procedure, as the operation came to be called, has saved thousands of lives and allowed many children to lead normal lives. The procedure also led to other experimental treatments for heart problems. A synthetic shunt to connect blood vessels in this type of surgery was first used by Frank Redo and Roger Ecker in 1963; this operation is called the modified Blalock-Taussig procedure.

Open-heart surgery, first developed in the 1950's, is now used to correct tetralogy of Fallot and other heart deformities. Because infants are usually too small for open-heart surgery, however, the Blalock-Taussig shunt is still used as the first step in a series of operations to treat heart problems in very young children.

See also Diphtheria Vaccine; Hand Transplantation; Heart Transplantation; Immunology; In Vitro Fertilization; Insulin; Ova Transfer; Polio

Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Streptomycin; Vitamin C; Vitamin D; Yellow Fever Vaccine.

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—*Rodney C. Mowbray*

BOOLEAN LOGIC

THE SCIENCE: Geoge Boole's publication of *The Mathematical Analysis of Logic* marked the first major advance in logic since the work of Aristotle over two thousand years before and contributed to the development of computer science a century later.

THE SCIENTISTS:

George Boole (1815-1864), British-Irish mathematician who created mathematical logic

Augustus De Morgan (1806-1871), English mathematician and logician, author of popular and influential texts

ORIGINS OF LOGIC

The origin of logic as the study of the validity of arguments (whether the truth of the premises guarantees the truth of the conclusion) goes back at least to Greek times. In the dialogues of Plato, there is much discussion of whether a conclusion follows, but it is in the work of his student Aristotle that formal logic first appears. Formal logic is built on the assumption that some arguments are true in virtue of their form, not because of the kinds of object being considered. For example, from the claims "All humans are animals" and "All animals are mortal creatures" one can conclude that "All humans are mortal creatures." One could reach that conclusion even if one did not know what humans or animals were, since it is the form of the argument that makes it convincing. This kind of argument was called a "syllogism" by Aristotle.

For many centuries, this syllogistic logic of Aristotle was the only sort taught in European universities. In the seventeenth century, the German mathematician Gottfried Wilhelm Leibniz put forward the idea of being able to translate any argument into a mathematical language and to determine whether the argument was valid by mathematical means. Leibniz did not propose in detail how such a method would work, and most of his speculations were in letters or notebooks that were not published at the time. While there were critics of Aristotle in European thought up through the nineteenth century, they did not have a formal alternative of their own to offer.

THE NEED FOR A NEW LOGIC

At the beginning of the nineteenth century, different number systems had been introduced and found to be governed by different laws. As a result, there were some algebraic equations that would always be true for some kinds of numbers and not true for other kinds of numbers. Just looking at an equation did not allow for the determination of whether the equation was sometimes, always, or never true. Instead, one had to know what sorts of objects the letters represented. In fact, by the 1840's, the letters were sometimes used to represent objects that could scarcely be called numbers at all, falling instead into the category of operations.

George Boole was a mathematician of limited formal education who had started to make a name for himself in the 1840's. He had been a bright child but did not come from a family wealthy enough to be able to send him to a university. His mathematical skills were sufficient to earn publication for his articles, and he may even have benefited from not having been exposed to the university curriculum typical of the age. In particular, he could bypass Aristotle's logic the extent that it was still being held up as essential for university students.

MATHEMATICAL LOGIC

Boole was a friend of the mathematician Augustus De Morgan, who had written a fair amount about logic himself and who had become embroiled in a dispute with a philosopher over plagiarism. Boole was sympathetic to De Morgan, but he found something to be said on behalf of the approach of De Morgan's opponent as well. What Boole did in his pamphlet *The Mathematical Analysis of Logic* (1847) was to illustrate how mathematics could be used to settle issues about the validity of logical arguments. This involved expressing the arguments in mathematical terms and then applying mathematical techniques to determining whether the arguments were legitimate.

Boole translated statements into equations by thinking of letters as representing classes of objects. He then represented combinations of those classes by algebraic expressions involving addition, subtraction, and multiplication. Addition corresponded to the logical connective "or" and multiplication to the connective "and." What enabled Boole to persuade readers of the usefulness of this approach was that the laws of logic, as expressed with these letters and operations, looked a great deal like the laws of algebra, to which mathematicians were accustomed. Because everyone was familiar with solving algebraic equations to get numerical solutions, Boole suggested that one could use similar techniques to determine whether the equation corresponded to a valid argument.

The analogy with the ordinary laws of algebra was not perfect. In particular, in the setting of logic, it turned out that any power of a variable was just equal to that variable itself. In ordinary algebra, the only numbers for which that was true were 0 and 1. As a result, Boole characterized the algebra of logic as the ordinary algebra of numbers if one were limited to only the numbers 0 and 1. Boole also had to develop an interpretation of those numbers in the setting of logic. This resulted in his using 0 to stand for the empty class (the set with no members) and 1 to stand for the universal class (in which everything is contained). This was a step well beyond anything Aristotle had discussed formally.

The ideas that Boole combined to turn logic into a mathematical science came from many settings. Obviously, contemporary work on algebra suggested the use of letters for different sorts of objects. In addition, Boole was an enthusiastic reader of theology, and he may have found the notion of 1 as standing for the universal class in line with his views about God. In any case, Boole continued to work on formulating the ideas of his pamphlet, which he described in a journal article in 1848 and articulated at greater length in *An Investigation of the Laws of Thought on Which Are Founded the Mathematical Theories of Logic and Probabilities*, published in 1854. De Morgan and he engaged in a correspondence that helped to clarify Boole's ideas in a way to make them more widely accessible, although none of his books ever sold well.

IMPACT

Bertrand Russell once claimed that pure mathematics was invented by George Boole, and he was thinking of Boole's work on mathematics and logic. The relationship between mathematics and logic had been a distant one up until Boole's time, but the two remained yoked together in the work of many mathematicians and philosophers who pursued the subject after Boole's death in 1864. In particular, the lack of progress in logic over the time since Aristotle contrasts sharply with the continuing progress in mathematical logic following in Boole's footsteps.

Boole's introduction of mathematics into logic did not enable logicians to analyze every argument mathematically. In particular, statements about relations could not easily be fit into Boole's machinery. The German mathematician Gottlob Frege created a notation in a work of his published in 1879, and his energetic efforts on behalf of his conception and notations led to Boole's work being shunted off to the side. If there is anyone who can

BOOLEAN SEARCHES

George Boole is today considered the father of mathematical logic. His mathematics were extremely complex but in one way his work has become very familiar to anyone who does "advanced" searches on computer databases. The Boolean "operators" AND, OR, and NOT are ubiquitous tools of advanced search engines:

AND: requires all results in a search to contain *both* words or expressions entered into the search.
OR: requires all results in a search to contain *at least one* word or expression entered into the search.
NOT: requires all results in a search to contain all words entered as the first word or expression in a search, *excluding* those entered as the second expression or word in the search.

compete with Boole for the distinction of having created mathematical logic, it would be Frege.

Boole's influence, however, became even more conspicuous with the rise of computer science. Terms involving the word "Boolean" bear witness to the extent to which his treatment of variables became a model for analyzing language, reasoning, and even switching circuits. Even the "New Math" introduced in elementary education in the 1960's started from Boolean algebra. Boole demonstrated that classical logic could be treated as a branch of mathematics. Mathematics and logic (and the world with which they deal) have been linked ever since.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Thomas Drucker*

BOURBAKI PROJECT

THE SCIENCE: The Bourbaki mathematicians worked, through their serial publication *Éléments de mathématique*, to expound in a highly original way the principal structures of modern mathematics with the goal of making each field of mathematical study have the widest possible sphere of applicability.

THE SCIENTISTS:

Claude Chevalley (1909-1984), French mathematician and a founding member of the Bourbaki group
Henri Cartan (b. 1904),
Jean Dieudonné (1906-1992),
André Weil (1906-1998),
Jean Delsarte (1903-1968),
Charles Ehresmann (1905-1979),
René de Possel (1905-1974),
Szolem Mandelbrojt (1899-1983), and
Jean Coulomb, other founding members

THE NEW MATH

Two essential characteristics of modern mathematics are an emphasis on abstraction and an increasing concern with the analysis of broad, underlying structures and patterns. By the middle of the twentieth century, these characterizing features were noted by those who were interested in mathematical education, and it was felt by some that these features should be incorporated into the teaching of mathematics. Accordingly, competent and enthusiastic writing groups were formed to redesign and modernize the school offerings in mathematics, and the so-called new math came into being.

Because abstract mathematical ideas often can be expressed most concisely in terms of "set" concepts and set notation, and because "set theory" had become recognized as a foundation of mathematics, the new math starts with an introduction to set theory and then continues with a persistent use of set ideas and set notation. The new math also stresses, as does twentieth century mathematics, the underlying structures of the subject. Thus, in the New Math treatment of elementary algebra, much more attention is given to the basic structures and laws of algebra (such as the commutative, associative, distributive, and other laws) than was the case previously.

THE BOURBAKI CIRCLE AND ITS MISSION

"Bourbaki" is the collective pseudonym of an influential group of mathematicians and their intellectual heirs who, beginning in 1935 (and continuing to this day), engaged in writing what they envisioned as a definitive survey of all of mathematics, or at least of all those parts of the subject that the group considered worthy of the name. Although many influential members of the group are well known, the exact composition of the Bourbaki group varies from year to year and is kept secret. The group, whose official title is L'Association des Collaborateurs de Nicolas Bourbaki, has an office in Paris at the École Normale Supérieure and a Web site.

The project was begun by a number of brilliant young mathematicians who made important contributions to mathematics under their own names. In the beginning, they made no particular attempt to keep their identities secret. With the passage of time, however, they became more and more fond of their joke, and they often tried to persuade people that there was indeed an individual named Nicolas Bourbaki who was the author of their books. In fact, a Nicolas Bourbaki applied for membership in the American Mathematical Society but was rejected on the grounds that he was not an individual.

Among the original members of the group were Henri Cartan, Claude Chevalley, Jean Dieudonné, and André Weil—all of whom were among the most eminent mathematicians of their generation. Many younger French mathematicians later joined the group, which is said to have ten to twenty members at any one time and has included two or three Americans. It has been said that the only rule of the group is mandatory retirement from membership at the age of fifty.

Although the Bourbaki group writes under the pseudonym Nicolas Bourbaki, no such person exists, and the origin of the name is obscure. It has been suggested, however, that the use of a collective pseudonym was intended to obviate title pages with long and changing lists of names and to provide a simple way of referring to the project. The family name appears to be that of General Charles Denis Sauter Bourbaki (1816-1897), a statue of whom stands at Nancy, France, where several members of the group once taught. It has also been suggested that the Christian name alludes to St. Nicholas, a bringer of gifts—in this case, gifts to the mathematical world.

Over the years, the Bourbaki group's major treatise, *Éléments de mathématique* (1939ff.; elements of mathematics), which is actually a series of volumes, has appeared in installments ranging from one hundred to three hundred pages in length. The first installment appeared in 1939 and the

WHERE IS NICOLAS BOURBAKI?

In an interview in 1997, one of the Bourbaki group's members, Pierre Cartier, responded to the question of why the group had not published since the mid-1980's:

> Under the pressure of [founding member] André Weil, Bourbaki insisted that every member should retire at fifty, and I remember that, in my eighties, I said, as a joke, that Bourbaki [the group's fictional founder] should retire when he reaches fifty. . . .
>
> Weil was fond of speaking of the Zeitgeist, the spirit of the times. It is no accident that Bourbaki lasted from the beginning of the thirties to the eighties. . . . The twentieth century, from 1917 to 1989, has been a century of ideology, the ideological age. . . . If you put the manifesto of the surrealists and the introduction of Bourbaki side by side, as well as other manifestos of the time, they look very similar. . . . In science, in art, in literature, in politics, economics, social affairs, there was the same spirit. The stated goal of Bourbaki was to create a new mathematics. . . . Bourbaki was to be the New Euclid, he would write a textbook for the next 2000 years. . . .
>
> When I began in mathematics the main task of a mathematician was to bring order and make a synthesis of existing material, to create what Thomas Kuhn called normal science. Mathematics, in the forties and fifties, was undergoing what Kuhn calls a solidification period. In a given science there are times when you have to take all the existing material and create a unified terminology, unified standards, and train people in a unified style. The purpose of mathematics, in the fifties and sixties, was that, to create a new era of normal science. Now we are again at the beginning of a new revolution. Mathematics is undergoing major changes. We don't know exactly where it will go. It is not yet time to make a synthesis of all these things—maybe in twenty or thirty years it will be time for a new Bourbaki.

Source: Cartier, Pierre. "The Continuing Silence of Bourbaki: An Interview with Pierre Cartier." Interviewed by Marjorie Senechal. *The Mathematical Intelligencer*, June 18, 1997.

thirty-third in 1967. Many intervening installments have been extensively revised and reissued.

The selection of topics in the work is unlike more traditional introductions to mathematics. In the Bourbaki arrangement, the history of mathematics begins with set theory, which is followed by abstract algebra, general topology, functions of a real variable (including ordinary calculus), topological vector spaces, and the general theory of integration. To some extent, the order is determined by the logical dependence of each topic on its predecessors.

MATHEMATICAL STRUCTURES

The most obvious aspects of the Bourbaki work are, first, its insistence on strict adherence to the axiomatic approach to mathematics and, second, the use of an individual and (originally) unconventional terminology—much of which has since been widely accepted. The group's axiomatizations are intended to be applied to what the group calls "mathematical structures." In principle, a mathematical structure consists of a set of objects of unspecified nature and a set of relationships among those objects. Once a structure has been ascertained, axioms are added to describe it more precisely.

By proceeding in this way, it is possible to obtain increasingly complex structures. The Bourbaki group, then, envisions mathematics as a system of structures ranging from the simple to the complex. Its aim is to make each field of mathematical study as general as possible in order to obtain the widest possible sphere of applicability.

IMPACT

The Bourbaki project has been influential for a number of reasons. Most important, the volumes in *Éléments de mathématique* have offered the first systematic account of a number of topics that previously were available only in scattered articles. The Bourbaki group's orderly and general approach, insistence on precision of terminology and argument, and advocacy of the axiomatic method all have had a strong appeal for pure mathematicians, who had been proceeding in the same direction. Since mathematicians had to learn Bourbaki terminology in order to read their work, that terminology has become widely known, and it has changed much of the vocabulary of mathematical research. Although the group published little after the 1980's, the effect of its work in the development of mathematics has been fully commensurate with the great effort that has gone into creating it.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Genevieve Slomski*

BOYLE'S LAW

THE SCIENCE: Often called the "father of modern chemistry," Robert Boyle discovered the inverse relationship between the pressure and volume of a gas. He devised influential definitions of a chemical element, compound, and reaction. He also used his corpuscular philosophy, an atomic theory of matter, to explain his experimental results.

THE SCIENTISTS:

Robert Boyle (1627-1691), Irish chemist and physicist
Robert Hooke (1635-1703), English physicist
René Descartes (1596-1650), French philosopher, physicist, and mathematician
Pierre Gassendi (1592-1655), French priest and atomist
Otto von Guericke (1602-1686), German physicist who invented the air pump
Edmé Mariotte (1620-1684), French priest and physicist
John Mayow (1641-1679), English physiologist
Richard Lower (1631-1691), English physician

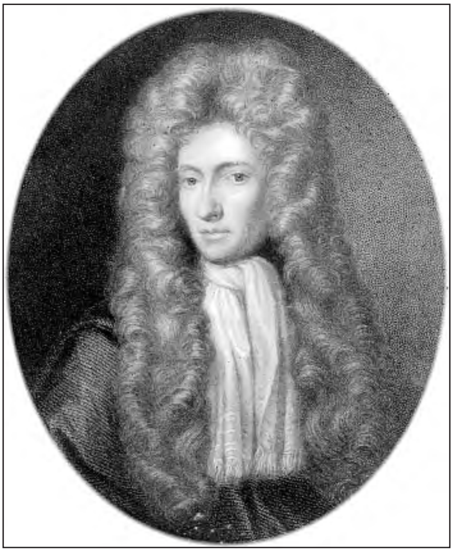
FROM ALCHEMY TO CHEMISTRY

For chemistry to become a modern science, old ideas had to be abandoned and new ideas introduced. During the seventeenth century the scientist most responsible for the transformation of alchemy into chemistry was Robert Boyle. Unlike many natural philosophers of the Scientific Revolution, who viewed chemistry as either a pseudoscience or a practical craft, Boyle treated chemistry as worthy of a rigorous experimental approach.

Born into the aristocracy in Ireland, Boyle had been a child prodigy who developed his intellectual skills at Eton and, with a tutor, on a tour throughout Europe. He studied the new scientific ideas of such natural philosophers as Galileo, Pierre Gassendi, and René Descartes. After his return to England in the mid-1640's, he devoted more and more of his time to scientific studies. He became a member of a group of science enthusiasts called the Invisible College, which was the forerunner of the Royal Society, an important institution in Boyle's later career.

AIR PUMPS AND VACUUMS

While at Oxford in the late 1650's, Boyle learned of Otto von Guericke's demonstration in Magdeburg, Germany, of the tremendous pressure of the atmosphere. Guericke used his invention, an air pump, to suck the air out of two metal hemispheres fitted together along a circumferential flange. Several teams of horses were unable to disjoin them, but as soon as air was reintroduced into the joined hemispheres, they readily fell apart. With the help of a talented assistant, Robert Hooke, Boyle constructed an air pump that was much more effective than the one used in Germany. Indeed, so effective was this pump at evacuating experimental vessels that *vacuum Boylianum* ("Boylean vacuum") became a standard scientific designation.



Robert Boyle. (Library of Congress)

For two years Boyle used his

air pump to perform a variety of experiments. He demonstrated that a feather and a lump of lead fell at the same velocity in a vacuum, that a clock's ticking was silent in a vacuum, and that electrical and magnetic attraction and repulsion remained undiminished in a vacuum. Birds and mice did not long survive in a vacuum, and a candle flame sputtered out when deprived of air. Boyle published an account of his research in his first scientific book, *New Experiments Physico-Mechanicall, Touching the Spring of the Air and Its Effects* (1660).

Boyle's Law

Because of Boyle's belief that he had created a vacuum, a controversial notion at the time, his book provoked criticisms from Aristotelians and Cartesians who believed that voided spaces were impossible in a universe completely filled with matter. In response to a particular critic, the Jesuit Franciscus Linus, Boyle devised his most famous experiment, an account of which he published in the second edition of his book in 1662. Using a seventeen-foot-long J-shaped glass tube sealed at the short end, Boyle trapped air in the sealed end by pouring mercury into the long open tube. He discovered that, when he doubled the weight of the mercury in the long tube, the volume of the trapped air was halved. This discovery of the inverse relationship between a gas's pressure and volume came to be called Boyle's law in English-speaking countries. It was called Mariotte's law in continental European countries, because, in 1676, Edmé Mariotte, independently of Boyle, discovered this inverse relationship with the important provision that the temperature during measurements had to be kept constant.

As a corpuscularian philosopher, Boyle tried to explain the results of his experiments mechanically, but his corpuscles were not the same as Gassendi's or Descartes's. Boyle's corpuscles had size, shape, and mobility, though he was cautious in using these theoretical entities to account for experimental phenomena. For example, in the case of the compressibility of air, he proposed that air corpuscles might be like tiny coiled springs, but since air was also involved in chemical processes such as combustion, Boyle believed that air was a peculiar substance, an elastic fluid teaming with foreign materials.

Simple and Complex Elements

Boyle's theoretical ideas made their appearance when he published *The Sceptical Chymist* (1661, rev. 1679). This work, often called his masterpiece, was written as a dialogue among spokespeople holding different views about the nature of chemistry. However, it was clearly an attack on the ancient Aristotelian notion that all matter is composed of four elements—earth, water, air, and fire—and a repudiation of the Renaissance view that all chemical phenomena can be explained through the three principles of salt, mercury, and sulfur.

Unwilling to rely on previous authorities, the "sceptical" Boyle emphasized that chemical ideas had to be grounded in observations and experiments. For him, no reason existed for limiting the elements to three or four, since an element was basically a substance that could not be broken down into simpler substances. These elemental substances, which are capable of combinations in various compounds, were behind all material things and their changes. Though Boyle's "operational definition" of elements became influential, he found it difficult in practice to determine whether particular substances were simple or complex.

Chemical Analysis

Not only did Boyle contribute to physical and theoretical chemistry; he also helped found qualitative and quantitative analysis. For example, he developed identification tests to make sure he was using pure materials. Gold was pure if it had the correct specific gravity and dissolved in aqua regia (a mixture of hydrochloric and nitric acids) but not in aqua fortis (nitric acid alone). He also used precipitates, solubility, and the colors of substances in flames as analytical tools. He was especially fascinated with color indicators as a way to distinguish acidic, alkaline, or neutral substances. He discovered that a blue plant material, "syrup of violets," turned red in acids, green in alkalis, and remained unchanged in neutral solutions.

Combustion

Throughout the history of chemistry, researchers used fire to study chemical changes. Boyle knew that combustion stopped in the absence of air, but he also knew that gunpowder burned under water (he thought that the saltpeter in gunpowder acted as an air substitute). Like other researchers, Boyle observed that, when metals were heated in air, they formed a powdery substance (a "calx") that was heavier than the original metal. He explained the weight increase as a result of the addition of "igneous corpuscles," but a contemporary, John Mayow, was closer to the truth when he speculated that a substance common to air and saltpeter (now known to be oxygen) might be the cause of combustion.

Like other experimenters, Boyle discovered a connection between combustion and respiration, since he observed that a burning candle and a breathing mouse both reduced the volume of air. Mayow believed that the blood in the lungs absorbed the "combustive principle" from the air and distributed it throughout the body. Another contemporary of Boyle, Richard Lower, discovered that air could change dark venous blood to bright red arterial blood. In addition to blood, Boyle was interested in urine, from which he prepared phosphorus, whose luminosity in air intrigued him (he initiated the practice of storing phosphorus under water). Although Boyle failed to find the true role that air played in respiration and in the combustion of phosphorus, his emphasis on methodical experimentation served as an exemplar for those eighteenth century scientists who would eventually make these discoveries.

Impact

Victorian writers bestowed on Boyle the epithet "father of modern chemistry" because of his realization that chemistry was worthy of study for its own sake and not just because of its usefulness to medicine and metallurgy. He also showed those natural philosophers who denigrated chemistry as an occult science that chemists, through rigorous experiments, could make important discoveries every bit as objective as those of physicists. On the other hand, some twentieth century scholars have questioned Boyle's traditional role as modern chemistry's founder. They emphasize that what Boyle meant by an element is not what modern chemists mean by it; Antoine-Laurent Lavoisier was largely responsible for the modern notion of chemical elements as related to specific types of atoms. For example, Boyle did not think that metals were elements, but the periodic table contains many metals that are genuine elements. Furthermore, Boyle did not really abandon alchemy; he believed in its central doctrine, transmutation. He was so convinced that lead could be transformed into gold that he campaigned against an old royal decree forbidding transmutation research.

Despite the caveats of modern scholars, more chemical discoveries and theoretical ideas found in Boyle's voluminous writings have become part of modern chemistry than the work of any of his contemporaries. The air pump he invented has been called the greatest machine of the Scientific Revolution, and Boyle's experimental studies became models of the most productive way to do science. As an advocate of the experimental philosophy, he was one of the most influential members of the Royal Society, though he declined its presidency over a personal scruple about taking oaths. Though

ROBERT BOYLE: SCIENCE AND FAITH

Robert Boyle made two important contributions to science, particularly physics and chemistry. The first is a tangible contribution: He was a founding member of the Royal Society of England in 1662. This group of eminent scientists—including William Brouncker, Robert Murray, Paul Neile, John Wilkins, and Sir Christopher Wren—met regularly to present papers on scientific thought and to discuss the results of experiments. The society also kept meticulous records of its proceedings (perhaps a direct result of Boyle's participation) and published the first science journal in England. The Royal Society promoted excellence and dedication in the sciences and attracted such men as Sir Isaac Newton to careers in science.

Boyle's second contribution is less concrete but just as vital. Boyle's experimental approach to chemistry helped to bring it into the realm of modern scholarship. Previously, a mystical or mysterious element was associated with chemistry. Alchemy, or the alleged changing of one substance into another (most often a base metal into a precious one), was almost the only chemical investigation done until Boyle's day. Fraudulent claims, farfetched speculation, and outright trickery made alchemy an unrespectable method of study. By replacing quasi-scientific work with the experimental method, Boyle did a great service for future generations of chemical researchers.

Ironically, at age thirteen, during a sudden and violent thunderstorm in Geneva, Boyle believed that he was truly converted to a fervent Christianity. He was a devout believer for the rest of his life, and his studies in the physical sciences were always conducted so as to demonstrate the existence of God in the universe. He saw no conflict between his scientific research and his faith: The regularity of physical and chemical laws convinced Boyle that an intelligent God had created the world.

praised by physicists, Boyle saw himself above all as a chemist, and in his development of new techniques and control experiments, he had a great influence on the modern scientific research laboratory.

For his contemporaries, Boyle was the preeminent mechanical philosopher in England. He trained some important scientists, including Robert Hooke, Denis Papin (the inventor of a forerunner of the pressure cooker), and Johann Joachim Becher, an influential German chemist. During his lifetime, Boyle was also honored for his writings on natural theology. Deeply religious, he considered himself a "priest of Nature," and in his will he left substantial funds to found the Boyle Lectures for the Defense of Christianity Against Its Enemies. These lectures, which have been given for over three centuries, symbolize the lasting significance of Boyle not only to scientists but also to all human beings trying to reconcile their search for meaning in life with the worldview created by modern science.

See also Atmospheric Pressure; Atomic Theory of Matter; Kinetic Theory of Gases; Thermodynamics: First and Second Laws; Thermodynamics: Third Law.

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—*Robert J. Paradowski*

Brahe's Supernova

The Science: Tycho Brahe's observation of a supernova led him to develop new, precise instruments for observing and measuring the locations and movements of celestial bodies. Johannes Kepler used Brahe's work to help demonstrate his radical theory that planets, including Earth, moved in ellipses around the Sun.

THE SCIENTISTS:

Tycho Brahe (1546-1601), Danish astronomer
Johannes Kepler (1571-1630), mathematician and astronomer

STARLIGHT IN THE DAYTIME

On November 11, 1572, as the Danish astronomer Tycho Brahe was about to leave his uncle's alchemy lab at Herreved Abbey when he noticed that a new star—one that he would call Stella Nova—had appeared in the constellation Cassiopeia. Brahe did not believe his eyes, so he called upon others to view the new star and to reassure him that it was really there. The new star, which he appropriately called Stella Nova, was brighter than the planet Venus and observable during daylight hours. It remained visible for eighteen months. The object Brahe and the others had seen is known now as a supernova, a rare astronomical event defined as a stellar explosion that expels a star's outer layers and fills the surrounding space with a cloud of gas and dust.

After Brahe's observation, astronomers and philosophers began to ask, Where, exactly, was this new star located? Tradition had always taught that Earth was the center of creation, and that the objects in the sky were located on spheres that rotated around Earth. The stars were located on the outermost sphere, and both Aristotelian and Christian philosophy taught that the sphere of the stars had remained unchanged since the day of creation. In this view, it was not possible for a new star to appear in the perfect and unchanging sky.

The planets and the Moon were known to move relative to the stars, so it was thought that this supernova was located either in the Earth's atmosphere or on one of the inner spheres, where the planets and the Moon were located. If so, then the supernova would move relative to the stars, as did the planets and the Moon.

BRAHE'S MEASUREMENTS

Two leading astronomers, Michael Maestlin in Tubingen and Thomas Diggs in England, tried to detect movement in the new star by lining it up with known fixed stars, using stretched threads to measure the separation. They saw no movement. Brahe, however, knew he could make more accurate measurements by using instruments that were built to precise standards and were much larger than those traditionally employed. Brahe had just finished building a new sextant, which had huge arms, 5.5 feet long. In addition, Brahe had developed a table of data allowing him to correct for

A Home for Tycho

By the time he observed the supernova, Tycho Brahe was a well-known figure: Bejeweled and flamboyantly dressed, he was stocky, with reddish-yellow hair combed forward to hide incipient baldness, and he sported a pointed beard and a flowing mustache. When he was young in Germany, he had been in a duel in which his opponent sliced off a large piece of his nose. Brahe had a substitute made of gold and silver and painted to look natural. Consequently, he always carried a box with glue and salve.


(Library of Congress)

Brahe's plan was to settle abroad, but when the Danish king gave him the small island of Ven, he was able to build his famous observatory: the architecturally beautiful Uraniborg, named after the muse of astronomy, Urania. It boasted a chemistry lab, his famous mural quadrant, and observatories in the attic. The smaller but equally famous Stellaburg—which, except for a cupola, was built underground—contained many observational instruments, including Brahe's renowned revolving quadrant, as well as portraits, in the round, of the great astronomers. Brahe even had his own printing press so he could publish his studies as well as calendars and horoscopes for the king and other high dignitaries who visited the island.

By 1582, Brahe had rejected both the static Earth-centered Ptolemaic system and the heliocentric Copernican system, preferring an amalgam. In Brahe's system, Earth was static and the Moon and the Sun revolve around it, while the other planets revolve around the Sun. It remained for Brahe's student Johannes Kepler to reinstate the correct Copernican system, reinforced by Brahe's observations.

Unfortunately, Brahe did not adhere to his scientific studies. As he grew older, his idiosyncrasies became more pronounced and he became involved in some petty suits that alienated the king. Brahe's intransigence finally caused the king to confiscate land that had been bequeathed to him, leaving Brahe without an adequate source of income. In July, 1597, Brahe moved to Rostock, Germany. A submissive letter to King Christian IV was met with an angry response, so Brahe approached Emperor Rudolf II in Prague. Rudolf had a reputation as a patron of the sciences and took Brahe and his collaborator Kepler under his wing. The two famous astronomers had, at times, a stormy relationship, and, after several years, Kepler had a nervous breakdown and left Prague. Brahe died shortly thereafter, on October 24, 1601.

the tiny errors in his sextant. Using this new sextant, Brahe determined that the new star did not move relative to the fixed stars. Thus, the new star was on the eighth, or outermost, sphere, a sphere that was not changing.

Brahe published a detailed account of his methods and results the next year. His book *De nova et nullius aevi memoria prius visa stella* (1573; better known as *De nova stella*; partial English translation in *A Source Book in Astronomy*, 1929) made him famous among astronomers throughout Europe. Other young noblemen asked Brahe to teach a course on astronomy, but he refused. He changed his mind only when the king asked him to teach. In September of 1574, Brahe began lecturing on astronomy at the University of Copenhagen. His fame would soon secure for him an island on which to build his observatories Uraniborn and Stellaburg, from which he would take detailed measurments of the stars and planets for the next twenty years.

A new king, Christian IV, came to power in Denmark in 1588 and chose not to support Brahe's astronomical efforts. Brahe moved to Prague shortly thereafter and was joined by a new assistant, Johannes Kepler. Upon Brahe's death, all of his astronomical measurements were given to Kepler, who used them to develop his three laws of planetary motion.

Impact

Brahe's demonstration that this new star was truly a star overturned prevailing religious dogma, which stated that the heavens were perfect and unchanging. Moreover, his observations and *De nova stella* brought his work to the attention of the king of Denmark, who gave him the island of Ven and the income generated by its inhabitants to build and equip the Uraniborg Observatory. At this facility he was able to collect twenty years' worth of critical astronomical measurements. The king's support also allowed Brahe to purchase or build the most precise instruments available to measure the positions of the stars and the planets, long before the invention of the telescope.

Finally, Brahe's precise measurements of the positions of the planets in the sky provided the foundation for Johannes Kepler's laws of planetary motion, which in turn were used by Sir Isaac Newton to demonstrate the validity of his law of gravity over the astronomical distance scale.

See also Big Bang; Black Holes; Cepheid Variables; Galactic Superclusters; Galaxies; Gamma-Ray Bursts; Nebular Hypothesis; Neutron Stars; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; Very Long Baseline Interferometry; X-Ray Astronomy.

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—*George J. Flynn*

BUCKMINSTERFULLERENE

THE SCIENCE: Buckminsterfullerene, which is produced when carbon is vaporized in a helium atmosphere, may always have been present in candle flames.

THE SCIENTISTS:

Robert F. Curl (b. 1933), American chemist
Harry W. Kroto (b. 1939), English chemist
Richard E. Smalley (b. 1943), American physical chemist
R. Buckminster Fuller (1895-1983), creator of the geodesic dome, for whom buckminsterfullerene is named

THE BUCKYBALL MYSTERY

In 1985, while astronomers peered into their telescopes and noted unusual features in the light that came from distant stars, physical chemists Robert F. Curl, Harry W. Kroto, and Richard E. Smalley stumbled on a previously unknown form of carbon that had been created in a chamber filled with helium gas in which graphite had been vaporized with a laser. This experiment was intended to re-create the conditions that exist in the outer reaches of the universe. The soot that remained in the chamber was found to contain a molecule of sixty carbon atoms that were arranged in a perfectly

The "Buckyball" Molecule

spherical shape resembling that of a soccer ball. This molecule of carbon, carbon 60, also resembled a geodesic sphere, and for that reason it was named buckminsterfullerene for R. Buckminster Fuller, the creator of the geodesic dome. Scientists affectionately call the buckminsterfullerene molecule "buckyball."

Buckminsterfullerene may be one of the most abundant and oldest molecules in the universe; it can be traced to the first generation of stars, which were formed some ten billion years ago. It also promises to be the favorite plaything of chemists for years to come. Fullerene chemistry—chemistry concerned with fullerene molecules, which are clusters of carbon atoms—has become a field of chemistry with a wide array of applications, including the creation of superconducting materials, lubricants, and spherical "cage compounds" that can be used to administer medications or radioisotopes to patients. Some chemists believe that the structure of the buckyball is so symmetrical and beautiful that it must have many applications that have not yet been discovered.

Buckyball's Magic Peak

Mountain climbers are thrilled when they sight a snow-capped mountain rising out of the surrounding countryside. Chemists feel that same kind of excitement when they come across their own kind of "magic peak." Such a peak occurs occasionally for chemists as an upward-pointing blip on the readout of a "mass spectrometer," an instrument that sorts molecules by mass (a molecule's mass is the amount of material that the molecule contains). Researchers find such peaks both baffling and fascinating, because they indicate that an experiment has yielded a large number of molecules of one particular mass.

Precisely that kind of peak led to the discovery of buckminsterfullerene, a cagelike molecule made up of sixty carbon atoms elegantly arranged in the shape of a soccer ball. The discovery of this form of carbon fascinated the chemistry and materials science communities.

As is often the case with scientific discoveries, the buckyball was discovered by accident rather than design. As early as 1983, scientists were studying the ultraviolet light given off by graphite smoke, hoping to learn

SIR HAROLD KROTO: WINNING ISN'T EVERYTHING

Upon winning the Nobel Prize in Chemistry for his part in the discovery of buckminsterfullerene, Sir Harold Kroto addressed young scientists with some wise advice:

> I have heard some scientists say that young scientists need prizes such as the Nobel Prize as an incentive. Maybe some do, but I don't. I never dreamed of winning the Nobel Prize—indeed I was very happy with my scientific work prior to the discovery of C_{60} in 1985. The creation of the first molecules with carbon/phosphorus double bonds and the discovery of the carbon chains in space seemed (to me) like nice contributions and even if I did not do anything else as significant I would have felt quite successful as a scientist.
>
> A youngster recently asked what advice I would give to a child who wanted to be where I am now. One thing I would not advise is to do science with the aim of winning any prizes, let alone the Nobel Prize; that seems like a recipe for eventual disillusionment for a lot of people. . . . I believe competition is to be avoided as much as possible. In fact this view applies to any interest—I thus have a problem with sport, which is inherently competitive.
>
> My advice is to do something which interests you or which you enjoy (though I am not sure about the definition of enjoyment) and do it to the absolute best of your ability. If it interests you, however mundane it might seem on the surface, still explore it because something unexpected often turns up just when you least expect it. With this recipe, whatever your limitations, you will almost certainly still do better than anyone else. Having chosen something worth doing, never give up and try not to let anyone down.

Source: Sir Harry Kroto, "Autobiography," *Les Prix Nobel: The Nobel Prizes 1996*, edited by Tore Frängsmyr (Stockholm: The Nobel Foundation, 1997). Available at http://nobelprize.org/chemistry. Accessed August, 2005.

something about the composition of interstellar dust. They noticed some unusual spectroscopic absorption patterns—the "magic peaks" referred to earlier. These patterns were not understood until 1985, when it was found that they had been produced by buckminsterfullerene.

The procedure used to produce the first crystals of carbon 60 involved studying the soot produced in a chamber. The hardware of the experiment was a cylindrical steel vacuum chamber three feet across. Within this cylinder was a steel block with a hollow tube that held a one-inch disk of a sample material—in this case, graphite. A laser was fired through a one-millimeter hole in the side of the block, blowing a plume of carbon atoms off the graphite. At the same time, a pressurized blast of helium (an inert gas) was sent through the end of the block and over the graphite. Because helium is inert, it did not interact with the carbon; instead, it captured and carried along the freed carbon atoms, allowing them to collide and cluster into groupings. Then, the high-pressure gas, now crowded with carbon clusters, rushed through a hole in the wall of the block and into the vacuum of the spacious main chamber. There, the atomic collisions diminished, their temperature dropped to just a few degrees above 0 Kelvin (absolute zero), and the clusters that were formed were preserved and recorded by the mass spectrometer. In the output recording of the mass spectrometer, chemists Smalley and Kroto observed the magic peaks of carbon 60, which caused great excitement in the scientific community.

Impact

For their discovery of buckminsterfullerene, Robert Curl, Harold Kroto and Richard Smalley won the 1996 Nobel Prize in Chemistry. It is now believed that fullerenes may be among the most common of molecules. Now that chemists know how to create carbon 60, they can modify it to create new chemicals—by encapsulating atoms or molecules inside its spherical "cage," for example. Scientists are also enjoying naming new derivatives of the buckyball molecule. Smalley has been able to "dope" the buckyball by placing atoms inside its "cage." He calls the resulting structure the "dopeyball."

Among the proposed uses of fullerenes are the creation of such novel products as specialized automotive lubricants; strong, light materials to be used for airplane wings; and rechargeable batteries. Carbon 60 can easily accept electrons and form negative ions. It can be paired with alkali metals such as potassium to form superconductors. Because carbon 60 can reversibly accept and donate electrons, fullerenes may function as catalysts in chemical processes.

Fullerenes have also been manipulated to produce extremely small pure-carbon tubes about one nanometer in diameter. These nanotubes can have a broad array of applications in electronics and other areas.

Fullerenes have led to the creation of hundreds of new compounds with unique chemical, optical, electrical, mechanical, and biological properties. Many of these compounds are now patented in anticipation that they will have lucrative commercial applications. As the efficiency of their manufacture increases and their cost decreases, fullerene technology promises to become a rich area of applied chemistry.

See also Atomic Theory of Matter; Definite Proportions Law; Isotopes; Periodic Table of Elements; Superconductivity.

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—*Jane A. Slezak, updated by Christina J. Moose*

CALCULUS

THE SCIENCE: Isaac Newton and Gottfried Wilhelm Leibniz, working independently and building on the work of predecessors, created the calculus, a new branch of mathematics.

THE SCIENTISTS:

Sir Isaac Newton (1642-1727), English natural philosopher and mathematician
Gottfried Wilhelm Leibniz (1646-1716), German philosopher and mathematician
John Wallis (1616-1703), English mathematician
Blaise Pascal (1623-1662), French mathematician and physicist
Pierre de Fermat (1601-1665), French mathematician
Bonaventura Cavalieri (1598-1647), Italian Jesuit priest and mathematician
Johannes Kepler (1571-1630), German astronomer and mathematician
Isaac Barrow (1630-1677), English mathematician and theologian

SHOULDERS OF GIANTS

No person, even a genius, creates in a vacuum. Sir Isaac Newton recognized this when he stated, "If I have seen further than other men, it is because I stood on the shoulders of giants." Even though the creation of the calculus has been associated more closely with Newton than with any other mathematician, his work depended on the contributions of others. That seventeenth century mathematicians had been primed for the calculus is evidenced by its independent discovery by Gottfried Wilhelm Leibniz, who also used the contributions of his mathematical precursors.

The calculus differed from such previous disciplines as geometry and algebra, since it involved a new operation by which, for example, a circle's area could be calculated by means of the limit of the areas of inscribed polygons, as their number of sides increased indefinitely.

During the first half of the seventeenth century, several mathematicians devised new methods for determining areas and volumes. For example, Johannes Kepler, stimulated by the problem of discovering the optimum proportions for a wine cask, published in 1615 a treatise in which he used immeasurably minute quantities, or "infinitesimals," in his volumetric calculations. Some scholars have seen Kepler's achievement as the inspiration for all later work in the calculus.

In 1635, Bonaventura Cavalieri published a book that challenged Kepler's in popularity, and some mathematicians attribute the development of the calculus to its appearance. Cavalieri used extremely small segments called "indivisibles" to devise theorems about areas and volumes. Although he compared these indivisibles to pages in a book, he made use of an infinite number of them in solving various problems. Blaise Pascal also used indivisibles in calculating the areas under various curves, but in his method he neglected "differences" of higher order, which some scholars see as the basic principle of the differential calculus. Building on the work of Pascal, his friend Pierre de Fermat formulated an ingenious method for determining the maximum and minimum values of curves.

In England, John Wallis, who had studied the mathematical methods of Fermat and others, attempted to arithmetize the geometric treatment of areas of volumes in his *Arithmetica infinitorum* (1655; arithmetic of infinitesimals), but Isaac Barrow was critical of Wallis's work. Barrow favored a geometric approach in determining tangents to curves, and his advocacy of geometry influenced Newton. In studying problems of tangents and quadratures (constructing squares equal in area to a surface), Barrow recognized the basic inverse relationship between differentiations and integrations, but he never generalized his method. This became the principal mathematical achievement of his pupil, Isaac Newton.

NEWTON AND LEIBNIZ

According to Newton's personal testimony, he began the steps that led to his invention of the calculus while he attended Barrow's lectures at

Gottfried Wilhelm Leibniz. (Library of Congress)

Cambridge University. He was also studying Wallis's work and the analytic geometry of René Descartes. Because of an outbreak of the bubonic plague, Newton returned to his home in Lincolnshire, where he derived a method of using infinite series to express the area of a circle. He also devised a differentiation method based not on ultimately vanishing quantities but on the "fluxion" of a variable. For example, Newton was able to determine instantaneous speeds through fluxions of distance with respect to time. Fluxions, Newton's name for the calculus, were descriptive of the rates of flow of variable quantities.

During the next four years, Newton made his methods more general through the use of infinite series, and he circulated his discoveries among his friends in a work entitled *De analysi per aquationes numero terminorum infinitas* (1669; on analysis by means of equations with an infinite series of terms), which was not formally published until 1711 (in *Analysis per quantitatum series, fluxiones, ad differentias: Cum enumeratione linearum tertii ordinis*).

Image Not Available

Not only did Newton describe his general method for finding the instantaneous rate of change of one variable with respect to another but he also showed that an area under a curve representing a changing variable could be obtained by reversing the procedure of finding a rate of change. This notion of summations being obtained by reversing differentiation came to be called the fundamental theorem of the calculus. Though Newton's predecessors had been groping toward it, he was able to understand and use it as a general mathematical truth,

THE CALCULUS CONTROVERSY

Both Gottfried Wilhelm Leibniz and Sir Isaac Newton saw the calculus as a general method of solving important mathematical problems. Though their methods were essentially equivalent, Newton, the geometer, and Leibniz, the algebraist, developed and justified their discoveries with different arguments. They both reduced such problems as tangents, rates, maxima and minima, and areas to operations of differentiation and integration, but Newton used infinitely small increments in determining fluxions whereas Leibniz dealt with differentials. Scholars have attributed this contrast to Newton's concern with the physics of motion and Leibniz's concern with the ultimate constituents of matter.

Initially, no priority debate existed between Newton and Leibniz, both of whom recognized the basic equivalence of their methods. Controversy began when some of Newton's disciples questioned Leibniz's originality, with a few going so far as to accuse Leibniz of plagiarism (since Leibniz had seen Newton's *De analysi* on a visit to London in 1676). Nationalism played a part in the controversy as well. The English and the Germans desired the glory of the calculus's discovery for their respective countries. Though the controversy generated many hurt feelings and some unethical behavior on both sides in the seventeenth century, scholars now agree that Newton and Leibniz discovered the calculus independently.

The significance of this priority controversy was not a question of victor and vanquished but the divisions it created between British and Continental mathematicians. The English continued to use Newton's cumbersome fluxional notation, whereas Continental mathematicians, using Leibniz's superior formalism, were able to systematize, extend, and make a powerful mathematical discipline of the calculus. Consequently, for the next century, British mathematicians fell behind the mathematicians of Germany, France, and Italy, who were able to develop the calculus into a powerful tool capable of helping mathematicians, physicists, and chemists solve a wide variety of important problems.

which he described fully in *Methodus fluxionum et serierum infinitarum* (*The Method of Fluxions and Infinite Series*, 1736), written in 1671 but not published until after Newton's death. In this work, he called a variable quantity a "fluent" and its rate of change the "fluxion," and he symbolized the fluxion by a dot over the letter representing the variable.

Newton's third work on the calculus, *Tractatus de quadratura curvarum* (treatise on the quadrature of curves), was completed in 1676 but published in 1711 (also part of *Analysis per quantitatum series*). He began this treatise by stating that, instead of using infinitesimals, he generated lines by the motion of points, angles by the rotation of sides, areas by the motion of lines, and solids by the motion of surfaces. This work exhibits Newton's mastery of the increasingly sophisticated and powerful methods he had developed. Though he made sparse use of fluxions in his greatest work, *Philosophiae naturalis principia mathematica* (1687; *The Mathematical Principles of Natural Philosophy*, 1729, better known as the *Principia*), he did offer three ways to interpret his new analysis: using infinitesimals (as he did in *De analysi*), limits (as he did in *De quadratura*), and fluxions (as he did in *Methodus fluxionum*). The *Principia* was Newton's last great work as a mathematician.

The chief work on the calculus that rivaled Newton's work was that of Leibniz. Leibniz's early mathematical interests were arithmetic and geometry, but in studying the problem of constructing tangents to curves he used a "differential triangle" (used earlier by Pascal, Fermat, and Barrow) to arrive at solutions. He recognized that the ratio of the differences in the horizontal and vertical coordinates of a curve was needed to determine tangents, and by making these differences infinitely small, he could solve these and other problems. He also realized that the operations of summation and determining differences were mutually inverse. In a 1675 manuscript on his "inverse method of tangents," Leibniz used an integral sign for the sum and "dx" for the difference. With his new notation he was able to show that integration is the inverse of differentiation. Like Newton, Leibniz did not circulate his ideas immediately, but, in 1682, he published his discoveries in a new journal, *Acta eruditorum* (proceedings of the learned). In this and later articles he presented his methods of determining integrals of algebraic functions and solving differential equations.

Impact

It is no accident that the calculus originated during the Scientific Revolution; it provided scientists with efficacious ways of determining centers of gravity, instantaneous velocities, and projectile trajectories. It provided Newton, Leibniz, and the scientists who followed with methods for solving important mathematical problems applicable in all the sciences.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum

Hypothesis; Integral Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Robert J. Paradowski*

CARBON DIOXIDE

THE SCIENCE: Joseph Black showed that, when intensely heated, magnesia alba (magnesium carbonate) and chalk (calcium carbonate) produced "fixed air" (carbon dioxide), a gas with unique physical and chemical properties.

THE SCIENTISTS:

Joseph Black (1728-1799), Scottish chemist, physicist, and physician whose discovery of carbon dioxide and its reactions transformed scientists' understanding of the chemical nature of gases

Daniel Rutherford (1749-1819), Scottish chemist and Black's student who discovered "mephitic air" (nitrogen)

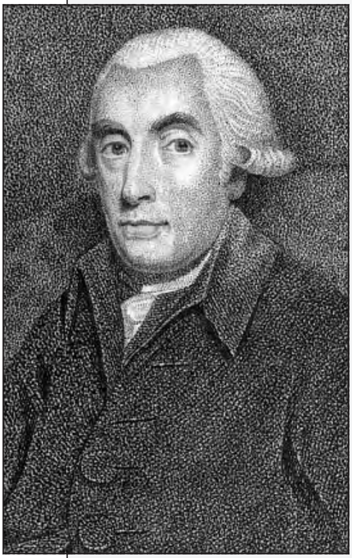
William Cullen (1710-1790), Glasgow University's first lecturer in chemistry who taught Black and who was succeeded by him

DIFFERENT KINDS OF AIR

For more than two thousand years, alchemists considered air an element, but the Scottish chemist Joseph Black, by discovering that carbon dioxide was a different kind of "air," made an important contribution to modern chemistry. His studies at the universities of Glasgow and Edinburgh prepared him for this discovery.

At Glasgow, where he studied medicine, William Cullen's lectures

JOSEPH BLACK: PHILOSOPHY AND IMPROVEMENT


(Library of Congress)

The Scottish chemist Joseph Black stood at the crossroads between the great cultural transformation that was the European Enlightenment and the great economic transformation that was the Industrial Revolution. His life work balanced a calling to make the study of chemistry "philosophical" (less subordinate to the pharmaceutical needs of medicine and more an autonomous science of its own) with a civic commitment to the "improvement" of Scotland.

In 1766, his mentor William Cullen having been appointed a professor of medicine, Black took up the chair of chemistry at Edinburgh. In his new position, Black increasingly focused on applied chemistry. Already at Glasgow Black had forged a close relationship with James Watt, who had been appointed instrument maker to the university. In 1769, Black loaned Watt the money needed to obtain a patent on his steam engine. As Watt himself affirmed, the methodological and theoretical foundation for his invention was laid by Black's meticulous program of experimentation and his investigation of latent and specific heats. Now, in the 1770's and 1780's, Scottish agricultural improvers like Henry Home, Lord Kames, sought Black's chemical imprimatur for their proposals even as entrepreneurs sought Black's advice on the metallurgy of coal and iron, the bleaching of textiles, and the manufacture of glass.

Britain's preeminent professor of chemistry, Black was uniquely influential. Across his career, he introduced Scottish "philosophical chemistry" to as many as five thousand students. He shared his dedication to university and industry, "philosophy" and "improvement," with the profusion of clubs in eighteenth century Scotland. He was a member not only of the Philosophical Society (later Royal Society) of Edinburgh but also of less formal civic groups such as the Select Society and the Poker Club. Dearest to Black was the Oyster Club, weekly dinners with his closest friends—William Cullen, the geologist James Hutton, and the author of *The Wealth of Nations*, Adam Smith.

The balance that Black achieved was a model for chemistry's continuing career in Britain as a public science and marked a critical moment in European cultural history, a moment before specialization would estrange the "two cultures" of the sciences and the humanities, a moment when chemistry remained a liberal, gentlemanly vocation.

sparked his interest in chemistry, and at Edinburgh, where he received his medical degree in 1754, his doctoral dissertation included the beginnings of his significant work in chemistry. This dissertation, *De humore acido a cibis orto et magnesia alba* (1754; the acid humours arising from food, and magnesia alba), had its origin in Black's desire to investigate magnesia alba's ability to dissolve gall and kidney stones, but when he found it lacked this ability, he decided to study its effect on stomach acidity. He prepared magnesia alba (magnesium carbonate) by reacting Epsom salt (magnesium sulfate) with pearl ash (potassium carbonate). Although the first part of Black's dissertation did deal with the medical use of magnesia alba as an antacid, the second, more creative part dealt with his experiments on magnesia and some of its chemical reactions.

Fixed Air

In the two years before his dissertation, Black discovered that magnesia alba, when vigorously heated, produced a new compound, "calcined magnesia" (magnesium oxide), which weighed less than the magnesia alba with which he had begun. Similarly, when he heated chalk (calcium carbonate), the quicklime (calcium oxide) he produced weighed less than the chalk. He attributed the lost weight of the chalk and magnesia alba to a new "air" that was not the same as ordinary air. Since this air could be combined with (or "fixed" into) quicklime to form chalk, he called the gas "fixed air" (carbon dioxide). He showed that birds and small animals perished in fixed air, and a candle flame was extinguished by it. Black also found that burning charcoal produced this gas, as did the respiration of humans and animals. Black even developed a specific reagent to test for fixed air. By dissolving quicklime in water, he made limewater, a reagent that turned cloudy in the presence of fixed air.

After solving the puzzle of magnesia alba's and chalk's weight loss on heating, Black investigated the other products of these reactions: quicklime and calcined magnesia and the puzzling observation that when milk alkalis were added to these substances they became caustic. The substances that Black called "mild alkalis" are today recognized as such compounds as potassium and sodium carbonate. For example, when Black reacted slaked lime (calcium hydroxide) with potash (potassium carbonate), he obtained chalk (calcium carbonate) and "caustic potash" (potassium hydroxide). Black was fascinated by what he called "caustication." He knew that limestone (calcium carbonate) became caustic (in the form of quicklime) when it lost its "fixed air," and he was able to explain why caustic alkalis became mild after standing for some time in air. The caustic alkali reacted with the fixed air in the atmosphere to form a mild alkali. Since, in these studies, Black carefully weighed both reactants and products, he was able to detail fixed air's participation in a cycle of reactions.

The first public presentation of Black's discoveries about fixed air occurred on June 5, 1755, when he read his paper "Experiments upon Magnesia Alba, Quicklime, and Some Other Alcaline Substances" before the Physical, Literary, and Philosophical Society of Edinburgh. It was published in 1756 in *Essays and Observations, Physical and Literary*. Its principal findings were that fixed air was a unique gaseous chemical substance and that it was a measurable part of such alkaline materials as magnesia alba, limestone, potash, and soda (sodium carbonate). Black intended to follow this influential paper with further serious studies of fixed air, but his increasingly burdensome responsibilities at Glasgow and, after 1766, at Edinburgh interfered with his chemical research.

Mephitic Air

Nevertheless, he turned over some of the problems raised by his fixed-air research to one of his students, Daniel Rutherford, who, in 1772, discovered another new "air." When Rutherford removed from ordinary air all the gases produced either by combustion (the burning of a candle) or respiration (the breathing of a mouse), what remained was a new gas that he called "mephitic air," because no animal could live in it. Today mephitic air is called nitrogen, and Rutherford is credited with its discovery.

Rutherford was not Black's only distinguished student. In his thirty-three-year career at Edinburgh, Black taught students from all over the world, including France, Germany, America, and Russia. Many of his students went on to distinguished careers in medicine, chemistry, and physics. Although he was aware of the weaknesses of the phlogiston theory, which tried to explain combustion, respiration, and other phenomena in terms of a "weightless fluid" called "phlogiston," Black did try to explain his experimental results in terms of its principles. However, late in his career Black began to teach the new chemical ideas of the French chemist Antoine-Laurent Lavoisier, who had been deeply influenced by Black's experiments on fixed air.

Impact

Traditional historians of science have seen Black as the founder of quantitative pneumatic chemistry because he reasoned on the basis of meticulously executed experiments to conclusions based on quantitative arguments. Using refined techniques of analysis and synthesis, Black falsified the old idea of a single elemental air and showed that a new gas could be created and that it could be combined chemically with a solid to produce a new compound. Once Black had established that fixed air was a unique chemical substance, other scientists, such as the English natural philosopher Joseph Priestley, discovered many new gases, including oxygen, which, in Lavoisier's hands, became the central element of the chemical revolution.

Some revisionist historians of science have questioned the classic characterization of Black as the great quantifier of chemistry, claiming that he emphasized micro-scale attractive forces rather than macro-scale weight relationships as the key to understanding chemical phenomena. Other scholars see Black's significance in his liberation of chemistry from such traditionally allied disciplines as medicine and metallurgy. Still other scholars see the importance of Black's studies on carbon dioxide as the beginning of the breakdown of the barrier between animate and inanimate substances, since carbon dioxide was produced both by burning inanimate charcoal and by animate mice. Because of his phlogistic views, Black is not categorized among the modern chemists, but his discoveries of chemical facts about some important substances had a significant influence on the new chemical ideas of Henry Cavendish, Priestley, and Lavoisier.

See also Global Warming; Oxygen; Periodic Table of Elements; Photosynthesis.

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—*Robert J. Paradowski*

CASSINI-HUYGENS MISSION

THE SCIENCE: Data from the Cassini mission were designed to investigate the atmosphere, rings, moons, and gravitational and magnetic fields of Saturn and to deposit a probe on the large moon Titan. The data from this mission would rewrite the textbooks on Saturn and assist in comparative planetology of the other gas giants: Jupiter, Uranus, and Neptune.

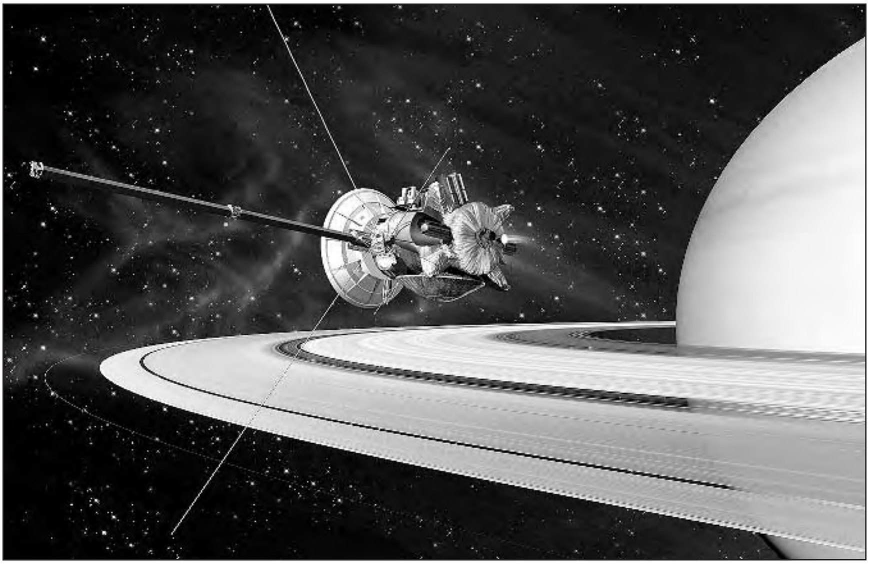
THE SCIENTISTS:

Earle K. Huckins, Cassini-Huygens program director
Robert Mitchell, Cassini program manager at the Jet Propulsion Laboratory (JPL)
Earl H. Maize, deputy program manager at JPL
Dennis L. Matson, Cassini project scientist at JPL
Linda J. Spilker, deputy project scientist at JPL
Mark Dahl, Cassini program executive NASA Headquarters
Denis Bogan, Cassini program scientist at NASA Headquarters
Jean-Pierre Lebreton, Huygens mission manager and project scientist at the European Space Agency

THE SPACECRAFT

The Cassini orbiter and its piggybacked entry probe Huygens together constituted the largest interplanetary spacecraft designed at the time of their launch in 1997. Their mission—to investigate the atmosphere, rings, moons, and gravitational and magnetic fields of Saturn and to deposit a probe on the large moon Titan—was the most complex investigation of a single planet and its moons ever planned.

Aboard the Cassini orbiter were subsystems designed to produce photographs in visible, ultraviolet, and near-infrared light; to locate and measure surface features through cloud layers on Titan; to study gravitational fields and the atmospheres and rings; to sense neutral and charged particles near Titan, Saturn, and the icy moons; to assay the chemical composition of the bodies' surfaces and atmospheres; to measure their heat; to gather data about the atmospheres and rings from their ultraviolet energy;



Artist's image of the Cassini-Huygens spacecraft orbiting Saturn. (NASA)

to study ice and dust particles in the system; to examine natural radio emissions and ionized gases flowing from the Sun or trapped in Saturn's magnetic field; and to determine the nature of Saturn's magnetic field and its interaction with the solar wind.

The Huygens probe carried six instrument packages. These would measure Titan's winds; investigate the physical properties of Titan after impact; take photographs during descent and measure temperature; analyze the atmosphere's components; and study gases, clouds, and suspended particles.

The Trip to Saturn

Under the overall direction of program director Earle K. Huckins, the mission began on October 15, 1997, with a Titan IV launch from Cape Canaveral during a one-month-long launch window with the most favorable arrangement of planets for the trip to Saturn. Because the spacecraft was so heavy (5,650 kilograms)—a record for an interplanetary probe—the launch vehicle, Centaur upper stage, and Cassini's engines were not powerful enough for a direct course to Saturn. Instead, the cruise segment of the mission involved a complex trajectory that swung the spacecraft by Venus twice, Earth once, and Jupiter once. Each encounter, called a gravity-assist maneuver, increased the spacecraft's velocity relative to the Sun, saving fuel and shortening flight time.

The probe entered the asteroid belt between Mars and Jupiter, in mid-November of 1999, and Cassini took the first images of asteroid 2685 Masursky on January 23, 2000. By April 14, 2000, Cassini had completed its passage through the asteroid belt, on its way to a Jupiter flyby at the end of the year. The spacecraft came within 10 million kilometers of Jupiter on December 30. The encounter boosted Cassini's speed by 2.2 kilometers per second and sent it off toward the Saturn system.

APPROACHING PHOEBE

Cassini passed within 2,068 kilometers of Saturn's outer moon Phoebe on June 11, 2004. Phoebe is the largest of Saturn's outermost moons and shows a heavily cratered surface that displays considerable variation in brightness. Scientists believed that Phoebe might be an object left over from early in the formation of the solar system. All instruments aboard the spacecraft provided data, determining Phoebe's composition, mass, and density. Five days after the Phoebe flyby, Cassini performed a modest trajectory correction maneuver to position itself for Saturn orbit encounter, and on July 1, 2004, Cassini entered Saturn orbit in such a way that as many as 76 orbits about the giant ringed planet might be possible. The initial orbital period was 116.3 days. Cassini came within 20,000 kilometers of Saturn's cloudtops and passed through the ring plane using its high-gain antenna as a dust shield against the high-speed impacts of small particles on the spacecraft's experiments and subsystems.

THE TITAN ENCOUNTER

Thirty-six hours after orbital insertion, Cassini encountered Titan for the first of its many planned close-flybys. The distance of closest approach would vary from one flyby to the next. Eventually the spacecraft's radar would be expected to provide a nearly complete surface map of this curious moon. This first encounter served to provide confidence that Cassini's instruments had survived the seven-year journey from Earth to Saturn.

Cassini was on a collision course with Titan on December 24, 2004, when it released the Huygens probe. The probe then continued along that trajectory toward entry into the atmosphere of Saturn's largest moon. On December 27, Cassini performed an avoidance maneuver so that it would be safely in position to relay data from the Huygens probe to Earth and avoid hitting Titan. Early on the morning of January 14, 2005, the Green Bank Telescope picked up radio waves indicating that the timer onboard the Huygens probe had turned on critical systems and experiments. The probe safely proceeded through atmospheric entry and touchdown on an unusual cryogenic (frozen) mud. The probe relayed data to the Cassini orbiter for storage until Cassini could turn to face Earth and transmit the data. Images from the probe's descent imager/spectral radiometer indicated ice blocks strewn about and features indicative of fluid flow. As the temperature at the surface was only 93 kelvins, that fluid was cryogenic hydrocarbons. The data provided evidence of physical processes shaping Titan's surface: precipitation, erosion, mechanical abrasion, and fluvial activity.

Huygens lasted far longer than had been anticipated and provided a considerable album of images during descent and after landing. All onboard experiments produced data except one, but examination of Doppler shifts of the probe's signal was able to supply the wind-speed data that the probe had not been able to collect due to a software error.

Mission in Progress

The remainder of the four-year primary mission would repeat extensive investigations with other moons, the rings, and Saturn itself, compiling the most detailed scientific portrait of an outer planet by any probe. Cassini was designed to assemble a visual record of 300,000 color images. Accomplishing these goals would require about sixty orbits of the planet, with Cassini swinging in as close as 180,000 kilometers from the cloudtops in orbits between ten and one hundred days long. Some orbits would bring Saturn's poles into view, allowing scientists to study the peculiarities of its atmosphere and magnetic fields there. Also, during these inclined orbits several important occultations will occur; that is, the Earth, Sun, or stars will, on these occasions, be hidden from Cassini by Saturn, a moon, or the rings. The occultations will offer scientists special opportunities to analyze the structure and composition of these bodies with radio waves or visual light.

Of particular interest during the tour would be the moons controlling Saturn's rings. Like a cowboy riding among cattle to herd them, small moons influence the positions of the myriad particles that compose the planetary rings. The interaction between a ring and its moons is gravitational in nature, but not fully understood, so mission scientists planned to scrutinize them as thoroughly as possible; however, the ice, dust, and small rocks nearby could damage Cassini, and so controllers would not risk extremely close flybys. On the other hand, flybys of the icy moons beyond the rings—Mimas, Enceladus, Dione, Rhea, and Iapetus—were targeted. Their surfaces, which showed signs of collisions, were expected to provide spectacular images.

DATA FROM SATURN AND ITS MOONS

Within its first six months in the Saturn system, Cassini produced more high-resolution images of Saturn, its moons, and rings than had been achieved throughout preceding history. Cassini data would rewrite the textbooks on Saturn and assist in comparative planetology of the other gas giants: Jupiter, Uranus, and Neptune.

Although there is probably no life on Titan, as some scientists have speculated, Huygens data will most likely settle the issue finally and make it possible to determine whether life could evolve there in the future. To do so it was programmed to search for organic chemicals and oceans. Because Titan's current atmospheric conditions resemble those of the Earth shortly after its formation, the moon may help scientists better understand terrestrial evolution after detailed data analysis is completed.

Cassini also investigated a number of the larger moons at close range. The probe passed within 123,400 kilometers of Iapetus on January 1, 2005. From a range ten times closer than the approach made by Voyager 2 more than two decades earlier, Cassini transmitted images that revealed one side of Iapetus to be as bright as snow and the other to be as dark as tar. This dark side might well be rich in carbon-based compounds and is the side of the moon that leads in the direction of its orbital motion about Saturn. Thus the moon might have been dusted with this orbital material; however, it was possible that the dark material originated from within the moon and was spewed out on the surface. The spacecraft detected a 400-kilometer circular crater in the southern hemisphere and a line of mountains around the moon's equator. The latter gave the moon the appearance characteristic of a walnut.

Cassini made its first close encounter with the icy moon Enceladus on February 17, 2005, coming within 1,167 kilometers of the surface. The spacecraft's magnetometer picked up a bending of the planet's magnetic field by the icy moon caused by molecules interacting with the field by spiraling along field lines. This was evidence of gases arising from the surface or from the interior of Enceladus, which suggested a tenuous atmosphere around this moon. The icy moon has regions that are old and retain a large number of craters, but younger areas do display tectonic troughs and ridges. In a way, Enceladus might be considered for the Saturn system a more benign counterpart of Io for the Jupiter system.

IMPACT

The Cassini-Huygens mission has delivered data about Saturn and its moons that provide evidence about the origin and evolution of the entire solar system and the processes responsible for planetary formation. Theories developed from these data will aid astronomers in analyzing planets around other stars and, perhaps, in estimating the chance that conditions suitable for life exist outside the solar system.

See also Galileo Mission; Herschel's Telescope; International Space Station; Mars Exploration Rovers; Moon Landing; Saturn's Rings; Space Shuttle; Voyager Missions.

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—*Roger Smith and David G. Fisher*

CELL THEORY

THE SCIENCE: Drawing extensively on previous work by Matthias Schleiden and other talented microanatomists, Theodor Schwann boldly proposed in 1839 that the single, indivisible structural unit of all living organisms was the cell. Further investigations into cellular behavior compelled Rudolf Virchow to augment this proposal with the concept that all living cells derive from other living cells. Collectively, these concepts form the cell theory, the cornerstone of modern cell biology.

THE SCIENTISTS:

- *Theodor Schwann* (1810-1882), professor of anatomy, University of Louvain
- *Matthias Schleiden* (1804-1881), professor of botany, University of Jena
- *Rudolf Virchow* (1821-1902), chair of pathological anatomy, general pathology, and therapeutics, University of Berlin
- *Johannes Müller* (1801-1858), chair of anatomy and physiology, University of Berlin
- *Jan Evangelista Purkyne* (1787-1868), chair of physiology and pathology, University of Breslau
- *Gabriel Gustav Valentin* (1810-1883), his student
- *Rudolf Wagner* (1805-1864), discoverer of the nucleolus in animal cells
- *Wilhelm Hofmeister* (1824-1877), biologist who described mitosis in plant cells
- *Robert Remak* (1815-1865), biologist who described mitosis in the red blood cells of chickens

EARLY OBSERVATIONS

During the 1830's, improvements in optical instruments and in the skill of those who used them generated a noticeable increase in the quality of microscopic observations. From 1832 on, Jan Evangelista Purkyne, with his student Gabriel Gustav Valentin, described cells in a host of animal tissues such as the spleen, bone, and the pigmented layers of the retina.

In 1835 Johannes Müller noted similarities between notochord cells in animals and plant cells, something Purkyne and Valentin had previously reported. Müller's observations were extended by his student, botanist Matthias Schleiden. Schleiden's *Beiträge zur Phytogenesis* (pb. 1838; *Contributions of Phytogenesis*, 1847) was the first to describe the nucleolus in plant cells; the same structure in animal cells had been discovered three years earlier by Rudolf Wagner. Schleiden postulated that the nucleus formed around the nucleolus, and the rest of the cell formed around the nucleus. Thus Schleiden postulated that new cells form by a kind of free-cell formation, similar to the formation of crystals.

SCHWANN'S THEORY OF CELL FORMATION

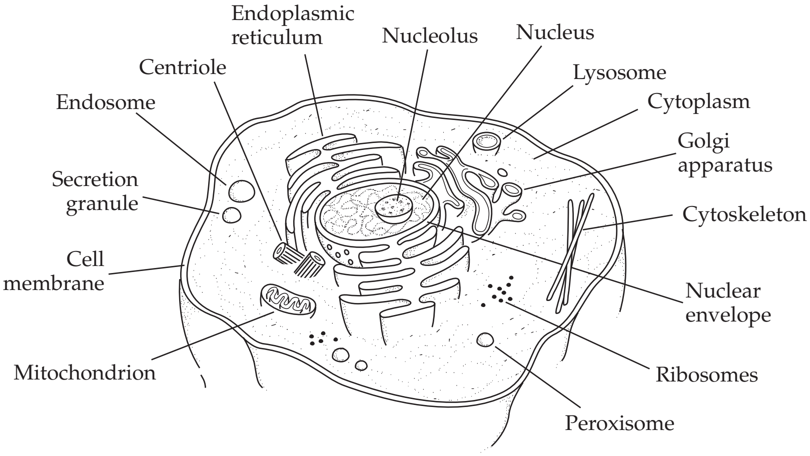
Schleiden's theory of cell formation was wrong, but it greatly influenced another student of Müller, Theodor Schwann. From conversations with Schleiden, Schwann became convinced of the overall similarity between plant and animal cells, since both cell types had a nucleus and a nucleolus. Schwann wholeheartedly adopted Schleiden's theory of cell generation in his monograph *Mikrokopische Untersuchungen* (pb. 1839; *Microscopical Researches*, 1847), but he also brought together a massive collection of evidence, from observations of animal cells and the work of Schleiden, to argue for the similarities between plant and animal cells, and between plant and animal fine structure.

It must be noted that only a few of the observations of Schleiden and Schwann were original. According to Schwann, because plants were largely aggregates of cells, animals had to be constructed in the same manner. Thus Schwann argued that cells are the elementary unit of structure, function, and organization in living things, and that cells exist as distinct entities, the building blocks for the construction of organisms. Even though Schwann failed to acknowledge his predecessors and contemporaries, his conclusions reached further than anyone had dared to postulate up to that time, and they were readily accepted by scientists throughout Europe.

Schleiden and Schwann's theory of cell generation was strongly disputed and clearly rebutted by many observations from many scientists, but mostly by the meticulous illustration and description of the stages of mitosis (cell division) in plant cells by Wilhelm Hofmeister in 1848-1849 and by Robert Remak in the red blood cells of chickens.

Despite such objections, Schwann's theory of cell generation was accepted for several decades after its proposal and produced some confusion, because the formation of cells via precipitation around the nucleus

AN ANIMAL CELL



(Electronic Illustrators Group)

was a form of spontaneous generation, and if cells formed this way then some other principle caused cells to form within organisms.

EVERY CELL FROM A CELL

The question of cell origins was put to rest once and for all by another student of Müller, Rudolf Virchow. Persuaded by data from Robert Remak and his own research on the biology of tumors, Virchow wrote *Die cellular Pathologie in ihrer Begründung auf physiologische und pathologische Gewebelehre* (1858; *Cellular Pathology as Based upon Physiological and Pathological Histology*, 1860), in which he asserted the aphorism *omnis cellula e cellula* (every cell from a cell). This principle is not original to Virchow; it was originally coined by the French natural scientist and politician François Vincent Raspail in 1825. Nevertheless, Virchow reinterpreted it and in so doing repudiated spontaneous generation as a means of cell generation.

This "theory of the cell" created distinct problems for the doctrine of vitalism, which asserted that no single part of an organism could exist apart from the whole organism, since the organism was alive as a result of its indwelling vital principle. The cell theory of Schwann and Schleiden had specified that individual cells were alive even apart from the body, which negated a major precept of vitalism. However, this same theory still advocated that something outside cells dictated their very life force. Virchow's emendation to the cell theory of Schwann and Schleiden essentially placed cells as self-contained and self-generating units of fundamental structure in all biological organisms that worked together to form the phenomenon known as a living organism. This principle effectively issued the finishing blow to vitalism and opened the field of biology to avenues of investigation unimagined at that time.

IMPACT

The ramifications of the cell theory were nothing less than momentous. The rapid acceptance of the cell theory, and its classic negation of vitalism, inspired biologists to elucidate the fine structure of living organisms and the processes that drive cell, tissue, and organ functions. Since a nonmaterial vital principle that could not be measured or directly examined was no longer considered to be responsible for life and its processes, scientists began to open all aspects of life to empirical inquiry. The cell theory is responsible for initiating investigations into the function of subcellular structures, eventually leading to molecular studies of development, gene regulation, and cell trafficking.

VIRCHOW AND THE DEATH OF VITALISM

For centuries before Rudolf Virchow, the origin of life and the seat of disease were the subjects of theories and controversies. By the nineteenth century, the microscope had disclosed the existence of cells and the study of pathological anatomy was directed to their study. However, cellular research was faced with two major hurdles: First, cells could not be demonstrated in several tissues, even in their most developed state; second, the origin of new cells was completely unknown.


(Library of Congress)

The answer to the latter question was heavily prejudiced by the so-called cell theory of Theodor Schwann, who asserted that new cells arose from unformed, amorphous matter, which he termed "cytoblastema." Called vitalism by later historians, this concept in earlier times had supported erroneous ideas such as "spontaneous generation."

In the early 1850's at the University of Würzburg, Virchow demonstrated the existence of cells in bone and in connective tissue, where their existence had hitherto been doubtful. This discovery offered him the possibility of finding a cellular matrix for many new growths, which led to his use of the aphorism *omnis cellula e cellula*—each cell stems from another cell—the motto of subsequent biological cell theory. It was the death blow to vitalism.

Virchow's conception of disease rested on four main hypotheses:

(1) All diseases are in essence active or passive disturbances of living cells.
(2) All cells arise from parent cells.
(3) Functional capacities of the cells depended on intracellular physicochemical processes.
(4) All pathological formations are degenerations, transformations, or repetitions of normal structures.

Virchow became internationally famous and was showered with honors from scientific academies in Germany, France, and England. Under his direction, the department of pathology at the Charité Hospital became a model for other institutions, and he personally supervised the establishment of one of the best pathology museums in the world.

Virchow also led a political life, taking a seat in the Prussian Diet in 1862, where he became a leader of the opposition Radical Party. He led a desperate fight against the dictatorship of Otto von Bismarck, and Bismarck is said to have been so annoyed with Virchow that he challenged him to a duel. The duel was averted, however, and in 1891 the emperor presented Virchow with a gold medal for his immense service to science.

See also Amino Acids; Chromosomes; DNA Sequencing; Double-Helix Model of DNA; Gene-Chromosome Theory; Genetic Code; Germ Theory; Hormones; Immunology; Mendelian Genetics; Microscopic Life; Mitosis; Neurons; Osmosis; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Michael A. Buratovich*

CELSIUS TEMPERATURE SCALE

THE SCIENCE: Anders Celsius conducted a series of precise experiments that demonstrated that the melting point of snow or ice and the boiling point of water, when adjusted for atmospheric pressure, were universal constants. He used these results to establish a uniform temperature scale, which allowed the calibration of thermometers worldwide.

THE SCIENTISTS:
Anders Celsius (1701-1744), Swedish astronomer
Daniel Gabriel Fahrenheit (1686-1736), German physicist
Carolus Linnaeus (Carl von Linné; 1707-1778), Swedish physician and botanist
Jean Pierre Christin (1683-1755), French scientist

EARLY THERMOMETERS

Although it is relatively easy for humans to determine that the temperature in a room is hot or cold or to compare the temperatures of two objects by touching, the precise measurement of temperature developed relatively recently. Galileo Galilei, an Italian mathematician and physicist, is generally credited with inventing the thermometer in 1592. His thermometer worked on the principle that fluids and solids expand or contract as the temperature changes. He therefore placed water in a glass bulb and measured the level of the surface of the water as it moved up and down in the bulb with changes in the water's temperature.

German physicist and inventor Daniel Fahrenheit significantly improved on the design of the thermometer. He filled capillary tubes with either alcohol (1709) or mercury (1714) so that the expansion of the fluid produced a significant change in its height in the tube. Fahrenheit's thermometers were capable of more precise measurements.

However, there was still no simple way to ensure that thermometers built by different people in different places around the world would give the same numerical value for the temperature of an object. A thermometer must be calibrated in order for the readings taken by different thermometers to be compared. This calibration requires that readings be taken at two standard temperatures, which are called its fixed points. The positions of these fixed points are noted and the number of divisions, or degrees, between the fixed points is specified, providing a numerical scale for the thermometer. Thermometers were used in meteorology, in agriculture, and sometimes indoors, so it was natural that scientists chose fixed points that fell within the temperature ranges of interest in those fields.

Fixed Points

Hence, there were many thermometers for many different purposes, with many different sets of fixed points. The challenge was to define the fixed points so that different types of thermometers could be calibrated easily and reproducibly all over the world. In the early years of temperature measurement, no one knew if fixed points were truly fixed. Fahrenheit constructed mercury thermometers with scales that used fixed points at the freezing point of water, which he set at 32°, and at human body temperature, which he set at 96°.

However, it was easy to demonstrate that the temperature of any individual varies a bit during the day and can vary significantly if the individual is ill, simply by taking repeated measurements of the body temperature of the individual and noting that these readings, even when taken on the same thermometer, are not always the same. In addition, two individuals are likely to have slightly different body temperatures. Thus, human body temperature is not truly a fixed point, and two thermometers calibrated using human body temperature as a fixed point will not record exactly the same temperature for an object. A variety of other fixed points, including the melting point of butter, had been suggested by other scientists. Scientists recognized that they needed to find physical phenomena that occur at precisely the same temperature all around the world. Only such phenomena can be used as fixed points to calibrate thermometers.

In 1702 Danish astronomer Ole Rømer developed one of the first temperature scales with fairly reliable fixed points. Rømer's scale was based on two physical phenomena: the boiling point of water and the temperature at which snow begins to form. Still, Rømer had to wait until it snowed in order to calibrate a new thermometer, and this technique would work only in those parts of the world that received snow.

Celsius's Experiments

Anders Celsius, a Swedish scientist, became interested in problems of weights and measures, including temperature measurements, early in his career. As a student, Celsius assisted Erik Burman, a professor of astronomy at Uppsala University, in meteorological observations. At that time there was still no accepted standard for thermometers. Thus, it was impossible to compare temperature readings taken in different places unless the same thermometer was taken from place to place or the two researchers used thermometers that had been calibrated against each other, a tedious system similar to synchronizing watches to ensure they each indicate the same time.

It had been established by this time that the freezing point of water was inadequate as a fixed point because water's freezing point varies if it contains dissolved contaminants. For example, saltwater freezes at a significantly lower temperature than does pure water. Celsius decided to attack the problem of establishing a universal temperature scale by conducting a series of careful experiments. He determined that the temperature at which pure water—in his case, newly fallen snow—melts is independent of latitude and also independent of the atmospheric pressure. Thus, Celsius was able to identify the melting point of snow, or of pure water ice, as one possible fixed point for measuring temperature.

The boiling point of water was more problematic. Celsius showed that it did not depend on latitude, but it did, in fact, vary with atmospheric pressure, which changed with altitude. To solve this problem, Celsius measured the dependence of the boiling point of pure water on the atmospheric pressure. The atmospheric pressure could be measured accurately using a barometer, which had been invented by the Italian physicist

ANDERS CELSIUS, ASTRONOMER

Born in Uppsala, Sweden, on November 27, 1701, Anders Celsius hailed from a long line of scientists and mathematicians, himself becoming a professor of astronomy in 1730.

Celsius traveled through Europe for four years (1732-1736); joined Pierre-Louis Moreau de Maupertuis's Lapland expedition to explore northern Sweden (1736) and conduct longitudinal studies that confirmed Sir Isaac Newton's assertion that Earth is an ellipsoid; undertook some early measurements of the magnitude of stars in the constellation Aries; and gained enough respect from the scientific community that the Swedish government subsidized his building of a state-of-the-art observatory in Uppsala (completed in 1741).

Besides developing the breakthrough centigrade (now Celsius) thermometer, he created a map of Sweden, conducted sea-level measurements, and identified that there was a relationship between the northern aurora and Earth's magnetic field. Celsius died in 1744, a victim of tuberculosis. In addition to his famous temperature scale, a crater on the Moon is named after him.

Evangelista Torricelli, one of Galileo's students, in 1643. Celsius's determination of the variation of the boiling point of water with atmospheric pressure allowed him to set a second fixed point, the boiling point of pure water at a given atmospheric pressure.

CALIBRATION

In 1742 Celsius published his results in the Annals of the Royal Swedish Academy of Science in a paper titled "Observations on Two Persistent Degrees on a Thermometer." In this paper Celsius proposed a three-step procedure for calibrating a thermometer. First the thermometer was to be placed in thawing snow or ice made from pure water and the freezing point of water was marked on the thermometer as 100°. Second, the thermometer was placed in boiling water, and that point, appropriately adjusted for the measured atmospheric pressure, was marked as 0°. Third, the distance between the two points was divided into 100 equal units.

There was one major difference between the temperature scale developed by Celsius and the Celsius temperature scale used now. Celsius set the freezing point of water at 100° and the boiling point at 0°. Carolus Linnaeus is generally credited with reversing the scale's direction, setting the freezing point of water at 0° and the boiling point at 100°. However, because Linnaeus's thermometers, as well as many of those used by Celsius, were built by Daniel Ekström, it is uncertain if Linnaeus or Ekström actually initiated the scale reversal.

IMPACT

Celsius's modified temperature scale was referred to as the centigrade scale for many years, in recognition of the one hundred (Latin, *centum*) divisions between the two fixed points. It is now called the Celsius scale, honoring its inventor.

From the scientific point of view, Celsius's most important contribution to the modern temperature scale was the result of his careful experiments to establish two universal fixed points, which allowed thermometers built in different laboratories to be calibrated using the same temperature scale. After Celsius developed this universal temperature scale, it was possible for scientists around the world to measure temperature very accurately—and, perhaps most important, to compare their results reliably. Scientists were then able to determine how various physical properties of materials vary with the temperature. They were also able to replicate one another's experiments more reliably.

The impact of this deceptively simple device was immense and had far-reaching consequences for all scientific and practical measurement. For example, the development of a universal temperature scale was essential to the understanding of the expansion of gases as a function of their temperature, as well as similar changes in the volumes of liquids and solids that depend on temperature. Later it was established that thermal and electrical conductivity also vary with temperature. The development of a universal temperature scale allowed weather records to be compared from one location to another, resulting in the eventual understanding of weather patterns and the development of weather forecasting.

See also Fahrenheit Temperature Scale; Kelvin Temperature Scale; Liquid Helium.

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—*George J. Flynn*

CEPHEID VARIABLES

THE SCIENCE: Using Cepheid variable stars, astronomers were able to demonstrate that the Milky Way is only one of many galaxies in the universe.

THE SCIENTISTS:

Edwin Powell Hubble (1889-1953), American astronomer who determined that galaxies exist external to the Milky Way

Heber Doust Curtis (1872-1942), American astronomer who debated with Harlow Shapley on the nature of "spiral nebulae"

Harlow Shapley (1885-1972), American astronomer who took the position that the spiral nebulae are parts of the Milky Way system

Adriaan van Maanen (1884-1946), Dutch astronomer

NEBULAE: NEAR OR FAR?

At the beginning of the twentieth century, there were two theories about spiral nebulae—groups of stars that appear as spiraling streams flowing outward from a central core. One theory held that such nebulae were part of the Milky Way galaxy. The other held that they were "island universes," large, distant, independent systems. To resolve this question, it was important to measure the distances of the nebulae. The island universe theory held that the nebulae were remote from the Milky Way; the other theory held that they were closer.

In 1914, the American astronomer Vesto Melvin Slipher announced that the spiral nebulae were moving away from the Milky Way at high speeds. He had drawn his conclusions from his spectral analysis of Doppler shifts in these star groups. His announcement was taken as evidence that these nebulae could not possibly be part of the Milky Way. Slipher had not conclusively solved the problem, however, because he had not determined the distances of these nebulae.

Distance has always been a difficult question for astronomers. By the early twentieth century, astronomers had measured distances to some nearby stars using the parallax method, which compares the different angles of nearby stars in relation to Earth and the Sun as Earth moves around the Sun. Unfortunately, spiral nebulae are too far away for parallax to be useful.

Working at the Mount Wilson Observatory, the Dutch astronomer Adriaan van Maanen compared the positions of bright spots within spiral nebulae in photographs taken at different times in order to observe the motions of the spots. In 1916, he published his results, which suggested that the spirals were rotating and that the rotation was rapid. If large distances and sizes were assumed for the nebulae, the nebulae would have to be rotating at immensely fast speeds, in some cases exceeding the speed of light.

How Far Are the Stars?

Variable stars can be of three principal types: novas, eclipsing binaries, and Cepheid variables. Novas are unstable stars which occasionally erupt and release envelopes of matter into space, temporarily increasing in brightness during the process. Eclipsing binaries are double-star systems in which two stars orbit a common center of gravity; periodically, one star will pass before its companion star, eclipsing it relative to the line of sight.

Cepheid variables and their similar RR Lyrae stars are older main sequence stars that have exhausted their hydrogen fuel and have switched to helium fusion for energy generation. Cepheids are unstable, periodically increasing and then decreasing their energy output. They become brighter, then dim, repeating the cycle every few days or weeks. Each Cepheid has a predictable, repeatable cycle of brightening and dimming. They are named after Delta Cephei, the first such variable star discovered (1768). Polaris, the North Star, is also a Cepheid.

Prior to 1912, the principal means of determining stellar distances was a trigonometric method known as parallax. A star's parallax is the line-by-sight angle subtended by the star as Earth orbits the Sun. Using a right triangle—formed by the observed star, the Sun, and Earth as the triangle's vertices—astronomers could calculate the star's distance by means of simple trigonometric equations involving the Earth-Sun distance and the subtended angle traced by the star in our sky. A large subtended angle indicated that the star was close; a small angle, that the star was far. During the twentieth century, more than ten thousand stellar distances were obtained using this method, but the method was not applicable to very distant stars.

In 1912, Helen Leavitt and Harlow Shapley developed the period-luminosity scale after studying Cepheids. With the understanding of Cepheids' apparent and absolute luminosities, it became possible to calculate their distances and, therefore, the distances of all the stars in the star cluster or galaxy containing a particular Cepheid variable. Shapley used Cepheid distances to demonstrate that the center of the Milky Way is directed toward the constellation Sagittarius and that the Sun is located approximately thirty thousand light-years from the galactic center. When Edwin Powell Hubble applied the technique to measure the distances to Cepheids located in distant galaxies, he obtained estimates of the distances between the Milky Way and other galaxies.

Since this was known to be impossible, van Maanen's results were taken as evidence that the spiral nebulae must be nearby parts of the Milky Way.

ISLAND UNIVERSES

In April, 1920, Harlow Shapley and Heber Doust Curtis debated their differing views before the National Academy of Sciences. Using a new distance determination method involving a type of star, a Cepheid variable, Shapley had arrived at a much larger size for our galaxy than had been previously deduced. Because of van Maanen's studies, Shapley argued that the spiral nebulae were part of this large Milky Way.

Curtis agreed with previous studies that indicated a smaller Milky Way. He also believed in the "island universe" theory—that the spiral nebulae were other galaxies similar to and outside the Milky Way. As evidence, Curtis used Slipher's measurements of the speed at which the nebulae were moving away from the Milky Way. Today it is recognized that Shapley's results for the size and shape of the galaxy were substantially correct. Yet the island universe hypothesis was strongly supported by evidence presented by Edwin Powell Hubble to the American Association for the Advancement of Science in December, 1924.

HUBBLE'S CEPHEIDS

In 1923, Hubble was working at Mount Wilson Observatory, studying photographs taken with the 254-centimeter Hooker telescope. He was the first to isolate Cepheid variables in the Andromeda nebula. Cepheid variables are stars whose brightnesses varies periodically and whose period of variation is related to their actual brightness. Once a star's actual brightness is known and its apparent brightness as seen from Earth is measured, its distance can be determined. This was the same method used by Shapley to determine the size of the Milky Way galaxy.

Hubble used the Cepheids to calculate that the nebulae are, in fact, at great distances and must

Edwin Hubble at the Mount Wilson Observatory near Pasadena, California. (NASA/GSFC) be huge, independent systems. The distance Hubble found for the Andromeda nebula is about 900,000 light-years and the diameter almost 33,000 light-years (a light-year is the distance light travels in a vacuum in one year, or approximately 9.6 trillion kilometers). These results later required correction, since it was found that there are two types of Cepheid variables, and the ones that Hubble studied had a different period-luminosity relationship; the distance is closer to 2 million light-years. Yet Hubble's results changed scientists' idea of the scale of the universe and of Earth's place in it.

Hubble was at first reluctant to publish his results, since he could not explain why van Maanen's results would be incorrect. Although many influential astronomers were immediately convinced by Hubble's results, controversy lingered for some years after these results were presented. Van Maanen's results could not be duplicated by others, and all other evidence indicated that the galaxies were distant and separate from the Milky Way; therefore, his work was gradually forgotten.

Impact

The philosophical consequences of Hubble's conclusions were immense. The great sizes and distances of the spirals meant that not only was Earth's sun only one of many in a huge galaxy but also that the Milky Way was merely one of many independent systems. This realization shifted humankind's place in the cosmos, a shift that could be said to be equal to that which the Polish astronomer Nicolaus Copernicus inaugurated when he suggested that the Sun, not the Earth, was the center of the solar system.

Hubble's work led to the beginning of the classification and study of galaxies. Once galaxies were identified as separate units of the cosmos, their shapes and sizes, their distances, and their distribution in space were studied. During the 1920's, Hubble presented a classification scheme for galaxies that is still in use.

There were important follow-ups to Hubble's work. Once Cepheids were found in other spirals and distances were known, Hubble was able to work out a plot of distance versus velocity; he found that the farther away a galaxy is, the faster it is moving away from Earth. This means that the universe is expanding. By using this plot to extrapolate backward in time to the so-called big bang, astronomers could estimate the age of the universe. Studies are still being conducted to determine the exact age, but data from the Wilkinson Microwave Anisotropy Probe have pinpointed it with incredible accuracy at 13.7 billion years. Hence, the discoveries surrounding Cepheid variables created a drastically different picture of the universe: a universe in motion, rushing away from an energetic beginning, rather than the static and stable universe that scientists had previously assumed.

See also Big Bang; Black Holes; Brahe's Supernova; Cosmic Rays; Expanding Universe; Galactic Superclusters; Galaxies; Gamma-Ray Bursts; Inflationary Model of the Universe; Neutron Stars; Oort Cloud; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Speed of Light; Stellar Evolution; Very Long Baseline Interferometry; X-Ray Astronomy.

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—*Mary Hrovat*

CHANDRASEKHAR LIMIT

THE SCIENCE: Subrahmanyan Chandrasekhar developed a mathematically rigorous theory of the structure of white dwarf stars, which indicated that their maximum mass is 1.4 solar masses.

THE SCIENTISTS:

Subrahmanyan Chandrasekhar (1910-1995), theoretical astrophysicist and cowinner of the 1983 Nobel Prize in Physics
Arthur Stanley Eddington (1882-1944), prominent astrophysicist who opposed Chandrasekhar's theory
Ralph Howard Bowler (1899-1944), respected astrophysicist and mentor to Chandrasekhar
Walter Sydney Adams (1876-1956), American astronomer specializing in stellar spectra

WHITE DWARFS

White dwarf stars have challenged and perplexed astronomers since their accidental discovery in the mid-nineteenth century. The German astronomer Friedrich Bessel noted a wobble in the path of the star Sirius as it moved across the sky. After eliminating recognizable sources of error, in 1844 he concluded that a small companion star must be affecting the motion of the larger, brighter Sirius. From the wobble in the motion of the larger star, the mass of the smaller star was calculated to be that of the Sun.

In 1915, Walter Sydney Adams managed to channel the light from the companion star into a spectrograph. The light from the star, now called Sirius B, indicated that the surface of the star was almost as hot as Sirius. From the temperature and the brightness of Sirius B, astronomers calculated that Sirius B had a radius of about 24,000 kilometers (about twice that of Earth). Packing a mass nearly that of the Sun into a volume fifty thousand times smaller yielded densities that were much larger than astronomers had ever known: One cubic centimeter of the star—less than the size of a throat lozenge—would weigh 100 kilograms.

Sir Arthur Stanley Eddington, the foremost astrophysicist of his time, was not completely convinced that these very small but bright stars, later called white dwarfs, were indeed so dense. Many other skeptics, however, were convinced by the 1925 measurement of the “redshift” of Sirius B. Light trying to escape from a white dwarf is strongly affected by the extreme gravitational force arising from the large mass of the white dwarf. The photons of light lose energy as they struggle against the intense gravity. The frequency of the light is “shifted” toward the red end of the spectrum (reflecting the loss of energy) as the light struggles to escape. Albert Einstein’s general theory of relativity predicts that light will be affected in this manner by gravity. The amount of “shift” was equal to that predicted by Einstein’s theory.

EDDINGTON’S PARADOX

Eddington’s influential *The Internal Constitution of the Stars* (1926) attempted to bring together fifty years of work involving the mechanical and physical conditions of stellar interiors. When it came to white dwarfs, his theory ran into problems. In his theory, most of a star’s lifetime was spent balancing the outward pressure of the escaping heat of nuclear reactions with the inward pressure of gravity. Eventually, the store of nuclear fuel would be depleted and the star would collapse into itself, becoming a white dwarf. The atomic nuclei, which make up the mass of the white dwarf, would then keep cooling and the electrons that had been ripped from the nuclei would be able to reattach themselves to the nuclei in the star. The problem was that the amount of energy required to re-form the atoms of the star would be more than that available in the star. In effect, the star would not have enough energy to cool down. This paradox puzzled Eddington.

ELECTRON DEGENERACY

Eddington believed that the pace of work in the field was quickening and that the newly developed field of quantum mechanics might be able to cast light on the theory of stellar interiors. He was correct on both counts. The paradox introduced by Eddington was resolved shortly after it was stated. Ralph Howard Bowler resolved the paradox using the recently developed quantum mechanics, but he showed that white dwarf stars were even stranger than anticipated. The pressure that kept the star from contracting indefinitely was the result not of the temperature of the star but of "electron degeneracy." In the intense heat and pressure of a star's interior, electrons are torn away from nuclei and move about freely. In the classical theory, the electrons can move about unrestricted. According to quantum theory, however, the electrons are restricted to a discrete set of energies. In a normal star, electrons typically occupy many of the higher allowed energy levels.

In the interior of a white dwarf star, however, the electrons enter a special energy state. Electrons occupy all the lower energy levels. In this special case, the pressure exerted by the electrons becomes independent of the temperature. The star, according to Bowler, can no longer contract. The electrons cannot be forced into lower energy levels. The electrons are said to be "degenerate" because the electrons have become "neutralized"—they are no longer a factor in determining the resistance to gravitational collapse. Bowler resolved Eddington's paradox by showing that a white dwarf can resist the force of gravity through electron degeneracy. The temperature of the star no longer matters. White dwarfs can live out their lives slowly cooling off.

CRITICAL MASS

Subrahmanyan Chandrasekhar followed the latest developments in astrophysics during his studies in theoretical physics in India. Upon graduation in 1930, he went to Trinity College, Cambridge, on a scholarship. He won a copy of Eddington's *The Internal Constitution of the Stars* in a physics contest. He began to question Eddington's conclusions concerning white dwarfs and Bowler's calculations concerning electron degeneracy. He calculated that electrons in the dense core of a white dwarf would be moving at a velocity nearly that of light, so corrections must be made to the classical formulas describing the behavior of matter.

Chandrasekhar made the necessary corrections and realized that the effect was dramatic. For stars with a mass greater than about 1.4 times that of the Sun, the "pressure" exerted by electron degeneracy would not be enough to overcome the force of gravity. Instead of a long, slow cooling off, such stars would continue to contract, apparently indefinitely. Chandrasekhar did not speculate on the ultimate fate of stars more than 1.4 solar masses. Calculations done years later by others showed that those stars form either neutron stars or black holes.

From 1931 to 1935, Chandrasekhar published a series of papers of his findings. During this time, he worked with Bowler and Eddington. By 1935, Chandrasekhar had developed a detailed, quantitative, mathematically rigorous theory of white dwarf stars, and he fully expected Eddington to accept his theory. Eddington gave no indication to Chandrasekhar that he had any doubts about the surprising results Chandrasekhar's theory predicted. In 1935, Chandrasekhar was scheduled to present his results to the Royal Astronomical Society. Eddington also presented a paper, but to Chandrasekhar's surprise it included an attack on Chandrasekhar's theory.

However, work on white dwarfs continued, and further evidence was presented in support for his calculations. Chandrasekhar's ideas gained gradual acceptance in the 1940's and 1950's as more white dwarfs were discovered and as spectrographic evidence mounted.

IMPACT

Chandrasekhar's theory introduced the notion that not all stars behave as benignly in their old age as white dwarfs. He did not speculate what would happen to a star with a mass above the limit. For stars with masses below the limit, he devised a complete theory to account for their properties. He won the Nobel Prize in 1983 for his theoretical studies on the structure and evolution of stars.

Chandrasekhar's limit is the dividing line between the strange but benign white dwarfs, and the truly exotic black holes, pulsars, and neutron stars. It established the possibility that the strange behavior of stars nearing the end of their lives as white dwarfs could get stranger. Chandrasekhar's legacy is the mathmatical order that he brought to the theory of

A Surprising Snub

In 1935, Subrahmanyan Chandrasekhar was scheduled to present his radical new theory of stellar evolution before the meeting of England's Royal Astronomical Society. Shortly before the meeting, Chandrasekhar received a program. He noticed that Arthur Stanley Eddington was also giving a paper. Chandrasekhar's findings contradicted those of Eddington.


(The Nobel Foundation)

At the meeting, Chandrasekhar discussed his results, which indicated that the lifetime of a star of small mass must be essentially different from that of a star of large mass. Edward Arthur Milne, also attending the meeting, said that he had achieved similar results using a cruder method. Eddington then launched into a personal attack on Chandrasekhar and his theory. Eddington was convinced that Chandrasekhar's method was faulty because it was based on a combination of relativistic mechanics and nonrelativistic quantum theory. He argued that his own result could still be obtained after suitable modifications of Chandrasekhar's theory. While Eddington freely admitted that he could find no fault with the technical details of Chandrasekhar's approach, he was compelled to challenge the results because of the unexpected result that large stars will continue to contract. The depth of Eddington's objections and the way in which they were made surprised and upset Chandrasekhar: "Eddington effectively made a fool of me," he later recalled.

The dispute with Eddington lasted years, yet the two remained cordial. Chandrasekhar left England in 1937 for Chicago. In 1939, he summed up his work on stellar structure. In 1974, Chandrasekhar accounted for the delay in the acceptance of his theory, stating that his conclusions "did not meet with the approval of the stalwarts of the day." He noted the irony of Eddington's position: Eddington argued against the continual collapse of stars with a mass over the Chandrasekhar limit because such stars would "go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few [kilometers'] radius when gravity becomes strong enough to hold the radiation and the star can at last find peace."

Chandrasekhar was describing what is now called a "black hole," which Eddington thought was an absurdity. Nevertheless, years later black holes were accepted as the final fate of stars that are so massive that their gravity prevents even light from escaping. Chandrasekhar's "foolishness" was ultimately proved correct.

white dwarfs. He continued to bring mathematical order to other areas of astrophysics, including black holes.

See also Black Holes.

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—*Roger Sensenbaugh*

CHAOTIC SYSTEMS

THE SCIENCE: An American meteorologist demonstrated that Earth's weather patterns constituted a chaotic system, inaugurating the modern study of chaos.

THE SCIENTIST:
Edward N. Lorenz (b. 1917), American meteorologist

MAKING SENSE OF CHAOS

Chaotic, or unpredictable, systems are found in many fields of science and engineering. The study of the dynamics of chaotic systems is an essential part of the growing science of complexity—the effort to understand the principles of order that underlie the patterns of all real systems, from ecosystems to social systems to the universe as a whole. Chaos theory, a modern development in mathematics and science, attempts to provide a framework for understanding these irregular or erratic fluctuations in the natural world.

Many bodies in the solar system have been shown to have chaotic orbits, and evidence of chaotic behavior has also been found in the pulsations of variable stars. Evidence of chaos occurs in models and experiments describing convection and mixing in fluids, in wave motion, in oscillating chemical reactions, and in electrical currents in semiconductors. Chaos is found in the dynamics of animal populations and of medical disorders such as heart arrhythmias and epileptic seizures. Attempts are also being made to apply chaos theory to the social sciences, such as the study of business cycles.

A chaotic system is defined as one that shows "sensitivity to initial conditions." That is, any uncertainty in the initial state of the given system, no matter how small, will lead to rapidly growing errors in any effort to predict the system's future behavior. For example, the motion of a dust particle floating on the surface of a pair of whirlpools can display chaotic behavior. The particle will move in well-defined circles around the centers of the whirlpools, alternating between the two in an irregular manner. An observer who wanted to predict the motion of this particle would first have to measure its initial location. Unless the measurement was infinitely precise, however, the observer would instead obtain the location of an imaginary particle very close by the real one. The "sensitivity to initial conditions" would cause the nearby imaginary particle to follow a path that would diverge from the path of the real particle, making any long-term prediction of the trajectory of the real particle impossible. In other words, such a system would be chaotic; its behavior could be predicted only if the initial conditions were known to an infinite degree of accuracy—an impossible standard to meet.

The possibility that chaos might exist in a natural, or deterministic, system was first envisioned in the late nineteenth century by the French mathematician Henri Poincaré who was investigating planetary orbits. For decades thereafter, however, the subject aroused little scientific interest.

The Chaos of Weather

The modern study of chaotic dynamics began in 1963, when the American meteorologist Edward N. Lorenz demonstrated that a simple model that he had created to analyze thermal convection in the atmosphere showed sensitivity to initial conditions—or, in other words, that weather patterns constituted a chaotic system.

Lorenz's work was part of the attempt to decipher the general circulation of the atmosphere. If a general law governing circulation could be discovered, the dream of accurate weather prediction would become a reality. Lorenz reviewed and built upon the works of numerous scientists. He concluded that, for an idealized atmosphere, certain specific features—such as circulation, kinetic energy, and the presence of easterly and westerly winds—could be explained by mathematical formulas.

In attempting to apply his conclusions to the actual atmosphere of Earth, however, Lorenz found that such a mathematical approach was of little use. The unknown quantities in the formulas he used to determine the behavior of the atmosphere turned out to be sensitive to initial conditions, meaning that they could not be statistically calculated with any level of certainty. Although the mathematical approach worked for the idealized atmosphere of theory, in the real world, the general circulation of the atmosphere could not be determined with precision, making accurate weather prediction impossible.

IMPACT

Following Lorenz's discovery, scientists and mathematicians began to study the progression from order to chaos in various systems. In 1971, Belgian physicist David Ruelle and Dutch mathematician Floris Takens predicted that the transition to chaotic turbulence in a moving fluid would take place at a certain well-defined critical point that depended on the fluid's velocity or on some other important factor controlling the fluid's behavior. They predicted that this transition to turbulence would occur after the system had developed oscillations with at least three different frequencies. Experiments conducted by American physicists Jerry Gollub and Harry Swinney in the mid-1970's supported these predictions.

Another American physicist, Mitchell Feigenbaum, then predicted that at the critical point when an ordered system begins to break down into chaos, a consistent sequence of period-doubling transitions would be observed. This so-called period-doubling route to chaos was thereafter observed experimentally by various investigators, including the French physicist Albert Libchaber and his coworkers. Feigenbaum went on to calculate a numerical constant that governs the doubling process (Feigenbaum's number), and he showed that his results were applicable to a wide range of chaotic systems. In fact, an infinite number of possible routes to chaos can be described, several of which are universal, or broadly applicable, in the sense that they obey proportionality laws that do not depend on details of a particular physical system.

The term "chaotic dynamics" refers only to the evolution of a system over time. Chaotic systems, however, also often display spatial disorder—for example, in complicated fluid flows. The attempt to incorporate an understanding of spatial patterns into theories of chaotic dynamics has become an active area of study. Researchers hope to extend theories to the realm of fully developed turbulence, where complete disorder exists in both space and time. This effort is widely viewed as among the greatest challenges of modern physics.

See also Fractals; Weather Fronts.

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—*Kevin B. Vichcales*

Chlorofluorocarbons

The Science: F. Sherwood Rowland and Mario José Molina warned that chlorofluorocarbons (CFCs, often found in refrigerants such as Freon), might be destroying the ozone layer of the stratosphere.

The Scientists:

F. Sherwood Rowland (b. 1927), physical chemist
Mario José Molina (b. 1943), physical chemist
Paul Crutzen (b. 1933), stratospheric chemist specializing in ozone
James Lovelock (b. 1919), English chemist

Nowhere to Go but Up

Ozone is an irritating bluish gas of pungent odor that is formed naturally in the upper atmosphere by a photochemical reaction with solar ultraviolet radiation. It is a rare gas that protects Earth from the most dangerous radiations of the Sun, such as ultraviolet radiation. Ozone can absorb ultraviolet rays efficiently even when it is present in very small amounts. Altogether, the ozone layer absorbs one-twentieth of the Sun's radiation, including the dangerous shortwave rays that can do great damage to living things. All biological systems have evolved under the protection of the ozone shield in the stratosphere. Humanity, however, has for many years been depleting this ozone layer by releasing human-made chlorofluorocarbons (CFCs). These compounds are known commercially as Freon.

CFCs were discovered in 1928 by Thomas Midgley, Jr., a Du Pont Corporation chemist, who developed the chemical in response to a request by General Motors' Frigidaire Division for a safer and more efficient refrigerant. In the 1950's, CFCs became widely used not only as materials in household and commercial refrigerators and air conditioners but also as propellants in aerosol sprays and as solvents. They are nonflammable, have excellent chemical and thermal stability, and are low in toxicity.

F. Sherwood Rowland, a physical chemist at the University of California at Irvine, first became interested in atmospheric chemistry in 1972. He was attending a meeting in Fort Lauderdale, Florida, that was organized by the U.S. Atomic Energy Commission (AEC). It was there that he heard that James Lovelock, an independent and creative English chemist, had invented an electron-capture gas chromatograph to detect atmospheric gases in minute amounts. With his invention, he had discovered a minute concentration of two commonly used CFCs in the atmosphere over Western Ireland. Rowland began to wonder what eventually became of the chemical.

Rowland later performed some calculations that showed that Lovelock's concentrations were very close to the rough estimate of the total amount of CFCs being produced. Rowland reasoned that if all the CFCs ever released were present in the lowest layer of the atmosphere, the troposphere, that meant that nothing in this layer was destroying them. Yet they had to go somewhere, and the only place to go was upward into the stratosphere, an upper portion of the atmosphere that is approximately 11 kilometers above the Earth. He believed that the CFCs would then decompose when exposed to ultraviolet radiation. Eighteen months later, Rowland turned this casual commentary into an elaborate study.

A Few Chlorine Atoms

In the fall of 1973, Mario José Molina, born in Mexico, had completed his doctorate at the University of California, Berkeley, and came to work with Rowland. Together, they set out to determine what would happen to the CFCs in the atmosphere. By November, 1973, Molina had already established that nothing happened to them in the troposphere. CFCs do not react with living things, they do not dissolve in oceans, and they are not washed out of the air by rain—they do nothing except float around and gradually work their way upward into the stratosphere. It was a simple chemical deduction that they would be broken apart by the Sun's ultraviolet radiation and that, as a result, chlorine atoms would be released into the stratosphere. At the time, a few chlorine atoms seemed unworthy of concern—that is, until Molina discovered that a single chlorine atom can scavenge and destroy many thousands of ozone molecules.

MARIO MOLINA: BRINGING SCIENCE TO SOCIETY

Born and educated in Mexico, Mario José Molina earned his graduate degree from the University of California, Berkeley, before moving to the University of California at Irvine. In a statement for the Nobel Foundation upon winning the Chemistry Prize in 1995, Molina recalled the discovery of ozone depletion by chlorofluorocarbons (CFCs).

Three months after I arrived at Irvine, Sherry [F. Sherwood Rowland] and I developed the "CFC-ozone depletion theory." At first the research did not seem to be particularly interesting—I carried out a systematic search for processes that might destroy the CFCs in the lower atmosphere, but nothing appeared to affect them. We knew, however, that they would eventually drift to sufficiently high altitudes to be destroyed by solar radiation. The question was not only what destroys them, but more importantly, what are the consequences. We realized that the chlorine atoms produced by the decomposition of the CFCs would catalytically destroy ozone. We became fully aware of the seriousness of the problem when we compared the industrial amounts of CFCs to the amounts of nitrogen oxides which control ozone levels; the role of these catalysts of natural origin had been established a few years earlier by Paul Crutzen. We were alarmed at the possibility that the continued release of CFCs into the atmosphere would cause a significant depletion of the Earth's stratospheric ozone layer. . . .

We published our findings in *Nature*, in a paper which appeared in the June 28, 1974 issue. The years following the publication of our paper were hectic, as we had decided to communicate the CFC—ozone issue not only to other scientists, but also to policy makers and to the news media; we realized this was the only way to insure that society would take some measures to alleviate the problem.

Source: Mario José Molina, "Autobiography," in *Les Prix Nobel: The Nobel Prizes 1996*, edited by Tore Frängsmyr (Stockholm: The Nobel Foundation, 1997). Available at http://nobelprize.org/chemistry. Accessed August, 2005.

Using detailed calculations for chemical reactions, Molina concluded that each chlorine atom from CFCs would collide with a molecule of the highly unstable ozone. The reaction did not end there. Once chlorine was freed from the CFC, the by-product would be oxygen and a chemical fragment with an odd number of electrons called "chlorine monoxide." The odd number of electrons, Molina knew, guaranteed that this fragment would react with a free oxygen atom to achieve an even number of electrons. He calculated that when the chlorine monoxide fragment met the free oxygen atom, the oxygen in chlorine monoxide would be attracted to the free oxygen atom and would split off to form a new oxygen molecule. Chlorine would then be freed and would collide with ozone, thus starting the cycle all over again.

In short, the breakdown of CFCs by sunlight would set off a chain reaction in which one chlorine atom could gobble up 100,000 molecules of ozone, turning them into ordinary oxygen with no power to absorb dangerous solar radiation. Rowland and Molina published their results in the June, 1974, issue of *Nature*.

Impact

On September 26, 1974, the CFC/ozone story made the front page of *The New York Times*. In October, 1974, a government committee recommended that the National Academy of Sciences conduct a study on the validity of this theory. In June of 1975, Johnson Wax, the nation's fifth largest manufacturer of aerosol sprays, announced that it would stop using CFCs in its products. In June, 1975, Oregon became the first state to ban CFCs in aerosol sprays. In October, 1976, the Food and Drug Administration and the Environmental Protection Agency (EPA) proposed a phaseout of CFCs used in aerosols. In October, 1978, CFCs used in aerosols were banned in the United States. In August, 1987, the McDonald's hamburger chain, which had been using CFCs to make polyurethane foam containers for hamburgers, announced that it would stop using the chemical.

In August, 1981, National Aeronautics and Space Administration (NASA) scientist Donald Heath announced that satellite records showed that the amount of ozone had declined 1 percent. In October, 1984, an English research group led by Joe Farman detected a 40 percent ozone loss over Antarctica during austral (Southern Hemisphere) spring, which was confirmed in August, 1985, by NASA satellite photographs showing the existence of an ozone "hole" over Antarctica. In May, 1988, preliminary findings of a hole in the ozone layer over the Arctic were discussed at a scientific conference in Colorado. In September, 1988, the EPA reported new evidence that showed that it had underestimated the degree of ozone depletion and announced that an 85 percent cutback on CFC use was needed.

Meanwhile, in 1987, many nations—including the United States—signed the Montreal Protocol on Substances That Deplete the Ozone Layer. This document was an internationally designed treaty to stop all production and consumption of ozone-depleting chemicals before the year 2010. Through various international agencies, such as the World Bank, encouragement was given to research into finding economical substitutes for CFCs. By the year 2001, most of the nations of the world had signed the Montreal Protocol or its amendments. In 1995, in recognition of their work concerning the formation and decomposition of ozone, the Royal Swedish Academy of Sciences award the Nobel Prize in Chemistry to F. Sherwood Rowland, Mario Molina, and Paul Crutzen.

See also Global Warming; Ozone Hole; Pesticide Toxicity.

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—*Earl G. Hoover*

CHROMOSOMES

The Science: In the late nineteenth century, biologists determined that inherited traits of organisms are physically located on chromosomes.

The Scientists:

Walter S. Sutton (1877-1916), American geneticist and surgeon
Theodor Boveri (1862-1915), German biologist
Gregor Johann Mendel (1822-1884), Austrian monk and scientist
Carl Erich Correns (1864-1933), German geneticist
Thomas Hunt Morgan (1866-1945), American geneticist and 1933 Nobel laureate in Physiology or Medicine

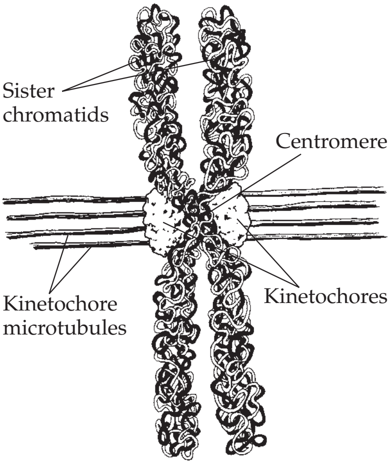
FARMING AS A SCIENTIFIC ENDEAVOR

Beginning in 1856, an Austrian monk named Gregor Johann Mendel initiated a series of experiments with garden peas that would revolutionize twentieth century biology. Mendel cross-pollinated different lines of garden peas that had been bred for certain characteristics (purple or white flower color, wrinkled or smooth seeds, and the like). From his extensive experiments, he concluded that each garden pea plant carries two copies of each characteristic trait (flower color, seed texture, and so forth). These traits would later come to be known as "genes."

Diploid organisms have two copies of each gene; the copies may or may not be identical. Different forms of the same gene are called "alleles." For example, the gene for flower color may have two alleles, one conferring purple flower color and the other conferring white flower color. In most cases, one allele is dominant over other alleles for the same gene. For example, a plant having two purple flower-color alleles will have purple flowers, while a plant having two white flower-color alleles will have white flowers. A plant having one purple and one white flower-color allele, however, will have purple flowers; the dominant purple allele will mask the white allele.

Since most plants and animals reproduce sexually by the means of fusion of pollen (or sperm) with eggs, Mendel discovered the pattern of transmission of these genetic traits (that is, inheritance) from parents to offspring. While each individual has two copies of every gene, each individual can transmit only one copy of each gene (that is, only one of two alleles) to each of its offspring. If a parent has two different alleles for a given gene, only one of the two alleles can be passed on to each of its children. There is a fifty-fifty chance of either allele being transmitted for each of thousands of different genes conferring different characteristic traits. Before Mendel's findings were rediscovered in 1900, most investigators were concluding

EXTERNAL STRUCTURE OF A CHROMOSOME



(Kimberly L. Dawson Kurnizki)

that the mechanism of heredity was a blending of characteristics, similar to the mixing of different colors of paint. According to Mendel's results, the mechanism was more similar to combining various colored balls.

Mendel summed up the random chance inheritance of different alleles of a gene in two principles. The first principle, allelic segregation, maintains that the different alleles for a given gene separate from each other during the formation of germ-line cells (that is, sperm and egg). The second principle, independent assortment, maintains that different alleles of different genes arrange themselves randomly during germ-cell production. When Mendel published his results in 1866, his work was scarcely noticed. Twenty years would pass before the importance of his research was understood.

The Chromosomal Theory of Inheritance

From 1885 to 1893, the German biologist Theodor Boveri researched the chromosomes of the roundworm *Ascaris*. Chromosomes are molecules composed mostly of deoxyribonucleic acid (DNA) and protein. They are located within the nuclei of the cells of all living organisms. In the late 1890's, Walter S. Sutton studied chromosomes of the grasshopper *Brachyostola magna*. Sutton constructed detailed diagrams of *Brachyostola* chromosomes during mitosis (chromosome doubling and separating prior to cell division) and meiosis (chromosome dividing and splitting in sperm and egg production). Both Sutton and Boveri were independently attempting to understand chromosomal structure and function.

The breakthrough came in 1900, when the German biologist Carl Erich Correns rediscovered Mendel's work with garden peas. Correns boldly proposed that the chromosomes of living organisms carried the organisms' inherited traits. Unfortunately, he did not provide an exact mechanism to support his hypothesis. Nevertheless, Correns's hypothesis eventually caught the attention of both Sutton and Boveri. With Correns's hypothesis and their own research on chromosome behavior, Sutton and Boveri began to derive a mechanism for the chromosomal transmission of inherited traits. Together, the results of the two scientists culminated in the chromosomal theory of inheritance, one of the basic tenets of genetics and modern biology.

The chromosomal theory of inheritance makes four assertions. First, the fusion of sperm and egg is responsible for reproduction—the formation of a new individual. Second, each sperm or egg cell carries one-half of the genes for the new individual, or one copy of each chromosome. Third, chromosomes carry genetic information and are separated during meiosis. Finally, meiosis is the mechanism that best explains Mendel's principles of allelic segregation and independent assortment. Sutton reported his conclusions in a 1902 article in *The Biological Bulletin*.

IMPACT

The Sutton and Boveri chromosomal theory of inheritance represented a landmark in the history of biological thought. It reestablished Mendelism and provided a definite physical mechanism for inheritance. It demonstrated the molecular basis of life and thereby launched two successive waves of biological revolution: the pre-World War II genetic and biochemical revolution and the postwar molecular biology revolution, which continues today. It has also been very useful for the study of human genetic disorders.

Thomas Hunt Morgan and his associates generated hundreds of mutations in the fruit fly *Drosophila melanogaster* and mapped these mutations to specific chromosome locations, thereby verifying Sutton and Boveri's theory. Mutations were generated using either chemicals or radiation such as ultraviolet light and X rays. This work demonstrated that exposing living organisms to radiation and certain chemicals can cause chromosome and gene damage, often resulting in severe abnormalities, and sometimes death, in the exposed individuals and their descendants.

Chromosome studies also proved useful as a tool for understanding evolution. Evolution consists of mutational changes that occur in organisms over time, thereby giving rise to new types of organisms and new species that are better adapted to their environments. The chromosomal theory of inheritance helped to explain the processes by which evolution takes place.

See also Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*David Wason Hollar, Jr.*

CITRIC ACID CYCLE

THE SCIENCE: Sir Hans Adolf Krebs announced the operation of a series of chemical reactions in the human body that convert food to chemical energy.

THE SCIENTISTS:

Sir Hans Adolf Krebs (1900-1981), biochemist who was awarded the 1953 Nobel Prize in Physiology or Medicine

Albert Szent-Györgyi (1893-1986), Hungarian biochemist who won the 1937 Nobel Prize in Physiology or Medicine

Franz Knoop (1875-1946), early contributor to the biochemical study of carbon compounds

Carl Martius (b. 1906), organic chemist who, with Knoop, provided Krebs with information vital to his work

CONVERTING FOOD TO ENERGY

The foods humans eat consist largely of carbohydrates, fats, and proteins; each of these classes represents a source of energy and molecules required for growth and repair of tissue. Maintaining or restoring health demands a detailed understanding of metabolism, the conversion of these foods into energy and chemical building blocks. The central problem in the early 1930's was that of describing exactly how this conversion is conducted in the cell.

When Sir Hans Adolf Krebs first became interested in this question, it had been established that the carbohydrates, or sugars and starches, are

Hans Adolf Krebs. (The Nobel Foundation)

converted to carbon dioxide, a gas. As these names imply, the chemical structures involve the carbon atom. It had been known for many years that carbon is the most essential element found in all living matter. What scientists did not yet fully understand was exactly how this conversion process worked. They did suspect, however, that such a process might take place in a series of steps rather than all at once; it was well known that energy is transformed more efficiently in such a series.

Krebs realized that the most promising approach to the problem of describing the chemistry that takes place in the cell was the study of the speed at which these acids are oxidized during the conversion process. Eventually, he found that a number of acids are oxidized rapidly enough to play a role in the overall conversion sequence.

His most important discovery concerned the common food substance citric acid, which had long been known to be connected directly with the healthy operation of the body. Not only does citrate—the form of citric acid in cells—undergo oxidation rapidly, but it also speeds up, or catalyzes, the process of chemical respiration. Hungarian biochemist Albert Szent-Györgyi had already demonstrated the effect of a compound causing a greater increase in the rate of a reaction for several other acids. Furthermore, in 1937, Carl Martius and Franz Knoop showed exactly how citrate is converted into succinate, which is a compound formed during the food-to-energy conversion process. Now Krebs had all the information he needed to propose a theory describing the conversion of a carbohydrate into carbon dioxide.

Final Stage of Metabolism

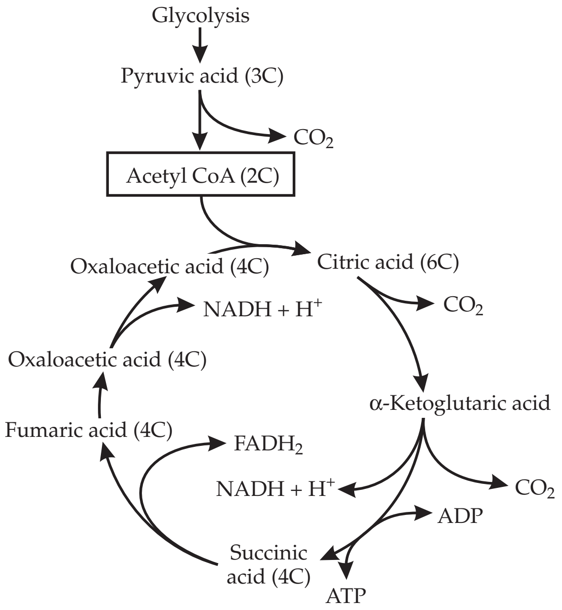
Krebs's proposal for what he called the tricarboxylic, or citric acid, cycle has come to be known as the Krebs cycle, the final stage of the metabolic process. In fact, the key feature of this idea is its cyclical nature. It is apparent that each step, or individual change of one molecule into another, must be connected to the next. Biochemists refer to such an arrangement as a pathway. Krebs discovered that the citric acid pathway is cyclic: One may visualize the scheme as involving some material being fed constantly into the pathway and reacting (undergoing a chemical change) with one of the substances produced during the previous reaction in the cycle.

In 1937, Krebs announced his configuration to describe the series of cellular chemical reactions in which food becomes energy. During the process, acids formed during the metabolism of food—proteins, fats, carbohydrates—undergo oxidation, releasing energy useful to the cell.

The cycle begins when acetate enters the pathway. It then reacts with another acid, oxaloacetate (which, as the end product of the final chemical conversion in the cycle, is already present).

The first result of this initial reaction is citrate. Next, the cycle converts the citrate into a series of "intermediate" compounds (of which succinate is one), while freeing up carbon dioxide and electrons. The carbon dioxide and electrons are then used immediately to form a high-energy substance called adenosine triphosphate (ATP, the form of chemical energy used by the cell). The end of the cycle is the production of more oxaloacetate (which

THE KREBS (CITRIC ACID) CYCLE



began the sequence). The Krebs conversion cycle is ready to begin again.

Each step of the process is catalyzed by a specific enzyme. These enzymes help the reaction sequence occur smoothly and rapidly, enabling the energy produced to be used efficiently by the cell.

IMPACT

At the start of the nineteenth century, chemists were fascinated by the extraordinary changes that matter undergoes in living organisms. During the early years of the next century, scientists continued to show interest, turning their attention toward more exacting studies of the body's chemical reactions.

Krebs, as one of the principal founders of such studies, provided a vital link between biology and chemistry. His work helped give birth to a new science, biochemistry. His other contributions included developing and using precise instruments and techniques for examining metabolic reactions.

The proposal of the Krebs cycle was met with characteristic skepticism; it was a breathtaking leap into uncharted territory. In time, though, most working biochemists came to accept the cycle at least in theory, and a huge amount of extremely important experimental work was conducted.

For example, while the proposal was originally conceived to explain the oxidation of carbohydrates, it was shown later that all major foodstuffs undergo the Krebs cycle. Furthermore, the functioning of the cycle in plant, as well as animal, tissue soon became apparent. About two-thirds of all the oxidation that takes place in plants and animals using carbohydrate, fat, or protein takes place through the Krebs cycle.

See also Cell Theory; Photosynthesis.

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—*K. Thomas Finley*

CLONING

THE SCIENCE: Experimental technique for creating exact duplicates of living organisms by re-creating their DNA.

THE SCIENTISTS:

Ian Wilmut (b. 1944), embryologist with the Roslin Institute
Keith H. S. Campbell, experiment supervisor with the Roslin Institute
J. McWhir, researcher with the Roslin Institute
W. A. Ritchie, researcher with the Roslin Institute

MAKING COPIES

On February 22, 1997, officials of the Roslin Institute, a biological research institution near Edinburgh, Scotland, held a press conference to announce startling news: They had succeeded in creating a clone—a biologically identical copy—from cells taken from an adult sheep. Although cloning had been performed previously with simpler organisms, the Roslin Institute's experiment marked the first time that a large, complex mammal had been successfully cloned.

Cloning, or the production of genetically identical individuals, has long been a staple of science fiction and other popular literature. Clones do exist naturally, as in the example of identical twins. Scientists have long understood the process by which identical twins are created, and agricultural researchers dreamed of a method by which cheap identical copies of superior livestock could be created. The discovery of the double helix structure of deoxyribonucleic acid (DNA) in the 1950's led to extensive research into cloning and genetic engineering. Using the discoveries of James Watson, Francis Crick, and other geneticists, scientists were soon able to develop techniques to clone laboratory mice.

However, the cloning of complex, valuable animals such as livestock proved to be hard going. Early versions of livestock cloning were technical attempts at duplicating the natural process of fertilized egg splitting that

Dolly the Sheep

In 1997, the world was taken aback when a group of scientists headed by embryologist Ian Wilmut at the Roslin Institute in Scotland announced the successful cloning of a sheep named Dolly. Scientists had already cloned cows and sheep, but they had used embryo cells. Dolly was the first vertebrate cloned from the cell of an adult vertebrate.

Although environmental factors would make Dolly individual, genetically she would never have the individuality that an organism produced by usual reproductive means would possess. Over the next six years, she gave birth to several, apparently healthy, offspring. In 2002, at the age of six, Dolly became lame in her left hind leg, a victim of arthritis. Although sheep commonly suffer arthritis, a veterinarian noted that both the location and the age of onset were uncommon. Then, in February, 2003, she was euthanized after the discovery of a progressive lung disease.

Dolly's health problems have led to speculations about premature aging in clones but are complicated by her unique experiences as well. As Wilmut noted, in the early years following the announcement of her cloning, she became something of a celebrity, which led to overfeeding by visitors and in turn a period of obesity, later corrected. More significant were the discovery of her arthritis and then her lung disease—conditions not uncommon in sheep but that tend to emerge later (sheep typically live to be eleven or twelve years old). Theories of premature aging are supported by the fact that Dolly's telomeres were shorter than normal. These cell structures function as "caps" that prevent "fraying" at the ends of DNA cells. As a cell ages, its telomeres become progressively shorter, until finally they disappear altogether and are no longer able to protect the cell, which then dies.

Was Dolly older genetically than she was chronologically? The answer to the question of whether Dolly was completely "normal" or aged prematurely as a result of being a clone must await full investigation of her autopsy results, as well as tracking of her offspring's lives and monitoring of other vertebrate clones through their life spans.

leads to the birth of identical twins. Artificially inseminated eggs were removed, split, and then reinserted into surrogate mothers. This method proved to be overly costly for commercial purposes, a situation aggravated by a low success rate.

NUCLEAR TRANSFER

Researchers at the Roslin Institute found these earlier attempts to be fundamentally flawed. Even if the success rate could be improved, the number of clones created (of sheep, in this case) would still be limited. The Scots, led by embryologist Ian Wilmut and experiment supervisor Keith Campbell, decided to take an entirely different approach. The result was the first live birth of a mammal produced through a process known as nuclear transfer.

Nuclear transfer involves the replacement of the nucleus of an immature egg with a nucleus taken from another cell. Previous attempts at nuclear transfer had cells from a single embryo divided up and implanted into an egg. Because a sheep embryo has only about forty usable cells, this method also proved limiting. The Roslin team therefore decided to grow their own cells in a laboratory culture. They took more mature embryonic cells than those previously used, and they experimented with the use of a nutrient mixture. One of their breakthroughs occurred when they discovered that these "cell lines" grew much more quickly when certain nutrients were absent. Using this technique, the Scots were able to produce a theoretically unlimited number of genetically identical cell lines.

The next step was to transfer the cell lines of the sheep into the nucleus of unfertilized sheep eggs. First, 277 nuclei with a full set of chromosomes were transferred to the unfertilized eggs. An electric shock was then used to cause the eggs to begin development, the shock performing the duty of fertilization. Of these eggs, twenty-nine developed enough to be inserted into surrogate mothers. All the embryos died before birth except one: a ewe the scientists named Dolly. Her birth on July 5, 1996, was witnessed by only a veterinarian and a few researchers. Not until the clone had survived the critical earliest stages of life was the success of the experiment disclosed; Dolly was more than seven months old by the time her birth was announced to a startled world.

IMPACT

The news that the cloning of sophisticated organisms had left the realm of science fiction and become a matter of accomplished scientific fact set off an immediate uproar. Ethicists and media commentators quickly began to debate the moral consequences of the use—and potential misuse—of the technology. Politicians in numerous countries responded to the news by calling for legal restrictions on cloning research. Scientists, meanwhile, speculated about the possible benefits and practical limitations of the process.

The issue that stirred the imagination of the broader public and sparked the most spirited debate was the possibility that similar experiments might soon be performed using human embryos. Although most commentators seemed to agree that such efforts would be profoundly immoral, many experts observed that they would be virtually impossible to prevent. "Could someone do this tomorrow morning on a human embryo?" reporters asked Arthur L. Caplan, the director of the Center for Bioethics at the University of Pennsylvania. "Yes. It would not even take too much science. The embryos are out there." Such observations conjured visions of a future that seemed marvelous to some, nightmarish to others. Optimists suggested that the best and brightest of humanity could be forever perpetuated, creating an endless supply of Albert Einsteins and Wolfgang Amadeus Mozarts. Pessimists warned of a world overrun by clones of self-serving narcissists and petty despots, or of the creation of a secondary class of humans to serve as organ donors for their progenitors. The Roslin Institute's researchers steadfastly proclaimed their own opposition to human experimentation. Moreover, most scientists were quick to point out that such scenarios were far from realization, noting the extremely high failure rate involved in the creation of even a single sheep.

Most experts emphasized more practical possible uses of the technology: improving agricultural stock by cloning productive and disease-resistant animals, for example, or regenerating endangered or even extinct species. Even such apparently benign schemes had their detractors, however, as other observers remarked on the potential dangers of thus narrowing a species' genetic pool. Even prior to the Roslin Institute's announcement, most European nations had adopted a bioethics code that flatly prohibited genetic experiments on human subjects.

Ten days after the announcement, U.S. president Bill Clinton issued an executive order that banned the use of federal money for human cloning research, and he called on researchers in the private sector to refrain from such experiments voluntarily. Nevertheless, few observers doubted that Dolly's birth marked only the beginning of an intriguing—and possibly frightening—new chapter in the history of science.

See also Chromosomes; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code;

Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Jeff Cupp*

COMPTON EFFECT

THE SCIENCE: Arthur Compton's experiment with the scattering of X rays from a solid showed that electromagnetic radiation exhibits both wave-like and particle-like properties, convincing scientists that light quanta are real.

THE SCIENTISTS:

Arthur Holly Compton (1892-1962), American physicist
Albert Einstein (1879-1955), German American theoretical physicist
Max Planck (1858-1947), German theoretical physicist

THE NATURE OF LIGHT

For centuries, people wondered about the nature of the light that is radiated from sources such as the Sun and lamps. During the nineteenth century, scientists became convinced that light was a form of wave motion that was similar in some ways to water waves and sound waves. Different colors in visible light were recognized as having different particular wavelengths—that is, different distances between any two consecutive wave crests in their individual wave patterns. Red light has the longest wavelength that human eyes can detect, and violet light has the shortest. The rainbow colors of red, orange, yellow, green, blue, and violet light form a continuous natural light "spectrum," or range, with electromagnetic properties.

It was also discovered that some "light" cannot be detected by human eyes. Infrared and ultraviolet radiation lie just beyond the visible range. Additional experiments revealed still other forms of radiation: radio waves beyond the infrared, X rays and gamma rays beyond the ultraviolet.

Before the beginning of the twentieth century, however, there were other experimental results that could not be explained by thinking of light as simply a wavelike disturbance. To explain some of those results, Max Planck proposed in 1899 that light consisted of tiny bundles of energy called "quanta" (the plural form of *quantum*, the Latin word for "how much"). Each quantum had its own particular energy; the longer the wavelength, the smaller the amount of energy. "Photons" is another name for light quanta.

In 1905, Albert Einstein, who later became famous for his theory of relativity, showed that the photoelectric effect (in which light falling on certain metals causes an electric current) could be explained readily if one regarded light as consisting of quanta. Each quantum could knock an electron out of a metallic surface, freeing the electron to move as part of an electric current.

Scientists had great difficulty reconciling these two different ideas about the nature of light. How could light be both waves and particles?

ARE QUANTA REAL?

By the 1920's, many theoretical physicists had found that quanta were useful in explaining certain observed phenomena, but the energy levels of quanta were so low that it was not possible at that time to observe individual quanta. Were quanta real or merely useful ideas?

Arthur Holly Compton, a professor of physics at Washington University in St. Louis, wanted to find out. He set up an experiment in which he directed a beam of X rays at a block of paraffin. Some of the X rays were scattered off to the side at various angles. To Compton's surprise, the scattered X rays had longer wavelengths than the incoming rays did; that is, they were of lower energy. This was comparable to shining blue light on white paper and finding green light reflected.

WAVES OR PARTICLES?

Arthur Holly Compton's doctoral dissertation research at Princeton, begun in 1914, involved reflecting X rays from certain crystals with the intent of using them as a probe to determine how the electrons are distributed about the center of the crystal atoms. For six years, Compton carried out a complex series of experimental and theoretical investigations of how X rays and even gamma rays are scattered by aluminum, carbon, and other elements.

(The Nobel Foundation)

Only very gradually did Compton come to understand that to explain the results that he and others were finding experimentally, he would have to assume that the X rays and gamma rays were behaving not like waves but like particles. For example, when an X ray strikes an electron in a carbon atom, it is just as if one little billiard ball has struck another, sending it on its way by transferring some energy and momentum to it. In the process, the incident X ray loses some energy and momentum, and since the energy of an X ray is proportional to its frequency, the scattered X ray has a lower frequency or higher wavelength than the incident X ray. By using a spectroscope, Compton was able to compare the wavelength of the scattered X ray to that of the incident X ray. He found that the scattered X ray's wavelength had increased by just the amount he had calculated on the basis of the billiard-ball model. X rays in this experiment did indeed behave just like little particles possessing energy and momentum.

Albert Einstein had argued as long before as 1905 that there were reasons to believe that in certain circumstances high-frequency electromagnetic radiation behaves like particles or quanta of energy, but Einstein's so-called light-quantum (wave-particle) hypothesis was greeted with profound skepticism in succeeding years. Therefore, Compton's findings came as a great surprise to most physicists when he published them in 1923. Although Compton's experimental and theoretical program was not motivated by a desire to test Einstein's hypothesis, Compton's results were recognized as the first conclusive experimental proof of that hypothesis. Physicists were now forced to consider anew the way radiation interacts with matter, and Compton's discovery was a crucial stimulus to the creation of modern quantum mechanics in 1925-1926. For his discovery—known ever after as the Compton effect—Compton won the 1927 Nobel Prize in Physics.

In addition, Compton found that electrons had been knocked loose from the paraffin. On measuring the angles between the scattered X rays and the freed electrons, he found that they were related to each other exactly as if an X-ray quantum (or photon) had collided with an electron and they had both shot off like colliding marbles or billiard balls.

In more technical language, the angles showed that, if the X rays were regarded as a stream of particle-like quanta, momentum was "conserved." In this context, conservation means that the total momentum of all the particles before a collision is the same as the total after the collision. Their individual values, however, may be quite different.

Furthermore, the missing energy in the scattered X rays corresponded to the energy of motion of the electron. These results agreed with the laws of conservation of energy and momentum that had long been established in the world of physics.

Compton's results were announced in December, 1922, and published in the spring of 1923. After some initial controversy about the reliability of those results and their interpretation by Compton, scientists became convinced that Compton's work definitely showed that quanta are real and behave like particles.

Impact

Word of Compton's results traveled to Europe, where physicists had been intensely studying the problems associated with light and other forms of radiation for several decades. At about the same time that Compton's results were published, Peter Debye, a Dutch physicist who was professor of physics at the Federal Institute of Technology in Zurich, Switzerland, independently came to the same conclusions about the quantum nature of radiation. Additional experiments were done by other physicists, and they confirmed Compton's results. Ever since, physicists have known that, in dealing with radiation, they must recognize that it has both wave and particle properties.

By 1927, Compton's results were part of the generally accepted views held by physicists everywhere, and Compton was given international recognition and honors, such as the 1927 Nobel Prize in Physics and invitations to participate in prestigious European scientific conferences. Throughout his life, Compton remained an important member of the worldwide community of physicists, studying physics, serving as a leader of American physicists—especially during World War II—and publicly expressing his deep concerns about the relationships among science, society, and religion.

See also Photoelectric Effect; Quantum Mechanics; Wave-Particle Duality of Light.

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—*Katherine R. Sopka*

CONDUCTIVITY

THE SCIENCE: Always a careful observer, Stephen Gray discovered by accident that electricity could flow from one object to another, and that some materials were conductors, while other materials were insulators. His meticulous and imaginative experiments lifted the study of static electricity from being only a parlor amusement to a science.

THE SCIENTISTS:

Stephen Gray (1666-1736), Englishman who discovered electrical conductivity

John Flamsteed (1646-1719), Astronomer Royal and Gray's role model

Francis Hauksbee (1660-1713), physicist reputed to have invented the first electrical machine

Jean-Théophile Desaguliers (1683-1744), paid demonstrator of experiments for the Royal Society

Charles-François de Cisternay Du Fay (1698-1739), French chemist who repeated many of Gray's experiments and continued Gray's work after his death

ELECTRIC VIRTUE

In 1696, the amber effect—the ability of amber to attract bits of fluff when it is rubbed—had been known since ancient times. William Gilbert had shown that glass, sulfur, precious stones, resin, and sealing wax could also be "electrified." In 1706 physicist Francis Hauksbee used a flint glass tube to demonstrate some effects of static electricity to the Royal Society of London (England's premier scientific body at the time), and hearing of this, Stephen Gray performed his own experiments and sent an account of them to the society in 1708. He later made friends with several members of the society when he became an assistant to Jean-Théophile Desaguliers, who performed demonstrations for the Society.

Gray was the son of a cloth dyer and had followed in the family business while dabbling in science. At some time he seems to have studied with John Flamsteed, England's Astronomer Royal. Gray ground his own telescope lenses and measured eclipses, sunspots, and the revolutions of Jupiter's satellites. He made a microscope using as a lens a water droplet in a tiny hole made in a brass plate. It worked well enough for him to see microscopic organisms swimming in the water, and he became widely known as a careful and talented observer. Although he was not a fellow of the Royal Society, the society published Gray's microscopic observations in 1696.

When Gray hurt his back and could no longer work at the family trade, he applied to become a resident of Sutton's Hospital, also known as the London Charterhouse. This request was finally granted in 1719. The Charterhouse was a day school for poor boys and provided room and board for eighty male pensioners who were required to be educated enough to teach the boys. Gray continued to dabble with electrostatics but made relatively little progress. Finally in 1729, at age sixty-three, he obtained a flint glass tube similar to the one used by Hauksbee. Just over three feet long and an inch in diameter, it acquired a static charge when rubbed with a cloth or by a dry hand.

To keep dust out of the tube when he was not using it, Gray placed corks in the ends. He could tell when the tube had acquired "electric virtue" (static electricity) because it would then attract bits of feather, thread, or leaf-brass, similar to the amber effect. Sometimes there would be a crackling sound and, in the dark, a flash of light or a spark. Gray wondered whether light falling on a metal would convey electric virtue to the metal.

THE FLYING BOY

In the 1720's and 1730's, as Stephen Gray conducted his experiments with static electricity, or "electric virtue," he succeeded in electrifying all manner of materials, and he wondered if even people could be "electrified." His curiosity led to a dramatic and entertaining demonstration that is still associated with Gray's name: The Flying Boy.

Gray suspended two large loops of horsehair clothesline from hooks in the ceiling. He took a "charity boy" (a volunteer looking for some amusement) and had him lie horizontally, suspended in the air by one loop about his chest and the other about his legs. Then Gray used his electrically charged glass tube to electrify the boy. Any guest who tried to touch the boy was zapped by a sharp spark, and when the boy extended his hands over insulated stands holding bits of feathers and leaf-brass, the bits jumped upward to his hands. If a guest brought a finger near the boy's nose, the finger would draw sparks from it.

The spectacle left no doubt that people could be electrified. Gray wrote a careful description of his experiments and findings which was published by the Royal Society in 1732.

He had previously attempted—without success—to electrify metals by rubbing them.

TRAVELING VIRTUE

Preparing for this experiment, Gray rubbed the tube, but then he noticed that small feathers were attracted to the corks as well as to the tube. This simple observation was a breakthrough: Evidently, "electric virtue" could be transferred, or *conducted*, from one body to another! Flush with excitement, Gray tried every object he had at hand: an ivory ball with a hole in it, which he stuck on a short stick with the stick inserted in the cork; the ball suspended by wire or 3 feet of twine; silver coins; a lead ball; the fire shovel; an iron poker; metal tongs; a copper teakettle (empty or full of hot or cold water); brick; tile; chalk; and a head of cabbage. All could be electrified when connected to the tube. (Gray later found that materials such as wood or twine conduct only when the humidity is high enough.)

Next Gray wondered how far the electric virtue could be made to travel. Limited by the size of his room, he assembled 18 feet of sticks and canes and connected one end to the tube and the other to the ivory ball which became electrified. Needing more space, over the next few months he visited his friends John Godfrey and Granville Wheler, both of whom had large homes and lands. They eventually succeeded in transmitting electric virtue down 886 feet of twine, but two more important discoveries were made along the way. Godfrey and Gray prepared a horizontal line of twine suspended by twine from nails in a ceiling beam and had absolutely no success. Gray correctly reasoned that electric virtue had flowed up the twine and was dissipated in the ceiling beam.

Gray's Experiments

When Gray visited Wheler and explained the problem of suspending a horizontal line, Wheler suggested that the twine line could be suspended with silk threads. This approach worked, and Gray theorized that the silk had blocked the flow of electric virtue because it had a much smaller diameter than the twine. Later, when the silk support lines broke under the weight of long lengths of twine, they used brass wire no thicker than the silk lines, and again got no electric flow. Gray now correctly reasoned that it was not the diameter of the support lines that was important but the fact that some materials allowed the flow of electric virtue while others blocked that flow. Gray even attempted, successfully, to electrify a human being. He wrote a careful description of his experiments and findings, which was published by the Royal Society in 1732.

Impact

The concept of static electricity is familiar to most people from common daily experience: If different materials, such as a wool cloth and a glass rod, are placed into close contact and then separated after rubbing, some electrons will be transferred from the glass to the wool, leaving the glass charged positively and the wool negatively charged. If a small feather is brought near to the positively charged glass, the positively charged glass will act on the atoms of the feather to pull some electrons in each atom to the side of the atom that is closest to the glass rod; the average negative charge in the feather, now slightly closer than the average positive charge, will draw the feather to the glass. If the feather now touches the glass rod, some electrons from the feather may transfer to the rod, leaving the feather positive and the rod less positive. Both rod and feather are positively charged and the feather will now be repelled from the rod. Gray, along with others, observed both the attractive and repulsive effects. In fact one of Gray's favorite demonstrations was to repel a feather and make it float in the air by holding the tube horizontally and keeping it beneath the feather.

Gray continued to experiment and publish until his death. He received the Royal Society's greatest honor, the Copley Medal, in the first year it was awarded, 1731, and again in 1732. He was also elected a fellow of the Royal Society. Desaguliers gave the modern names "conductor" and "insulator" to the two classes of material Gray had discovered: those that allowed electric flow and those that blocked it. French scientist Charles Du Fay visited Wheler and Gray in 1732 and, inspired by their work, developed the two-fluid theory of electricity, which attained wide acceptance until it was superseded by Benjamin Franklin's demonstration of the single-fluid theory. Because Gray was the first to send electrical signals hundreds of feet down a line, he is an ancestor of the telegraph, the telephone, and long-distance communication. Perhaps most important, just as William Gilbert had made the study of magnets scientific, Gray more than any of his predecessors made the study of electricity scientific.

See also Electric Charge; Electrodynamics; Electromagnetism; Electrons; Lightning; Magnetism; Superconductivity; Superconductivity at High Temperatures.

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—*Charles W. Rogers*

CONTAGION

THE SCIENCE: Girolamo Fracastoro's *De contagionibus et contagiosis morbis et eorum curatione libri tres*, in which he postulates that diseases are caused by the spread of "seeds" or "seminaria" that could self-multiply, is generally considered to be the first work to attribute disease to unseen "germs" and helped lay a foundation for modern understanding of infectious disease.

THE SCIENTISTS:

Girolamo Fracastoro (c. 1478-1553), Italian physician, astronomer, and poet

Antoni van Leeuwenhoek (1632-1723), Dutch biologist and microscopist

A NEW DISEASE

Girolamo Fracastoro epitomized the Renaissance thinker. He studied medicine at Padua and became a physician, but he was also a poet, a philosopher, a natural historian who developed theories of fossils, and, like his contemporary at Padua—Nicolaus Copernicus—an astronomer. Medicine, however, is the field in which Fracastoro's contributions are most noted.

In the early 1500's, after the return of Spanish explorers from the New World, Europe was experiencing a new, virulent infectious disease. Now known as syphilis, this disease derives its name from a 1,300-verse poem, *Syphilis sive morbus Gallicus* (1530; *Syphilis: Or, A Poetical History of the French Disease*, 1686; better known as *Syphilis*), published by Fracastoro under his Latin name, Hieronymous Fracastorius. This poetic work gives a mythical account of a shepherd, Syphilis, who angers Apollo and is cursed with the disease. In this poem, Fracastoro first articulates his thoughts on contagion and the spread of disease.

Fracastoro argues that nature is complex but understandable through careful study. He suggests a natural cause for the disease. He also suggests that the particles that cause the disease can be carried by air and that they can remain dormant for years before "breaking out."

SEMINARIA AND MODES OF TRANSMISSION

Fracastoro continued his observations about infectious disease and his studies of syphilis, and in 1546 he published a treatise on infectious diseases, *De contagionibus et contagiosis morbis et eorum curatione* (1546; *De contagione et contagiosis morbis et eorum curatione*, 1930), in which he is the first person to use the word "contagion." Fracastoro defines contagion as an infection passing from one person to another. He accurately describes the three stages of syphilis: the small genital sore (primary syphilis), lesions and a body rash several months after the initial sore (secondary syphilis), and dementia (caused by brain deterioration) and other organ destruction (tertiary syphilis). He also describes the mode of transmission of syphilis, noting that it is a sexually transmitted disease, and he recognizes the fact that a woman infected with syphilis can pass the disease to her child during pregnancy or after birth through her breast milk.

THE STORY OF SYPHILIS

(Library of Congress)

The work that brought the most fame to Fracastoro was his lengthy narrative poem *Syphilis sive morbus Gallicus* (1530; *Syphilis: Or, A Poetical History of the French Disease*, 1686), consisting of three books of some thirteen hundred hexameters. In the first book, Girolamo Fracastoro describes the horrors of the disease, which had appeared in 1495 and after a few years spread across the whole European continent. The second book is devoted to preventatives and cures, and the third to an extended tale of Christopher Columbus's voyage to the West Indies and the discovery of the Holy Tree (the guaiacum), which offered a remedy. What is most notable about the poem is Fracastoro's steadfast belief that syphilis could be traced to natural causes, which, no matter how difficult the job, would eventually be understood:

Nor can th'infection first be charged on Spain
That sought new worlds beyond the Western main.
Since from Pyrene's foot, to Italy
It shed its bane on France while Spain was free.

. . . 'tis plain this Pest must be assigned
To some more pow'rful cause and hard to find. . . .

Since nature's then so liable to change
Why should we think this late contagion strange?

The offices of nature to define
And to each cause a true effect assign
Must be a task both hard and doubtful too.

[But] nature always to herself is true.

Source: From Girolamo Fracastoro, *Syphilis*, quoted by Stephen Jay Gould in "Syphilis and the Shepherd of Atlantis: Renaissance Poem About Syphilis Attempts to Explain Its Origin." Available at www.findarticles.com. Accessed September, 2005.

Fracastoro described the causative agents of syphilis as "seeds" or "seminaria." Since the first microorganisms were not seen until the 1670's and 1680's by Antoni van Leeuwenhoek and others, it is unlikely that Fracastoro envisioned the seminaria as the microorganisms described by those scientists. However, Fracastoro did propose three modes of transmission of seminaria between individuals. In the 1546 treatise, he states that diseases could be transmitted by direct contact, indirectly by contact with infected objects such as dirty linens, or across a distance by contaminated air.

Fracastoro was able to apply his theories to practical situations. When plague broke out in Verona, Fracastoro left for Lake Garda. There he practiced medicine from his country house and served as physician to Pope Paul III. After the Treaty of Crespi (1544) ended the wars between the Holy Roman Emperor Charles V (r. 1519-1558) and the French king Francis I (r. 1515-1547), Pope Paul III convened the Council of Trent (1545-1563). The purpose of the council was to address important questions of Catholic faith and discipline including the canonization of the Scriptures. The council met seven times, but an outbreak of the plague disrupted the work of the council. Fracastoro urged that the Council of Trent be moved to Bologna to avoid the contagion of the plague. However, members of the council who supported Charles V refused to leave, and Pope Paul III postponed the meeting indefinitely in April, 1547, to avoid a schism within the Church.

Animalcules and Spontaneous Generation

Fracastoro's description of disease transmission and contagion did not immediately lead to the development of sterile techniques or successful treatments directed at the "seminaria" that he believed caused diseases. In fact, more than three hundred years passed after the 1546 publication of *De contagione et contagiosis morbis et eorum curatione* before the modern germ theory of disease was developed by Louis Pasteur and Robert Koch. The development of the modern germ theory required several technological and intellectual developments, including the design of the compound microscope, with which Leeuwenhoek first observed microorganisms, or as he called them, animalcules.

Additionally, the theory of "spontaneous generation" of organisms had to be disproved before the science of modern bacteriology could develop. This theory held that life could arise spontaneously out of inanimate matter (as appeared to be the case when maggots appeared in dead meat); Leeuwenhoek held that life could arise only from life, and eventually Lazzaro Spallanzani (1729-1799) disproved spontaneous generation through experiments he conducted in 1765.

In the early 1860's, Louis Pasteur (1822-1895) concluded that "diseases of wine" were caused by microorganisms, or "germs." Shortly after, Joseph Lister (1827-1912) extended Pasteur's work to show that microorganisms cause infection in wounds, and he developed antiseptic techniques in surgery.

IMPACT

In many ways Fracastoro's theories culminated in the work of Koch, who in 1876 developed the germ theory of disease through which he identified the bacterium (now known as *Bacillus anthraxis*) responsible for causing anthrax. In this work, Koch used four steps to prove that the bacterium caused anthrax. He first isolated the bacterium from all of the infected animals; next he grew anthrax bacteria in "pure culture" in the laboratory; then he infected a healthy animal with the cultured bacteria; and finally he re-isolated the same bacteria from the infected test animal after it developed the disease. These same steps are followed by twenty-first century epidemiologists as they search for the causes of emerging diseases.

See also AIDS; Antisepsis; Diphtheria Vaccine; Galen's Medicine; Germ Theory; Greek Medicine; Human Immunodeficiency Virus; Hybridomas; Immunology; Oncogenes; Penicillin; Polio Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Streptomycin; Viruses; Yellow Fever Vaccine.

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—*Michele Arduengo*

CONTINENTAL DRIFT

THE SCIENCE: Alfred Lothar Wegener proposed that all lands were once part of the supercontinent of Pangaea, which then fragmented and whose pieces drifted apart to form present-day continents.

THE SCIENTISTS:

Alfred Lothar Wegener (1880-1930), German meteorologist and earth scientist

Frank Bursley Taylor (1860-1938), American student of geology and astronomy

Alexander Logie Du Toit (1878-1948), South African geologist

Arthur Holmes (1890-1965), British geologist

A GIANT JIGSAW PUZZLE

The concept of continental drift was developed, at least in part, to explain the striking parallelism between the coasts of continents bordering the Atlantic Ocean, which seem as though they could fit together as pieces of a giant jigsaw puzzle. In particular, the fit between the eastern coast of South America and the Western coast of Africa is very striking.

The idea that continents were once joined together as part of a single landmass has been around for several centuries. As early as 1620, the English philosopher and author Sir Francis Bacon had discussed the possibility that the Western Hemisphere had once been joined to Africa and Europe. In 1668, a scientist by the name of Placet expressed similar ideas. Antonio Snider-Pellegrini in his book *La Création et ses mystères dévoilés* (1859; creation and its mysteries revealed) recognized the similarities between American and European fossil plants of the Carboniferous period (about 300 million years ago) and proposed that all continents were once part of a single landmass.

By the end of the nineteenth century, Austrian geologist Eduard Suess had noticed the close correspondence between geological formations in the lands of the Southern Hemisphere and had fitted them together into a single landmass he termed Gondwanaland. In 1908, Frank Bursley Taylor of the United States, and in 1910, Alfred Lothar Wegener of Germany, independently suggested mechanisms that could account for large, lateral displacements of the Earth's crust and, therefore, how continents could be driven apart. Wegener's work became the center of the debate that has lasted until the present.

Supercontinents

The concept of continental drift was best expressed by Wegener in his book *Die Entstehung der Kontinente und Ozeane* (1912; *The Origin of Continents and Oceans*, 1924). He based the theory not only on the shape of

At Home in Greenland

Although Alfred Lothar Wegener is now known for his lifelong advocacy of the theory of continental drift, he was also an adventurer and explorer: As a young man, he and his brother Kurt broke the world's record for long-distance balloon travel (52 hours). He also made pioneering expeditions to explore the Greenland ice cap in 1906-1908 and again in 1912. During the 1912 trip, he and Danish explorer J. P. Koch made the first successful east-west 1,000-kilometer crossing of the ice cap at its widest point, using sledges hauled by ponies.

Wegener was therefore no stranger to polar expeditions when he agreed to lead the German Inland Ice Expedition of 1930. The jet stream—the fast-moving current in the upper atmosphere which circles the Earth in northern latitudes—had just been discovered, and the expedition's goal was to establish three year-round stations on the Greenland ice cap in order to study jet stream flow. The expedition was also to make pioneering measurements of the thickness of the ice cap using echo-sounding techniques.

Two of the three stations were to be on opposite coasts, and the third, named Eismitte (mid-ice), was to be in the center of the ice cap at an elevation of 3,000 meters. Two members of the expedition had already set up a temporary camp there by the fall of 1930. Their quarters consisted of a pit dug into the ice and roofed over.

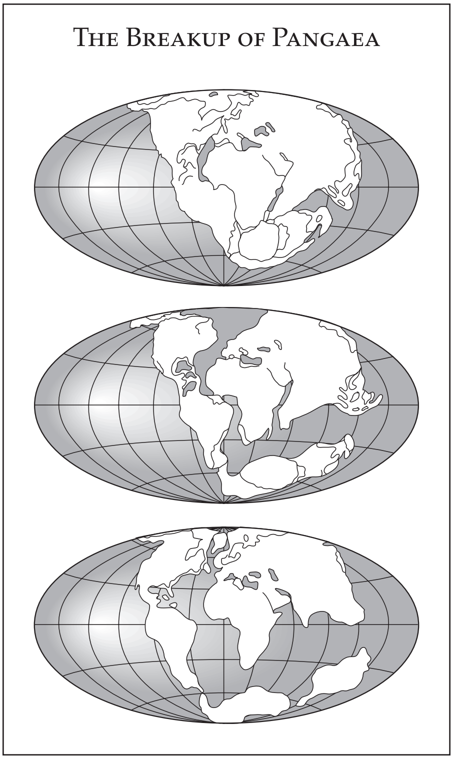
Wegener and a fourth member followed with the necessary supplies but did not arrive until October 29 because of bad weather. Most of the supplies had been lost en route, so Wegener and his Eskimo companion decided to return to the coastal base before the onset of the polar night. They never made it. Wegener's body was later found halfway back, neatly sewn into his sleeping bag and buried in the snow with upright skis as a marker. His Eskimo companion apparently had gone on, but no trace of him or his sledge was ever found.

the continents but also on geologic evidence found around the world. Wegener specifically cited similarities in fossil fauna and flora (extinct animals and plants) found in Brazil and Africa. A series of maps were developed to show three stages of the drift process, and the original supercontinent was named Pangaea (a word meaning "all lands").

Wegener believed that the continents, composed of light-density granitic rocks, were independently propelled and plowed through the denser basalts of the ocean floor driven by forces related to the rotation of the Earth. He provided evidence based on detailed correlations of geological features and fossils indicating a common historical record on both sides of the Atlantic. He also proposed that the supercontinent of Pangaea existed before the beginning of the Mesozoic era (about 200 million years ago).

The split of Pangaea was visualized as beginning during the Jurassic period (about 190 million years ago), with the southern continents moving westward and toward the equator. South America and Africa began to drift apart during the Cretaceous period (70 million years ago). The opening of the north Atlantic was accomplished during the Pleistocene epoch (approximately 2.5 million years ago). Greenland and Norway started to separate as recently as 1.5 million years ago.

The Indian peninsula drifted northward, colliding with the Asian continent and giving rise to the folded mountains of the Himalayas. Similarly, the European Alps and the Atlas Mountains of North Africa were explained as a westward extension of the Himalayan chain. Wegener also suggested that as the drifting continents met the resistance of the ocean floor, their leading edges were compressed and folded into mountains. In this way, he also explained the Western Cordillera of the Ameri-


THE BREAKUP OF PANGAEA

Alfred Wegener theorized that the continents began as one great landmass, Pangaea, more than 200 million years ago (top), which drifted apart beginning about 190 million years ago (middle), eventually resembling the world as we know it today (bottom).

cas and the mountains of New Zealand and New Guinea. The tapering ends of Greenland and South America and the island arcs of the Antilles and East Asia were visualized as stragglers trailing behind the moving continents. Periods of glaciation found in the southern part of South America, Africa, Australia, peninsular India, and Madagascar provided further evidence of drift.

Detailed studies by the South African geologist Alexander Logie Du Toit provided strong support to Wegener's concepts. Du Toit postulated two continental masses rather than the single entity of Pangaea. He visualized the northern supercontinent of Laurasia and its southern counterpart, Gondwanaland, separated by a seaway called Tethys. Du Toit was also the first to propose that the continental masses of the Southern Hemisphere had moved relative to the position of the South Pole. His ideas were published in *Our Wandering Continents* (1937), a book he dedicated to Wegener.

IMPACT

Although Wegener and Du Toit had provided compelling evidence in favor of the drift theory, one monumental problem remained: What forces could be strong enough to rupture, fragment, and cause the continents to drift? Arthur Holmes of the University of Edinburgh was the originator of the concept of thermal convection in the Earth's mantle as the main cause of drift. Holmes's model, published in 1931, was very similar to that presently used in the widely accepted theory of plate tectonics (the modern version of Wegener's theory). Holmes was also the first to introduce the idea that the continents are being carried along by a moving mantle in a sort of conveyor-belt motion.

Although appealing, Wegener's theory of continental drift remained controversial and was not widely accepted until the American geologist Harry Hammond Hess and the American geophysicist Robert Sinclair Dietz introduced the theory of seafloor spreading in the early 1960's. Once seafloor spreading was understood, the theory of continental drift was transformed into the concept of plate tectonics, which remains as one of the most significant theories in earth science. Indeed, with the discovering of the mid-oceanic rifts the concept of plate tectonics has come to be accepted by most earth scientists worldwide.

See also Earth's Core; Earth's Structure; Geomagnetic Reversals; Hydrothermal Vents; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating; Seafloor Spreading.

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—*Robert G. Font*

COPERNICAN REVOLUTION

THE SCIENCE: Copernicus's work *De revolutionibus* (*On the Revolutions of the Heavenly Spheres*) replaced the ancient Greek idea of an Earth-centered solar system, the geocentric model, with the modern heliocentric model that placed the Sun at the center of the solar system.

THE SCIENTISTS:

Nicolaus Copernicus (1473-1543), astronomer
Rheticus (1514-1574), Austrian astronomer and mathematician
Andreas Osiander of Wittenberg (1498-1552), Protestant scholar who oversaw publication of *De revolutionibus*

SEEKING THE CENTER OF THE UNIVERSE

Since at least ancient times, humans have been fascinated with the motion of the objects in the sky. They recognized that most of these objects, the stars in particular, appeared to rotate in circles around the fixed pole star, Polaris, in the Northern Hemisphere, as if the stars were fixed to a rigid sphere that surrounds the Earth and that rotated once each day.

More than two thousand years ago, humans recognized that there were several unusual objects in the sky, called the wanderers, because they appeared to move relative to the stars. In addition to the Sun and the Moon, these wanderers included five planets visible without telescopes: Mercury, Venus, Mars, Jupiter, and Saturn. The paths of these wanderers were observed and recorded. Astronomers wanted to know what caused the motion of the wanderers and how this motion could be predicted, while astrologers believed the positions of these wanderers influenced the daily lives of individuals on Earth.

The Ptolemaic Model

Ancient Greek philosophers tried to develop models for the motion of the wanderers that would be in accord with all past measurements and allow prediction of their future positions. The most successful among them, the Greek philosopher Ptolemy (c. 100-c. 178 C.E.), constructed a model in which all the objects in the sky moved around the Earth on progressively larger concentric circles. This model, however, did not accurately predict the motions of the wanderers, so Ptolemy fixed the planets to other circles that rolled around larger concentric circles.

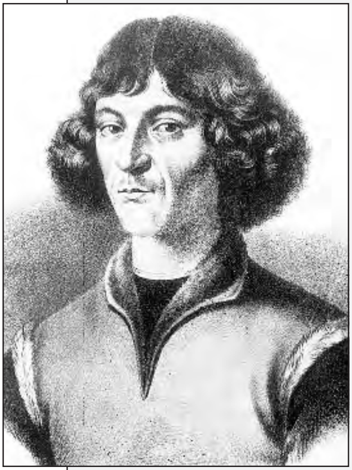
The Ptolemaic model, as it came to be called, was later adopted by Roman Catholic religious leaders because it was consistent with their idea that humans were a "special creation" of God, and thus it seemed appropriate for humankind to occupy a "special position" at the center of all creation. The Ptolemaic model dominated religious thinking in Europe as Europe emerged from the Middle Ages.

The Heliocentric Model

This idea that the Earth occupied a special position in the solar system was challenged by Nicolaus Copernicus, an astronomer and a Roman Catholic canon of the Church. Copernicus, who was born in the Prussian city of Thorn (modern Toruń, Poland), received his advanced education in Italy, where he studied astronomy, mathematics, and medicine and received a doctor's degree in canon law. Copernicus's long service in the religious office as canon of Ermland made him an odd candidate to defy Church teachings, but his study of astronomy led him on a path of conflict with the Church.

Copernicus was an avid observer who compiled twenty years of observations of the positions of the wanderers in the sky. By combining his observations with those recorded by earlier observers, Copernicus was able to observe flaws in the predictions of Ptolemy's model. By 1513, when Copernicus returned to Poland from Italy, he had formulated his own model of the motion in the solar system, reviving an idea proposed more than seventeen hundred years earlier by Greek astronomer Aristarchus of Samos. In the Copernican model, the Sun was stationary at the center of the

COPERNICUS: FACING RELIGIOUS CONTROVERSY


(Library of Congress)

Nicolaus Copernicus was so utterly unremarkable that few anecdotes about him exist, leaving relatively little information about his personal life. At one time or another, he was a medical doctor, an astrologer, a cartographer, an administrator of episcopal lands, a diplomat, a garrison commander in wartime, an economic theorist, an adviser to the Prussian diet (parliament), and a guardian to numerous nieces and nephews. Yet two facts stand out: He was a Humanist, and he was a bureaucrat whose busy life made it difficult for him to make the observations on which his famous theory was based.

About 1507, he was persuaded that the Ptolemaic system—which asserted that the Earth was the center of the universe—was incorrect. From that point on, he spent every spare moment trying to demonstrate the correctness of his insight that the Sun was the center of the planetary movements. For years, his work was interrupted by war, then his effort to restore the finances of his native Ermland. As conflict between Lutherans and Catholics became strident—fanatics on both sides demanding that all parties commit themselves to a struggle against ultimate evil—Copernicus sought to avoid this controversy but could not. The Ermland bishop, Johann Dantiscus, sought to rid himself of all who gave the appearance of Protestant leanings, and his eye fell on Copernicus, whose friends were prominent Protestants. Copernicus became isolated from friends and family.

In 1539, a Lutheran mathematician at Wittenberg, Rheticus, visited Copernicus. Finding him ill and without prospect of publishing the theories he had worked so hard to develop, Rheticus extended his stay so he could personally copy Copernicus's manuscripts and then arranged for their printing under the supervision of Protestant scholar Andreas Osiander of Wittenberg. Osiander, however, saw that Copernicus was treading on dangerous ground by suggesting a view of the universe different from the one accepted by the Church. Fearing that the theory would be rejected without a fair hearing, Osiander wrote an unauthorized introduction (which readers assumed was by Copernicus) in which he stated that his solar system was merely a hypothesis. This angered Copernicus considerably, but he was too ill to do anything about it. Nevertheless—with a justice that is all too rare in this world—a copy of *De revolutionibus* arrived in time for him to know that his life's work would survive.

solar system, with the Earth and the other planets moving around the Sun in concentric circular orbits. Copernicus wrote: "As if seated on a royal throne, the Sun rules the family of planets as they circle around him." The Earth, in this model, was reduced to the status of one of the several planets circling around the Sun. It held no special status from a location at the center of all creation.

Copernicus circulated his idea among his friends in a manuscript entitled *Commentariolus* (1514; English translation, 1939). This manuscript asserted that "The center of the Earth is not the center of the universe. . . . All the spheres revolve around the Sun, as if it were in the middle of everything." Copernicus recognized, however, that his idea was contrary to the teaching of the Church. Therefore, he refrained from widespread distribution of this manuscript. Nevertheless, Pope Clement VII became aware of *Commentariolus* in 1533 but took no action to suppress Copernicus's idea.

The first serious attack on Copernicus's model came from Protestant religious leaders. Martin Luther said of Copernicus, "This fool wants to turn the whole art of astronomy upside down! But as the Holy Scripture testifies Joshua bade the Sun to stand still, not the earth." Luther's appeal to Scripture, and thus faith in the word of God, to explain the behavior of nature was in sharp contrast to Copernicus's belief that the behavior of natural objects could be understood by a combination of observation or experimentation and reasoning in what has come to be called the scientific method.

DE REVOLUTIONIBUS

Perhaps because of the attacks by religious leaders, Copernicus did not publish the full description of his idea, in *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*, 1952; better known as *De revolutionibus*), until 1543. Georg Joachim, called Rheticus, a professor of mathematics, had heard of Copernicus's idea and then journeyed to Ermland in 1539 to learn more about it from Copernicus himself. Rheticus encouraged Copernicus, who was nearing seventy years of age, to commit his ideas to writing. Copernicus agreed.

He divided the text of *De revolutionibus* into six parts: the first, and most controversial, concerned the arrangement of objects within the solar system; the second contained his new star catalog; the third covered precession, that is, how the motion of the Earth's pole causes the fixed star about which the sky appears to rotate to change with time; the fourth discussed the Moon's motions; and the fifth and sixth examined the motions of the planets.

The book was typeset in Nuremberg, Germany, initially under the supervision of Rheticus. Andreas Osiander, who took over supervision when Rheticus left Nuremberg, wrote to Copernicus in 1541, urging him to avoid a direct attack on the teachings of the Church about the arrangement of the solar system. Osiander suggested that the introduction to *De revolutionibus* should indicate that either the hypothesis of Copernicus or that of Ptolemy could explain the observed planetary motion. Copernicus rejected this, but Osiander removed the introduction Copernicus had written and substituted his own preface, which emphasized that *De revolutionibus* presented a hypothesis. Since Osiander did not sign the new preface, readers generally assumed it was written by Copernicus, who did not see a copy of the printed work until he was near death in 1543.

Osiander's preface might have kept Roman Catholic theologians from attacking the book for some time. *De revolutionibus* was not placed on the *Index librorum prohibitorum* (the *Index of Prohibited Books*) of the Roman Catholic Church until 1616, when the Holy Office in the Vatican began its investigation of the astronomer Galileo Galilei, who had spoken openly of his admiration for the work of Copernicus. At that time the Holy Office pronounced the idea of a Sun-centered solar system to be "foolish and philosophically absurd." In the intervening years, Roman Catholic leaders faced another challenge to the special status of the Earth and of humankind. Giordano Bruno, an Italian astronomer, philosopher, and Catholic cleric, was burned alive in 1600 for suggesting that the universe might contain other inhabited worlds.

IMPACT

Although Christian religious leaders rejected Copernicus's work, it was widely adopted by astronomers and astrologers throughout Europe as the method to predict planetary positions because of the simplicity of calculating the positions using this method.

The publication of *De revolutionibus* began what is called the Copernican Revolution. Copernicus's work influenced later European astronomers, including Johannes Kepler and Galileo Galilei, and set the stage for the adoption of the Sun-centered model of the solar system by the scientific world. Kepler replaced the concentric circles of the Copernican model with elliptical paths for the planets and removed all the remaining discrepancies between observed planetary positions and the predictions of the Sun-centered model. Galileo, whose *Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano* (*Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*, 1661) was published in 1632, firmly established the Sun-centered solar system in the minds of European astronomers.

See also Brahe's Supernova; Heliocentric Universe; Inflationary Model of the Universe; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mayan Astronomy; Speed of Light.

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—George J. Flynn

COSMIC MICROWAVE BACKGROUND RADIATION

THE SCIENCE: Arno A. Penzias and Robert W. Wilson discovered that the sky is filled with a uniform background radiation, supporting the view that the universe began with a "big bang."

THE SCIENTISTS:

- *Arno A. Penzias* (b. 1933), German-born radio astronomer and cowinner of the 1978 Nobel Prize in Physics
- *Robert W. Wilson* (b. 1936), American radio astronomer and cowinner of the 1978 Nobel Prize in Physics
- *Robert H. Dicke* (1916-1997), experimental physicist at Princeton University

RADIO SIGNALS

In 1961, Arno A. Penzias completed a doctoral thesis on the use of masers (which stands for microwave amplification by the stimulated emission of radiation) to amplify and then measure the radio signal coming from intergalactic hydrogen, the most abundant element in the universe. Penzias would note in his 1978 Nobel Prize lecture that the equipment-building went better than the observations. At the suggestion of Charles Hard Townes, who would win the 1964 Nobel Prize in Physics for his work on masers and lasers (light amplification by the stimulated emission of radiation), Penzias began working for Bell Laboratories. He wanted to use Bell's 6-meter horn-shaped radio antenna to continue the observations he had begun in his dissertation.

FROM DUNG TO GOLD

In 1963, Arno Penzias and Robert Wilson got permission from Bell Labs in Holmdel, New Jersey, to use the company's horn-shaped radio antenna to study radio waves coming from the Milky Way. However, they were surprised to note that the antenna continuously emitted an excess noise of about 3 Kelvins. "We call it noise because it's completely unstructured, it's random signals," Wilson said.

Then they noticed that pigeons were roosting inside the horn. Could they be the source of the random noise? After trapping them and releasing them miles from the site of the antenna, the two researchers were dismayed to see the birds return to their home. Ivan Kaminow, one their colleagues at Bell Labs, recalled Penzias and Wilson's frustration: "They spent hours searching for and removing the pigeon dung. Still the noise remained." Penzias and Wilson finally decided to kill the pigeons. "It seemed like the only way out of our dilemma," recalled Penzias. The noise, however, remained: Everywhere they pointed the antenna, they picked up the faint hiss of excess noise. From all directions, it seemed, the entire universe was mocking them in a whisper.

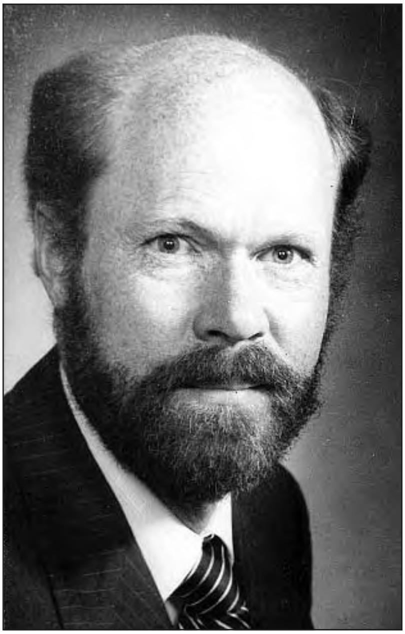
When they finally learned of the work of Robert H. Dicke and P. J. Peebles, which predicted that a low-level background radiation would exist throughout the universe as a residue of the big bang, they realized what they were hearing. As Kaminow put it, "they looked for dung but found gold, which is just opposite of the experience of most of us."

Source: Quotations from Bell Labs, history page, http://www.bell-labs.com/history/laser/invention/cosmology.html. Accessed September, 2005.

Robert W. Wilson was also using masers to amplify weak astronomical radio signals. Wilson was helping in the making of a map of the radio signals from the Milky Way. He also wanted to use the horn antenna to do pure research. Bell Laboratories let Penzias and Wilson spend half of their time doing applied research in the field of radio astronomy.

Arno Penzias. (The Nobel Foundation)

The horn antenna had originally been designed in 1960 to collect and amplify the weak radio signals that were bounced off a large balloon that orbited Earth. Called Echo, this early telecommunications satellite was used to send radio signals over very long distances by "passive relay" (simply bouncing the signal off its surface). Telstar, the first telecommunications satellite that amplified incoming signals, replaced the Echo system. Nevertheless, Echo at the time was essentially the world's most sensitive radio telescope.



Robert Wilson. (The Nobel Foundation)

In 1963, while getting ready to make their delicate observations, Penzias and Wilson began to identify and measure the various sources of "noise" (unwanted radio signals or other interfering signals) in the antenna. One source of noise was the thermal noise of the antenna itself: The electrons in the atoms of the antenna underwent random thermal motion that generated weak radio signals. E. A. Ohm, one of the engineers on the Echo project, had noted in 1961 an "excess" noise of 3 Kelvins. Little notice was taken of this observation, because the amount of discrepancy was small enough not to upset the functioning of the Echo project. Identifying and eliminating such excesses was crucial, however, for the kinds of sensitive astronomical observations Penzias and Wilson intended to make.

What's Making That Noise?

Penzias and Wilson spent much time and energy trying to track down the source of this excess noise. They ruled out artificial sources by pointing the antenna at New York City and noticing no added noise. They ruled out radiation from the galaxy and from extraterrestrial radio sources. They evicted a pair of pigeons that had taken up residence in the antenna. No change in the amount of noise was seen, even after the antenna had been cleaned of pigeon droppings. They put metallic tape over the riveted joints of the antenna yet noticed no change. By now it was spring, 1965, and more than a year had passed since the first measurement of the excess noise.

Two additional sources of noise were ruled out because of the long period of observation. First, any source in the solar system would have exhibited variation as Earth moved in its orbit, yet no variation was seen. Second, if the excess noise was what was left over from a 1962 aboveground nuclear test, then the noise should have decreased as the radioactivity decreased. No change, however, was seen. As it would turn out, Penzias and Wilson would later win Nobel Prizes for their work in pursuing the source of the stubborn noise.

Big Bang in the Background

The "answer" to their problem was that there was no instrument error or random noise. What Penzias and Wilson had measured was in fact a uniform radio signal in the microwave region of the spectrum coming from all directions. They called Bernard Burke at the Massachusetts Institute of Technology and told him of the mysterious noise. Burke recalled hearing of the work of P. J. Peebles, then working with Robert H. Dicke at Princeton University. Penzias and Wilson received a preprint of Peebles's paper that calculated that the universe should be filled with a background radiation of about 10 Kelvins (later revised downward). This radiation was thought to be the aftermath of the hot and highly condensed first few minutes of the life of the universe: the so-called big bang.

Penzias and Wilson's measurement of the cosmic microwave radiation represented an interesting case study in the history of science. On numerous occasions for at least twenty years before the 1965 measurements, both theoreticians and experimentalists had run across "evidence" for a 3-

Kelvin cosmic radiation. After completing their measurements, Penzias and Wilson learned of the work of the American physicist George Gamow (who first came up with the ideas that led to the big bang theory) and others in the late 1940's, which led to a prediction of 5 Kelvins for the background radiation. Astrophysicists in the Soviet Union and England, working independently of Peebles, performed calculations that also indicated about 5 Kelvins for the background radiation. Probably the most ironic of these measurements was by Dicke himself in the 1940's. His measurement of the maximum background cosmic radiation was a byproduct of his research on the absorption of radio signals by the Earth's atmosphere. By the 1960's, he had forgotten about his own measurements made twenty years earlier.

IMPACT

Penzias and Wilson's measurement of the cosmic microwave background radiation has been called one of the most important scientific discoveries in the twentieth century. The demonstration of the cosmic microwave background radiation, combined with the earlier demonstration by the American astronomer Edwin Powell Hubble that the galaxies are receding (and the universe expanding), provided very strong evidence for the big bang model of the universe. By the mid-1970's, a new name had been coined for the big bang model—astronomers simply referred to it as the "standard model."

In the 1950's, few scientists were willing to spend a lot of time studying the early universe. Among other things, there was just not enough experimental or theoretical evidence to back up the notion of the early universe. In the decades after Penzias and Wilson's measurement, the big bang model was developed by the work of many other physicists. The early universe now had become a respectable field in which to work.

See also Big Bang; Expanding Universe; Gravitation: Einstein; Inflationary Model of the Universe; Jupiter's Great Red Spot; String Theory; Wilkinson Microwave Anisotropy Probe.

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—*Roger Sensenbaugh*

COSMIC RAYS

THE SCIENCE: Robert Andrews Millikan and his colleagues proved that upper atmospheric radiation was of extraterrestrial origin and led in its exploration.

THE SCIENTISTS:

Robert Andrews Millikan (1868-1953), American physicist who won the 1923 Nobel Prize in Physics

Victor Franz Hess (1883-1964), Austrian physicist who shared the 1936 Nobel Prize in Physics with Carl David Anderson

Arthur Holly Compton (1892-1962), American physicist who won the 1927 Nobel Prize in Physics

Werner Kolhörster (1887-1946), German physicist

RADIATION IN THE ATMOSPHERE

Cosmic radiation was discovered by the Swiss physicist Albert Gockel in 1910. It was the Austrian physicist Victor Franz Hess, however, who first proposed that the radiation was of extraterrestrial origin.

Hess had been working on the problem of air ionization, a phenomenon known since the beginning of the twentieth century. It was initially supposed that this slight ionization was caused by radioactive elements in the Earth. This meant that at greater altitudes the radiation should decrease.

Yet in 1911, when Hess ascended in a balloon to 5,200 meters, he found that the radiation increased above 2,000 meters and that above 3,000 meters there was an even sharper rise in intensity. Hess concluded that the "penetrating radiation," as it was then known, entered the atmosphere from above. Hess's work was confirmed in 1913 by Werner Kolhörster, a German physicist who made a balloon ascent to 9,000 meters.

Not all physicists believed the explanation Hess and Kolhörster gave, however, and even the very existence of the radiation remained in some doubt. The idea that a strong source of radiation existed in outer space was simply unimaginable to some scientists. Some believed that radioactive uranium and thorium in the soil caused the radiation. Others believed that the equipment used by Hess was flawed. Still others sought a compromise position, believing that the radiation was produced somewhere higher up in the Earth's atmosphere, something that Hess admitted was a possibility. Robert Andrews Millikan, an American physicist, decided to try to settle the matter.

RAYS FROM OUTER SPACE

Millikan's first experiments were carried out in 1921-1922 and involved sending a number of sounding balloons into the atmosphere. These experiments were inconclusive. More tests were performed in 1922 and 1923 and were similarly inconclusive.

Then, in the summer of 1925, Millikan designed an experiment to determine the penetrating power of the rays, which had not yet been measured. If the rays were of external origin, they would have to have a penetrating power great enough to get through the atmosphere, which was equivalent to penetrating 10 meters of water. The strongest rays produced by known radioactive elements could not penetrate more than about 2 meters of water.

With his assistant, George Harvey Cameron, Millikan took measurements from two California lakes, Muir Lake (elevation 3,650 meters), near Mount Whitney, and Lake Arrowhead (elevation 1,500 meters). At Muir Lake, Millikan and Cameron lowered their electroscopes into the water. They found that the radiation, coming exclusively from above, was eighteen times greater than that of the strongest known gamma ray (gamma rays are the strongest of the three types of radioactive emissions). This radiation was strong enough to penetrate the atmosphere, proving that the radiation certainly could come from space.

At Lake Arrowhead, Millikan and Cameron found that the readings were identical to the Muir Lake readings when the difference in lake elevation was taken into account. This proved to Millikan that the atmosphere played no part in transmitting the rays but acted merely as an absorbing medium. Millikan now believed that the rays came from outer space.

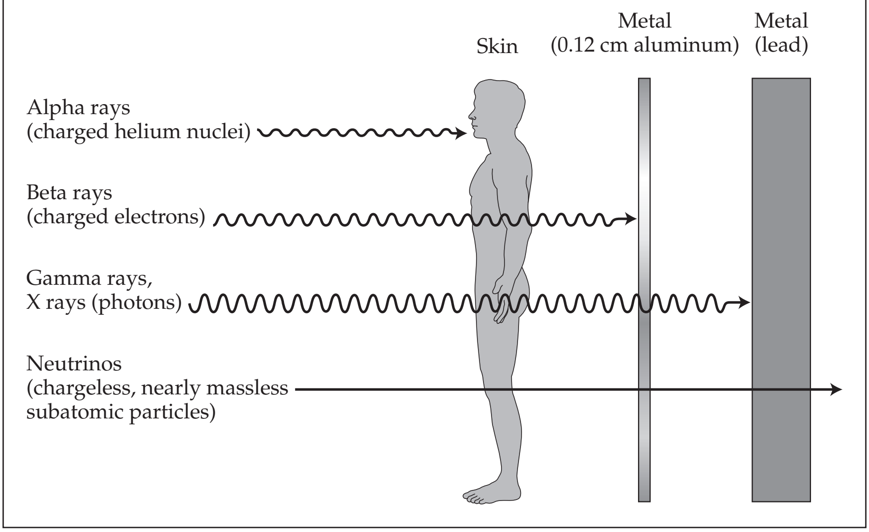
In late 1925, before a meeting of the National Academy of Sciences, Millikan announced his findings, calling the new radiation "cosmic rays." He believed that since the strongest radiation previously known was that produced in radioactive transformations, these cosmic rays were the result also of some sort of nuclear charge. The strongest rays on Earth were photons (particles of electromagnetic radiation), which were produced when helium was produced from hydrogen atoms and when an electron was captured by a light nucleus. Millikan inferred, therefore, that cosmic rays were photons produced from some type of atom formation.

Millikan next tested his assumption that cosmic rays were composed of high-energy photons. In a 1926 trip to Lake Titicaca in South America, he noticed almost no difference between the findings there and at Muir Lake. If cosmic rays had instead been composed of charged particles, the Earth's magnetic field would have affected the radiation distribution across the globe. Measurements on the return boat trip from Peru to Los Angeles also showed no variation.

IMPACT

The notion that photons were the primary constituents of cosmic rays was challenged in 1929. Kolhörster and German physicist Walther Bothe, after a series of experiments with a Geiger-Müller counter, concluded that cosmic rays were, in fact, composed of charged particles. Following this

FORMS OF COSMIC RADIATION



Different forms of cosmic radiation can penetrate different forms of matter: Alpha rays cannot penetrate skin; beta rays can penetrate skin but not metal; gamma rays can penetrate both but are stopped by lead; and neutrinos—chargeless, nearly massless particles—can penetrate even lead, making them extremely difficult to detect. Although neutrinos interact very little with matter, they are believed to be produced in the nuclear reactions at the core of the Sun and other stars and may constitute a large portion of the "missing mass" of the universe.

work, many physicists turned to the problem of which model was correct.

The decisive experiment was made by Nobel laureate Arthur Holly Compton. He turned again to the question of what effect, if any, the Earth's magnetic field had on the intensity of cosmic rays. Even though Millikan, and later Kolhörster, failed to notice any appreciable difference, a growing body of work, beginning in 1927, pointed toward a "latitude effect." In 1932, Compton organized a massive survey of the globe, trying to detect such an effect. By September, 1932, the results of the survey showed that there was, indeed, a latitude effect, and thus that cosmic rays were composed at least partly of charged particles, a fact that Millikan was forced to accept.

See also Compton Effect; Cosmic Microwave Background Radiation; Gamma-Ray Bursts; Wilkinson Microwave Anisotropy Probe; X-Ray Astronomy.

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—*George R. Ehrhardt*

CRO-MAGNON MAN

THE SCIENCE: Louis Lartet's discoveries at a rock shelter called Cro-Magnon in Les Eyzies in the Dordogne region of France led to the discovery and establishment of “Cro-Magnon man” as the earliest known example in Europe of the subspecies *Homo sapiens sapiens*, to which modern human beings belong.

The Scientists:

Édouard Hippolyte Lartet (1801-1871), French archaeologist, one of the founders of modern paleontology

Louis Lartet (1840-1899), French geologist and paleontologist, son of Édouard

Henry Christy (1810-1865), English ethnologist

A Love of the Past

Édouard Hippolyte Lartet, one of the founders of modern paleontology, made three important contributions to the field. First, believing that the Stone Age was not a single phase in human evolution, he proposed dividing it into a series of phases and established a system of classifications to that end; his research led to the establishment of the Upper Paleolithic as a distinctive period of the Stone Age. Second, he discovered the first evidence of Paleolithic art; although he had completed a degree in law after studying at Auch and Toulouse and begun the practice of law in Gers, his real interest lay in science, specifically archaeology. In 1834 inspired by the work of Georges Cuvier, he began doing excavations around Auch, France, where he found fossil remains which led him to devote himself full time to excavation and research. He set about a systematic investigation of the caves in the area.

In 1858, he was joined by his friend Henry Christy, an Englishman who had been working in ethnology. Christy, the son of a London hatter, had joined his father’s firm but had become interested in ethnology as a result of his travels. Then he attended the Great Exhibition of 1851 and was so impressed that he, like Lartet, changed careers and devoted the rest of his life to travel and research into human evolution. Lartet and Christy concentrated their work in the caves located in the valley of the Vezere, a tributary of the Dordogne River. By 1861, Lartet had begun publishing the results of his investigations and excavations in the cave of Aurignac, as well as the evidence that he had found of the existence of human beings at the same time as that of a number of extinct mammals.

In 1863, Lartet and Christy became involved in a series of excavations in the Dordogne Valley with sites at Gorge d’Enfer, Laugerie Haute, La Madeleine, Le Moustier, and Les Eyzies. They published several articles on their findings, the most important of which was “Caverns of the Perigord” in the *Revue archéologique*. They had planned to publish a book, *Reliquiae Acquitanicae*, on the research they had done; however, on May 4, 1865, Christy died of lung inflammation. The book was only partially written at this time; Lartet continued working on it, and it finally appeared posthumously in 1875.

A Railway and a Rock Shelter

Lartet continued his work in archaeology and paleontology until his health began to fail in 1870. He died the following year. During this time his son Louis, who was also a paleontologist and a geologist, had begun working with him. In 1868, a railway was being built through the hilly countryside of Les Eyzies-de-Tayac. A crew of workmen who were excavating the hillsides found chipped flints, animal bones, and human remains in a rock shelter called Cro-Magnon.

The contractors in charge of building the railway contacted Louis Lartet, and he took charge of a scientific excavation of the rock shelter. In his excavations he determined that there were five archaeological layers in the rock shelter. In the topmost layer he found human remains, bones of animals belonging to extinct species, and flint that showed evidence of having been worked with tools. Lartet determined that these remains and flints were from the Upper Paleolithic age (a period dating from approximately 35,000 to 10,000 years ago). In the back of the shelter he found five skeletons or parts of skeletons decorated with ornaments, many of which were made from pierced seashells.

It is thought that there were originally remains of ten skeletons found in the shelter but only the fragments of five were preserved and studied. There were parts of skeletons of four adult individuals and of one newborn child. Among the skeletal remains were the cranium and a mandible of a male believed to have been about fifty years old at the time of his death. This specimen became known as the Old Man of Cro-Magnon. It is considered to be a typical example of the peoples who have become known as Cro-Magnon.

Impact

The remains Louis Lartet found in the rock shelter at Cro-Magnon were the first human remains recognized as being from the Upper Paleolithic period. Lartet's discovery advanced the work his father had done on the cultural sequencing of human existence. Édouard Lartet and Henry Christy had found evidence of art that was created during the Paleolithic

UNEARTHING CRO-MAGNON

In 1868, Édouard and Louis Lartet recalled their discovery of Cro-Magnon remains in one of the caves near the Vezère River.

At the back of the cave was found an old man's skull, which alone was on a level with the surface, in the cavity not filled up in the back of the cave, and was therefore exposed to the calcareous drip from the roof, as is shown by its having a stalagmitic coating on some parts. The other human bones, referable to four other skeletons, were found around the first, within a radius of about 1.50 meters. Among these bones were found, on the left of the old man, the skeleton of a woman, whose skull presents in front a deep wound, made by a cutting instrument, but which did not kill her at once, as the bone has been partly repaired within; indeed our physicians think that she survived several weeks. By the side of the woman's skeleton was that of an infant which had not arrived at its full time of foetal development. The other skeletons seem to have been those of men. . . .

Whence came these ancient men of the Vezère? Here the geologist must be silent. His duty is to confirm the facts forming the subject of this introductory notice, as far as they belong to his domain. To the anthropologist we look to enlighten us on the characters of the race. It may, however, be remarked that the seashells associated with the sepulture at Cro-Magnon are in no wise of Mediterranean origin, but belong only to the Atlantic Ocean. . . . This fact may be taken in consideration from the Cro-Magnons together with the circumstance of there being in this sepulture several pebbles of basalt, which could not have been taken from the valley of the Vezère, but might well have been brought from that of the Dordogne. Hence we are led to suppose that before coming to the Cave District, where they found conditions so favorable for their mode of life, the reindeer-hunters had sojourned on our Atlantic coasts, and that they arrived at the banks of the Vezère after having ascended the Valley of the Dordogne.

Source: From Édouard and Louis Lartet, *Reliquiae Acquitanicae*. Quoted in *Eyewitness to Discovery*, edited by Brian M. Fagan (Oxford: Oxford University Press, 1996), pp. 62-68.

period, and Louis Lartet's discovery of the skeletons decorated with ornamentation and the pierced sea shells provided further evidence of intellectual and creative abilities of the human beings of the period.

In addition, the findings at Cro-Magnon showed that the people living during the Upper Paleolithic were deliberately burying their dead—not only placing the bodies in special locations but also preparing the bodies with ornamentation. Thus, the discoveries made in the rock shelter at Cro-Magnon helped to complete the definition of Upper Paleolithic man as a toolmaker, an artist, and a thinking individual who was conscious of past and future, life and death.

In Lartet's opinion the flint tools that he found along with the skeletons linked the Cro-Magnons to the Aurignacian culture that he had identified a few years earlier. The tools had many features characteristic of the tool industry of the Aurignacian period. Lartet's findings at Cro-Magnon also added a phase and new element of terminology to the cultural sequencing of human evolution which his father had created. The Cro-Magnon skeletal remains are the earliest known example in Europe of the subspecies to which humankind belongs. Although Cro-Magnon originally indicated the site at which the rock shelter was located, the term has come to be used in a general sense to refer to the oldest modern people of Europe.

See also *Australopithecus*; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Shawncey Webb*

D'Alembert's Axioms of Motion

The Science: Drawing upon elements of Cartesian and Newtonian thought, d'Alembert formulated a set of laws describing the behavior of bodies in motion. The laws, all derived completely through mathematical calculation, combined to produce a general principle for solving problems in rational mechanics.

The Scientists:

Jean le Rond d'Alembert (1717-1783), French mathematician, physicist, and encyclopedia contributor
Alexis-Claude Clairaut (1713-1765), French Newtonian mathematician
Sir Isaac Newton (1642-1727), English scientist and mathematician
Daniel Bernoulli (1700-1782), Swiss physicist
René Descartes (1596-1650), French philosopher and mathematician

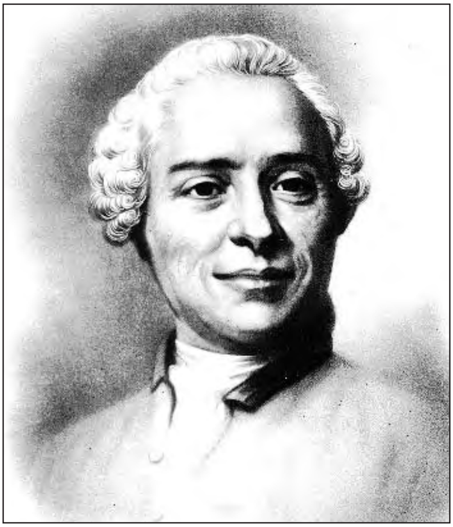
The Cartesians

Jean le Rond d'Alembert is probably best known for his collaboration with Denis Diderot on the *Encyclopédie: Ou, Dictionnaire raisonné des sciences, des arts, et des métiers* (1751-1772; partial translation *Selected Essays from the Encyclopedy*, 1772; complete translation *Encyclopedia*, 1965). His "Discours préliminaire" (preliminary discourse), which prefaced the work, was known and admired throughout Europe, and he was responsible for many of the *Encyclopedia*'s technical articles. A favorite in the salons of Paris, d'Alembert was involved in all aspects of the intellectual life of his century. Beyond these pursuits, however, d'Alembert was a mathematician and scientist of considerable expertise who made significant contributions in the field of rational mechanics. In 1741, he was admitted as a member to the French Academy of Sciences. There he met and competed with men such as Alexis-Claude Clairaut and Daniel Bernoulli.

Newton's Influence

D'Alembert received his first instruction in mathematics at the Jansenist Collège des Quatres Nations. In his classes, he was introduced to the work of Cartesian thinkers such as Pierre Varignon, N. Guinée, Charles Reyneau, and Nicolas Malebranche. Thus, his early education in mathematics was strongly influenced by the ideas of René Descartes. This background did not, however, prevent d'Alembert from recognizing the value of Sir Isaac Newton's work. He read Newton's *Philosophiae Naturalis Principia Mathematica* (1687; *The Mathematical Principles of Natural Philosophy*, 1729; best known as the *Principia*) shortly after 1739 and Colin Maclaurin's *A Treatise of Fluxions* (1742), which gave detailed explanations of Newton's methods, before publishing his own *Traité de dynamique* (1743; treatise on dynamics) and *Traité de l'équilibre et du mouvement des fluides* (1744; treatise on equilibrium and on movement of fluids). D'Alembert believed that mathematics was the key to solving all problems. He rejected the use of experiments and observation. He maintained that rational mechanics was a component of mathematics along with geometry and analysis.

When d'Alembert set about writing his *Traité de dynamique*, an enormous amount of work had already been done on the laws of motion. Much of existing theory was contradictory, however, due to the problems involved in defining terms such as force, motion, and mass. D'Alembert was convinced that a logical foundation applicable to all mechanics could be found through the use of mathematics. Although d'Alembert insisted that he had rejected the theories of Descartes that he had studied in his youth, his approach to mechanics still relied heavily on Descartes's method of deduction. D'Alembert wished to discover laws of mechanics that would be as logical and self-evident as the laws of geometry. Above all, he was determined to "save" mechanics from being an experimental science.


Jean le Rond d'Alembert. (National Library of Medicine)

D'Alembert, like his fellow scientists, was a great admirer of Newton, and Newton's *Principia* was for him the starting point in a study of mechanics. Thus, he developed his laws of mechanics using Newton's work as a model. In his first law, d'Alembert expressed his agreement with Newton's law of inertia, that is, that bodies do not change their state of rest or motion by themselves. They tend to remain in the same state; Newton would say, they remain in the same state until acted upon by a force. D'Alembert also was in accord with Newton's concept of hard bodies moving in a void.

THE PROBLEM OF FORCE

D'Alembert, however, found Newton's second and third laws unacceptable, because they acknowledged force as real and relied upon experiments and observation. The logical geometric basis that d'Alembert sought for the foundation of mechanics allowed no room for experiment and observation. Force was for d'Alembert a concept to be avoided, because it did not lend itself to definition. He rejected not only innate force but all force. In contrast, Newton recognized force as having real existence. D'Alembert acknowledged that bodies would not move unless some external cause acted upon them but defined causes only in terms of their effects. His third law was similar to Newton's third law. Newton had stated that two bodies must act on each other equally. D'Alembert proposed the concept of equilibrium, resulting from two bodies of equal mass moving in opposite directions at equal velocities.

Because of his rejection of force as a scientific concept, d'Alembert was closer in his theories to Malebranche, who viewed the laws of motion as entirely geometrical, than he was to Newton. D'Alembert's laws of motion dealt with idealized geometrical figures rather than real objects. These figures moved through space until they impacted, causing them either to stop or to slip past one another. Change of motion was necessitated by geometry; force was an unnecessary element and only brought into play disturbing metaphysical concepts.

D'Alembert's Principle

From the last two laws of his axioms of motion, d'Alembert derived what is now known as d'Alembert's principle: The impact of two hard bodies either is direct or is transmitted by an intermediate inflexible object or constraint. He applied his principle the next year in his *Traité de l'équilibre et du mouvement des fluides*, which was for the most part a criticism of Bernoulli's work on hydrodynamics. Although d'Alembert had used his principle successfully in his 1743 treatise, however, it failed to be very useful in fluid mechanics.

Impact

During the eighteenth century, opinions about d'Alembert's contributions to science were many and varied. Some of his contemporaries credited him with having successfully found a set of principles for rational mechanics; for some, his work verified Descartes's beliefs that the laws of mechanics could be deduced from matter and motion and that there was no force involved in movement. However, others criticized and rejected d'Alembert, because he refused to accept experimentation and simply eliminated concepts that he found metaphysical and resistant to mathematical expression. His most important contribution was d'Alembert's principle, which provided a general approach to solving mechanical problems. It was one of the first attempts to find simple and general rules for the movements of mechanical systems.

D'Alembert's laws of motion were accepted as the logical foundation of mechanics well into the nineteenth century. Ultimately, however, his refusal to discuss force proved a fatal flaw. Today, Newton's *Principia* is viewed as containing the basic laws of mechanics.

See also Ballistics; Falling Bodies; Gravitation: Newton; Medieval Physics.

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—*Shawncey Webb*

DEAD SEA SCROLLS

THE SCIENCE: The discovery of the Dead Sea scrolls allowed investigators to understand the text of the Old Testament, the early growth of the Christian church, and the nature of Judaism.

THE SCIENTISTS:

Eliezer Sukenik (1889-1953), Polish-born Israeli professor of archaeology who first recognized the age and value of the scrolls

Roland de Vaux (1903-1971), archaeologist who explored the caves and excavated the Qumran ruins

John Strugnell (b. 1930), American professor at Harvard University Divinity School and chief editor of the scrolls since 1987

BEDOUIN DISCOVERY

Accounts of the discovery of the Dead Sea scrolls do not always agree. The number of people involved and the political upheaval at the time seem to have clouded the event, leading to both exaggeration and omission. In the spring of 1947, young Bedouins of the Ta'amireh tribe watched their goats and sheep graze among the cliffs in the wilderness near Khirbet Qumran. Some of the flock had climbed up the cliffs by the end of the day. As Muhammad adh-Dhib and a friend climbed after the animals, they found a cave. Without much thought, one of the shepherds threw a rock inside and was surprised by the sound of breaking pottery. The lateness of the day and awkward entry prevented further exploration; but with hopes of hidden treasure, the shepherds resolved to return.

Days later, they returned and with effort lowered themselves into what would become known as Qumran Cave 1. The floor was covered with debris, but along one wall were several narrow jars. They looked into one, tore the cover from another, but found nothing. Another contained dirt. Finally, in one they pulled out three smelly old leather scrolls wrapped like mummies. They could not read them. Hopes for hidden treasure faded.

The Bedouins could not know that the Hebrew and Aramaic scrolls were the oldest biblical book of Isaiah in Hebrew, a commentary on the biblical book of Habakkuk, and a book of guidelines belonging to a religious sect called *The Manual of Discipline*. A few weeks later, one of the young men returned with other Bedouins to find and remove four more scrolls. These included a second scroll of Isaiah; a damaged but fascinating narrative in the first person, called Genesis Apocryphon; a book of thanksgiving psalms; and a work titled *The War of the Sons of Light Against the Sons of Darkness*. The Bedouins could only hope that perhaps some scholar or collector of antiquities might want the writings on rolled-up sheepskins.

SCROLLS FOR SALE

The political unrest in Palestine did not favor trade and archaeological investigation. English rule was ending, and the Jews wished to establish an independent state of Israel. The English, Jews, and Arabs turned against one another. Acts of terrorism were common, and war was pending. In the middle of this upheaval in early 1947, two of the Bedouins brought the first three scrolls and two of the jars to Bethlehem with hopes of selling them.

One of the Dead Sea scrolls, from "The War of the Sons of Light Against the Sons of Darkness." (Library of Congress)

They contacted George Isaiah and Khalil Iskander Shahin (Kando), who agreed to handle the scrolls for one-third of the eventual sale price. During Holy Week, Isaiah mentioned the scrolls to the Syrian Orthodox archbishop, Mar Athanasius Yeshue Samuel, at St. Mark's Monastery in Jerusalem. Within the week, *The Manual of Discipline* was brought to the archbishop. Samuel could not read the language of the leather scroll but decided to buy the lot. Kando agreed and left with the sample. Weeks passed, and the clergyman began to wonder if he would hear more of the scrolls.

Despite increased violence, Kando and the Bedouins brought the scrolls to Jerusalem in July. One of the fathers at St. Mark's, however, not realizing his archbishop's interest, turned Kando away, and some of the scrolls transferred to yet another dealer. This dealer contacted Eliezer L. Sukenik, a professor of archaeology at the Hebrew University. Sukenik eventually was shown four pieces of leather inscribed in a type of Hebrew script used between 100 B.C.E. and 100 C.E. In November, Sukenik risked traveling to see more scrolls and two of the jars from the cave. He recorded in his diary that this was one of the greatest finds ever made in Palestine. Sukenik was able to purchase three of the seven scrolls. He correctly judged them at a time when faked documents were common.

Archbishop Samuel, in the meantime, had purchased the other four scrolls from Kando but had not been able to determine their value. In late January, 1948, Sukenik asked to see them. He recognized the scrolls as belonging with those he had already purchased. Assurance was given that he would have the first chance to purchase them. Archbishop Samuel, still not sure of the scrolls' value, called on John Trever at the American School of Oriental Research. Trever excitedly sent photographs to William Foxwell Albright of Johns Hopkins University. Albright airmailed his reaction: "incredible . . . there can happily not be the slightest doubt in the world about the genuineness." The discovery of the scrolls was confirmed and announced on April 26, 1948, by Millar Burrows.

A Library in the Wilderness

With thoughts of similar profit, Bedouins began to comb the hills and in 1952 found a second cave at Murabbaat. By 1956, Bedouins and archaeologists had found eleven caves with approximately eight hundred scrolls. Clearly, an ancient library was being discovered. Interestingly, all books of the Hebrew Bible, or Old Testament, were represented at least in part except for Esther. Many copies of some books seem to indicate favorite writings. About one-third of the scrolls were biblical. Others included commentaries on the books of the Bible, a copper scroll that told of hidden treasure, religious writings, a marriage contract, and correspondence by Simeon ben Kozibah (Bar Kokhba), the leader of the second revolt against the Romans. The manuscripts were in Aramaic, Hebrew, and even Greek. Each writing was given a code that indicated the cave number, the geographical area, and the title. The "4QSam" scroll was taken from cave 4 near Qumran and contained the book of Samuel.

Many scrolls were damaged and incomplete. The Bedouins were not as careful as the archaeologists. There was even evidence of deliberate destruction during ancient times. Cave 4, the main library, contained fifteen thousand postage-stamp-sized scraps of some seven hundred different writings. Professor Frank Cross rightly called the situation "the ultimate in jigsaw puzzles."

Besides physically assembling the fragments, archaeologists had to use space-age technologies to reconstruct these manuscripts. For example, the gooey, black Genesis Apocryphon scroll looked as though coffee had been spilled all over it. Nevertheless, when heated with back lights, the carbon ink absorbed more heat than the surrounding leather, and the letters became visible on a new infrared film. Noah's words after the Flood appeared: ". . . we gathered together and went . . . to see the Lord of Heaven . . . who saved us from ruin."

Father Roland de Vaux, an archaeologist who also explored the caves, excavated the nearby ruin of Qumran. Pottery from the caves matched pottery found at Qumran. Coins found at Qumran allowed dating. Pieces of the puzzle began to fall into place. Qumran was occupied for sometime shortly before and during the life of Jesus. *The Manual of Discipline* (a book of rules for a sect) and the Damascus Documents (found in both Qumran and Cairo) indicated that a group of Jews had split off from the group. The ancient historians Pliny, Josephus, and Philo had recorded that a group called the Essenes lived near the Dead Sea. Many scholars concluded that the scrolls belonged to the library of this group. Qumran evidently functioned as a religious center that emphasized baptism, a facility where scribes copied scrolls, and a pottery center to make storage jars.

Biblical Interpretation

The scrolls are extremely important for the understanding of the text of the Hebrew (Old Testament) Scriptures, the background to early growth of the Christian church, and the nature of Judaism at that time.

Before the discovery of the scrolls, scholars had to be content with ninth century medieval texts of the Hebrew Scriptures, called Masoretic texts. Comparisons were often made, however, to an older Greek translation called the Septuagint, which dated from the period 285-246 B.C.E., and a third reference source was the Samaritan Pentateuch. Actual original manuscripts of the Bible are lacking. The scrolls at Qumran, however, allowed investigators to see a thousand years beyond the previous Hebrew texts and opened a new era in textual studies and comparisons.

Norman L. Geisler and William E. Nix call the Bible "the most quoted, the most published, the most translated, and the most influential book in the history of mankind." Any discovery about the Bible that promises more information or new insights excites many. The Hebrew Bible, or Old Testament, is the foundation of both Judaism and Christianity. Although it was formed in the ancient Middle East, it has shaped modern Western thought. For example, the growth of science in the West is thought to be tied to believing that God, as described in Scriptures, is a God of consistency and order in nature.

Impact

Many questioned if the scrolls would change religious belief, but scholars expected no change in theology or doctrine to occur. The standards for making copies were high, and the scrolls appear not to differ in any fundamental respect from the Scriptures as they have been traditionally rendered. Minor variant readings do excite scholars, however, along with new theories that explain the relationships of the texts.

Insights into the times during which Jesus lived were another contribution made by this discovery. The Pharisees, Sadducees, and Zealots were familiar, but not the Essenes. Ethelbert Stauffer of Erlangen University pointed out that *The Manual of Discipline* taught to "love all sons of light" and "hate all the sons of darkness." Jesus may have been thinking of Essene teaching when he proclaimed, "You have heard that it was said, 'Love your neighbor and hate your enemy.' But I tell you, always love your enemies and always pray for those who persecute you" (Matthew 5:43).

Most have concluded that the Essenes operated the settlement and caves at Qumran, but serious questions still remain. Some Essene doctrines, such as celibacy, divorce, and monogamy, parallel teachings of the early Christian church. Publication of the Damascus Documents, which correlate with documents found in Egypt, promises a fuller understanding of Qumran teachings.

See also Pompeii; Rosetta Stone; Stonehenge; Troy.

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—*Paul R. Boehlke*

DECIMALS AND NEGATIVE NUMBERS

THE SCIENCE: The development of a decimal place-value system made numbers easier to use, while acceptance of negative numbers made possible the development of algebra and new physical applications. The best evidence available points to India as the locale for the most significant steps in this process.

THE SCIENTISTS:
Āryabhaṭa the Elder (c. 476-c. 550), Indian mathematician and astronomer
Brahmagupta (c. 598-c. 660), Indian mathematician and astronomer
Mahāvīra (c. 800-c. 870), Jain mathematician
Bhāskara (1114-c. 1185), Indian mathematician and astronomer
al-Khwārizmī (c. 780-c. 850), Indian mathematician

THE CONCEPT OF NUMBER

The awareness of the "number" concept and its applications is fundamental to civilization and the building of knowledge. Indeed, many ancient cultures around the world developed the ability to count, measure time and space, and make arithmetical and geometric calculations for astronomy and other scientific endeavors. The various numeral systems that resulted generally denoted numbers by words or by a large set of symbols. Only positive numbers were considered.

PLACE-VALUE SYSTEMS

Place-value systems—meaning that each "digit" in a number represents a multiple of the base—existed in Babylonia at least in part around 2000 B.C.E., in China by 200 B.C.E., and in the Maya Empire between 200 and 665 C.E. Sometime between 200 B.C.E. and 600 C.E., however, Indian mathematicians and scribes began writing numbers in true place-value notation with symbols for the numerals 1 through 9, which had evolved from the middle of the third century B.C.E. Writers gradually discarded the separate symbols they had for 10, 100, 1000, . . . ; 20, 30, 40, . . . 90; and 200, 300, 400, . . . 900. For example, Āryabhaṭa the Elder wrote a mathematics and astronomy textbook called *Āryabhaṭīya* (499; *The Aryabhatiya*, 1927) that contained numbers in place-value form with nine symbols (but no zero). A donation charter of Dadda III of Sankheda in the Bharukachcha region prepared in 595 is the oldest known dated Indian document containing a number in decimal place-value notation including zero.

THE NEED FOR ZERO

A symbol for zero is necessary for a fully decimal-positional system. Empty spaces in numbers may have been marked in ancient Egypt, Babylonia, and Greece. The Maya certainly used zero as a placeholder in their base-20 system by 665. In India, a dot as a zero to mark an empty place appeared in the Bakhshali manuscript, which may date to the 600's or earlier. Other Indian texts used ten symbols in a decimal place-value system to facilitate such tasks as multiplication. The word *kha* was sometimes used instead of a zero symbol, and the empty circle was widely adopted late in the ninth century.

Unlike Mayan numerals, which were confined to that civilization, the Indian system quickly spread into other regions of the world. Inscriptions that date to 683 and 684 and employ zero as a placeholder have been found in Cambodia and in Sumatra, Indonesia. Indian astronomers used their numerals in the service of the Chinese emperor by 718. Arab scholars and merchants learned of the nine-sign Indian system in the 600's and 700's. All ten digits had reached Baghdad by 773, and they were used for positional notation in Spain by the 800's.

However, the symbols used to represent the numbers evolved separately in the western and eastern regions of the Arab Empire, with the symbols in the west (North Africa and Spain) remaining more like the original Indian versions by 1000. These symbols were standardized into today's form with the advent of printing in the 1400's. Many European scholars were introduced to the decimal place-value system through a book on the Indian symbols written in 825 by al-Khwārizmī, which was anonymously revised and translated into Latin in the 1100's as *Algoritmi de numero Indorum* (al-Khwārizmī on the Indian art of reckoning; "Thus Spake al-Khwarizmi," 1990). Some European Christians were already familiar with Indian number symbols, though; for example, they have been found in the *Codex Vigilanus*, which was copied by a Spanish monk in 976.

NEGATIVE NUMBERS

Negative numbers most likely first appeared in China. The anonymous work *Jiuzhang suanshu* (nine chapters on the mathematical art), which dates approximately to the second century, provides correct rules for adding and subtracting with both negative and positive numbers. The concept of negative numbers was apparently transmitted to India in the second century, where mathematicians developed true fluency in handling negatives, including the ability to multiply and divide these numbers. These Indian advancements were then transmitted back to China by the 1300's. For instance, Brahmagupta introduced negative numbers to an Indian audience in 628 through the astronomy text *Brahmasphuṭasiddhānta* (the opening of the universe). His arithmetical rules of operation were updated by Mahāvīra in *Ganita sara sangraha* (850; compendium of the essence of mathematics). In the twelfth century, the six books by Bhāskara represented the peak of contemporary mathematical knowledge. He improved notation by placing a dot over a number to denote that it was negative. He accepted negative solutions and encouraged others to accept them as well, providing several word problems to test the reader's calculating skills.

Many of these works were also notable for their authors' efforts to treat zero as an abstract number and to understand its properties. Brahmagupta and Bhāskara agreed that any number minus itself was zero and that any number multiplied by zero was zero. They disagreed on the result when dividing by zero. Brahmagupta said the result when dividing zero by zero was zero. Bhāskara realized that Brahmagupta was incorrect, but he concluded that $(a.0)/0$ is a in his work on mathematics, *Līlāvatī* (c. 1100's; the beautiful). In a later book on algebra, *Bījaganita* (c. 1100's; seed counting or root extraction), he suggested that a divided by zero yielded infinity. This would force zero multiplied by infinity to equal every number a, or to prove that all numbers are equal. Bhāskara did not attempt to resolve this issue or to admit that dividing by zero is impossible.

IMPACT

Although the decimal place-value system facilitates arithmetical computation, it was not easily accepted as it moved outward from India. The dissemination of Indian numeral symbols was necessarily slowed by the complex paths of transmission that roughly followed medieval trade routes. Additionally, even though writers such as al-Uqlīdisī trumpeted the utility of decimal numbers in *Kitāb al-fuḥūl fi al-ḥisāb al-Hindī* (952-953; *The Arithmetic of al-Uqlidisi*, 1978), artisans and merchants often saw no compelling reason to give up their existing numerical practices, such as finger reckoning. Indian number symbols also sometimes mixed with existing symbol sets as they entered new cultures. Finally, it took time for mathematicians to understand and adopt ten-character decimal symbols (rather than nine) that employed zero first as a placeholder and then as an abstract number in its own right.

Negative numbers also aroused the foundational concerns, definitional difficulties, and philosophical baggage of the number zero. Although writers such as al-Khwārizmī did not recognize negative numbers or zero as algebraic coefficients, this stumbling block was perhaps especially prevalent in Europe, where the rules for decimal and negative numbers in Leonardo of Pisa's *Liber abaci* (English translation, 2002), were widely read but not always taken up immediately. In fact, as late as the eighteenth century European mathematicians questioned the validity of negative numbers and often made computational errors when they did work with these numbers. Such influential Renaissance and early modern mathematicians as Regiomontanus, Gerolamo Cardano, and François Viète went so far as to discard negative solutions.

Nevertheless, these numbers simultaneously enabled the development of modern algebra. In the end, the decimal and negative numbers that arrived in Europe from India via Islam revolutionized and algebraized mathematics. They became the basis of the European number system and were key components of the new mathematical discipline—including analytical geometry, mechanics, and differential and integral calculus—that emerged in the early modern period.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Amy Ackerberg-Hastings*

DEFINITE PROPORTIONS LAW

THE SCIENCE: Through a series of meticulous experiments Proust proved that all chemical compounds, whether isolated from nature or prepared in the laboratory, consist of elements in definite ratios by weight.

THE SCIENTISTS:

Joseph-Louis Proust (1754-1826), French chemist credited with discovering the law of definite proportions

Claude Louis Berthollet (1748-1822), French chemist who believed that the composition of a chemical reaction's products varied with the masses of its reactants

Antoine-Laurent Lavoisier (1743-1794), French chemist whose ideas on oxygen, elements, and nomenclature helped make chemistry into a modern science

John Dalton (1766-1844), English chemist whose discovery of the law of multiple proportions helped him to establish modern atomic theory

CONSTANT COMPOSITION

In the late eighteenth century, the idea that chemical compounds had stable ratios of elements was not uncommon. In fact, many analytic chemists based their work on just such an idea. However, the attitude of chemists toward what came to be called "definite proportions" was complex. Such distinguished scientists as Claude Louis Berthollet questioned definite proportions and backed his skepticism with experiments that demonstrated varying compositions of alloys, glasses, and solutions. Although Antoine-Laurent Lavoisier, the founder of the oxygen theory of combustion, made use of compounds with fixed weight ratios, he admitted that some substances might have degrees of oxygenation. Lavoisier had helped establish that true chemical compounds possessed uniform properties, but the claim by some scholars that the constancy of components in these compounds was a common assumption in the eighteenth century has been refuted by the detailed historical analyses of other scholars.

The person who did more than any other to create and authenticate the principle of constant composition was Joseph-Louis Proust. He pursued the profession of his father, an apothecary, and he worked for several years in the pharmaceutical department of the Saltpêtrière Hospital in Paris. With this background it is understandable why Proust tended to approach chemical problems pragmatically. With the help of Lavoisier, he was able, during the 1780's, to obtain academic positions in Spain, first at Madrid, then at the Royal Artillery College in Segovia. After a stay in Salamanca, he returned to Madrid in 1791, when he began to study the issue of definite proportions.

Combining Ratios

Scholars differ on how much such early ideas as "constant saturation proportions" influenced Proust. Many chemists had established that a certain amount of acid neutralized a specific quantity of base, and some posited that such reacting substances had a unique property of combination, which was sometimes called the "saturation proportion." Proust knew of these unique combining ratios, but these previous efforts did not result in the clear recognition that all chemical substances actually combine in only a small number of fixed proportions. Proust knew that the French mineralogist René Just Haüy had discovered a relationship between chemical composition and fixed crystal form, and this influenced his thinking on definite proportions. Proust also did research on chemical compounds of interest to pharmacists, physicians, metallurgists, and painters, and these studies deepened his knowledge of the differences between true chemical compounds and physical mixtures.

Precisely when Proust first formulated his famous law has been controversial. Some scholars argue for 1794, others for 1797, and still others for 1799. Proust did publish in 1794 a paper in which he clearly recognized that iron not only had two oxides but also two sulfates, and he went on to state that all metals follow the same natural law regulating their definite combinations with other elements. By 1797 Proust had shown that antimony, tin, mercury, lead, cobalt, nickel, and copper formed distinct oxides with constant proportions. The oxides of these metals had specific physical and chemical characteristics, and Proust responded to those who claimed that metal oxides had variable proportions by showing that these chemists were confusing "maximum and minimum" oxides with their mixtures. He was able to separate mixtures of these maximum and minimum oxides by selective solubilities of the compounds in alcohol or other solvents.

Proust was now a firm believer that nature's "invisible hand" bound together elements into real combinations. In 1799, in a series of painstaking analyses, he demonstrated that the copper carbonate he prepared in his laboratory was identical in composition to the compound found in nature. Both the artificial and natural copper carbonate contained the identical proportions by weight of copper, carbon, and oxygen. He concluded that natural laws acted the same in the earth's depths as in a chemist's flask.

Proust explained the immutability of true compounds through nature's ordering power, which he called election or affinity. This attraction between certain substances was responsible for the fixity of composition.

THE PROUST-BERTHOLLET DEBATE

On the other hand, in France, Claude Berthollet, a Newtonian, assumed that affinity, like gravity, brought about continuous attractions between substances, and he opposed Proust's "elective" characterization of chemical affinity. He interpreted affinity not as a determinative force but as a physical power that could be influenced by the relative concentrations of reactants. In this way the products of chemical reactions were conditioned to have indefinite compositions.

During the first decade of the nineteenth century Proust and Berthollet, in a series of journal articles, debated whether compounds had fixed or variable compositions. In this gentlemanly dispute Berthollet argued that not only alloys, glasses, and solutions exhibited variable compositions but also oxides, sulfates, and other salts. For example, he produced experimental evidence that mercury sulfates exhibited a continuous range of combinations between two extremes, but Proust refuted Berthollet's interpretation of his observations by showing that he was actually dealing with a mixture of two distinct compounds. Similarly Proust proved that tin had two oxides and iron two sulfides, and all of these compounds had fixed compositions. When Proust was unable to disprove variable compositions, as for alloys and solutions, he declared them to be mixtures, an argument that Berthollet found circular. Although Proust was not correct in all particulars, and although he demeaned Berthollet's valid observations about the effects of "active masses" on the direction of chemical reactions, his principal conclusion that true compounds have properties that are as "invariable as is the ratio of their constituents" was not only true but also important for the future of chemistry.

IMPACT

Proust's law of definite composition ultimately became a fundamental principle of modern chemistry, but it took the work of many experimenters to establish it as an exact law. In a way, the debate between Berthollet, an insightful theoretician, and Proust, a meticulous experimenter, continued through their disciples. Proust's followers certainly had the early victories when many chemical compounds clearly exhibited that their constituents always occurred in fixed weight ratios.

Proust's law was also important in helping to establish the modern atomic theory of John Dalton, even though Dalton himself made only cursory references to Proust in his publications. More important for Dalton was the law of multiple proportions, which he discovered when he showed that two elements could combine in more than one set of definite

PROUST ON COMPOUNDS

During the nineteenth century, the concept of a chemical compound was still being defined and discovered. Joseph-Louis Proust held that the chemical elements in a true compound must combine in certain definite proportions to one another. Others, such as Claude Berthollet, held that a compound could be composed of elements combined in any proportion. It may seem obvious that Proust was distinguishing chemical elements from chemical compounds (and Berthollet was not), but in their day the idea that chemical elements were formed by distinct types of atoms was unclear. John Dalton would make that notion clear, but he owed much of his theory to Proust's law of definite proportions, which Proust summarized in 1806:

> Everything in mineralogy is not a compound [*combinaison*] . . . [T]here is a large number of substances to which this name should not be applied indiscriminately, as some authors do for want of having thought sufficiently about what is understood by this word in chemistry. Because they have not noticed that the science has made a rule of reserving its use, they have applied it indifferently to substances which it deliberately avoids describing thus. They therefore confuse compounds with certain concrete solutions, certain combinations, certain systems of compound bodies to which it attaches a quite contrary idea. Nature, for example, presents us with compounds of elements, but also with combinations formed by a multiple aggregation of these same compounds. . . .
>
> Let us stop for a moment to satisfy an objection which d'Aubuisson certainly addresses to me, when he says in a memoir in which he so justly sees the futility of certain definitions, "The analyses of the copper ore [cuivre gris], which Klaproth has just published, are a new example of compounds formed in variable proportions." I would reply that the copper ore does not belong at all to the order of compounds which chemists are examining at the moment in order to unravel the principles of their formation. A compound according to our principles, as Klaproth would tell you, is something like sulphide of silver, of antimony, of mercury, of copper; it is an acidified combustible substance, etc.; it is a privileged product to which nature assigns fixed proportions; it is in a word a being which she never creates, even in the hands of man, except with the aid of a balance, *pondere et mensura*.

Source: Excerpt translated by Maurice Crosland, ed., in *The Science of Matter: A Historical Survey* (Harmondsworth, Middlesex, England: Penguin, 1971).

proportions. Proust, the empiricist and not the atomist, came close to finding this law because he had recognized cases in which the same elements formed two combinations, each with definite compositions, but he expressed his relationships in percentages, whereas Dalton expressed them in atomic weights. Both Proust and Dalton saw the same regularities, but Dalton creatively envisioned a new way of interpreting them. Indeed, Dalton was able to answer a question that Proust could not: Why should chemical compounds have definite compositions and exist in multiple proportions? Dalton's answer was simple: Matter is atomistic, and when atoms combine with each other, their distinctive weights naturally result in definitely composed compounds or series of compounds.

The significance of some of Berthollet's arguments in the Proust-Berthollet debate did not become obvious until late in the nineteenth century, when the new disipline of physical chemistry was founded. Berthollet had believed that chemical reactions are influenced by the masses of the reacting substances, and these "active masses" prescribed the reaction's speed as well as the nature and amounts of the products. Although Berthollet was wrong about the nature of the products, he was right about the reaction rates. The law of mass action, in which physical chemists quantitatively detailed how chemical reactions are influenced by the quantities of reacting substances, became a basic principle of chemical kinetics.

Like many controversies in the history of science, the Proust-Berthollet debate was not simply an instance of truth (Proust's law) triumphing over error (Berthollet's variable composition). Berthollet, who emphasized how compounds were formed, grasped (albeit inchoately) the law of mass action. Proust, who emphasized the empirical study of the nature of compounds, grasped the law of definite proportions but not the law of multiple proportions. Furthermore, neither Proust nor Berthollet fully understood the significance of Dalton's atomic theory, which would ultimately, in the hands of future chemists, make sense not only of definite and multiple proportions but also of most of chemistry.

See also Atomic Theory of Matter; Isotopes; Periodic Table of Elements.

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—*Robert J. Paradowski*

DIFFRACTION

THE SCIENCE: Light passing through a small opening cannot be prevented from slightly spreading on the farther side of the opening. When Francesco Maria Grimaldi discovered this principle, he termed the phenomenon "diffraction" and postulated that it results from the fluid nature of light, analogous to a flowing stream of water.

THE SCIENTISTS:

Francesco Maria Grimaldi (1618-1663), Italian mathematician
Christiaan Huygens (1629-1695), Dutch scientist and mathematician whose work on wave theory was confirmed by the ideas of Grimaldi
Sir Isaac Newton (1642-1727), English mathematician who was greatly influenced by Grimaldi's work

LIGHT BENDS

In about 1655, while serving as a mathematics instructor at the Jesuit college at Santa Lucia in Bologna, Francesco Maria Grimaldi began an elaborate set of optical experiments that occupied him for the remainder of his life. These experiments clearly demonstrated that light propagating through air does not simply travel in straight lines but tends to bend slightly around objects. This new phenomenon Grimaldi termed "diffraction" (from the Latin for "breaking up") because it indicated that light has a fluid nature allowing it to flow around objects just as a stream of water divides around an obstacle in its path.

Prior to Grimaldi's experiments, scientists assumed that light always propagates rectilinearly if it remains in the same medium, which gave credence to the prevailing corpuscular theory of light, that it consisted of small, rapidly moving particles. It was known since antiquity that when light enters a different medium—for example, when it moves from air to water—it is bent, or refracted. Diffraction, by contrast, is a bending of light around objects or through openings in the *same* medium. Diffraction is ex-

ABOUT FRANCESCO GRIMALDI

Francesco Maria Grimaldi was the fourth son of Paride Grimaldi, a wealthy silk merchant, and his second wife, Anna Cattani. After his father's death, Francesco entered the Society of Jesus (Jesuits), eventually training in philosophy (1635-1638) and consecutively attending Jesuit colleges in Parma, Ferrara, and Bologna. From 1638 through 1642, Grimaldi taught humanities and rhetoric at the College of Santa Lucia, Bologna. From 1642 through 1645, he studied theology at the same school; additional study in philosophy earned him a doctorate in 1647. He was then appointed as a professor of philosophy, but ill health forced him to assume a less demanding position teaching mathematics, a post he occupied for the remainder of his life.

Although Grimaldi was ostensibly a mathematician and philosopher, in his day natural philosophy included the sciences, where his main interests lay. His immediate supervisor was Giambattista Riccioli, an amateur scientist with considerable interest in physics and astronomy. Encountering a kindred spirit in Grimaldi, he enlisted his aid in scientific endeavors. In the period from 1640 through 1650, Grimaldi conducted experiments on falling bodies. He was able to verify that for a freely falling body vertical displacement is proportional to the square of the time the object has been falling from rest.

Beginning in 1645, Grimaldi engaged in mathematical analyses and geographic surveys to determine the meridian line for Bologna. During the course of these measurements, he had to make many of his own instruments, including an efficient quadrant to measure the heights of lunar mountains, which were to be included in the accurate map he compiled from telescopic observations during different lunar phases. In preparing this map, Grimaldi inaugurated the procedure of naming prominent craters after illustrious philosophers, scientists, and astronomers. These names, still in use, include a crater named Grimaldi.

All of Grimaldi's work was incorporated into Riccioli's *Almagestum novum* (1651). He also arrayed most of the astronomical tables and measurements on fixed stars that are featured in the second volume of Riccioli's *Astronomia reformata* (1665). Although Grimaldi and Riccioli worked together on these projects, Grimaldi's most successful research was in the emerging field of optics.

hibited by all types of waves—water, sound, and light—but had not been observed previously for light because the extremely small wavelengths render the effects difficult to perceive. Grimaldi's experiments on diffraction were of two different types: one type examined the shadows produced by opaque objects of different shapes, the other type examined light passing through circular apertures.

GRIMALDI'S SHADOW EXPERIMENTS

For the shadow experiments, Grimaldi allowed bright sunlight to enter a darkened room through a tiny hole (one-sixtieth of an inch in diameter). This created a cone of light that Grimaldi projected on a white screen set obliquely to form an elliptical image of the Sun. Between the hole and the screen he inserted a narrow, opaque rod to create a shadow. Examining this shadow carefully, Grimaldi observed that its size was somewhat smaller than the linear projection of light rays predicted and, even more surprising, the shadow's border was bounded by narrow fringes of color. He described these diffraction bands in some detail; there are usually three and they increase in intensity and width nearer to the shadow. The closest band consists of a central white region flanked by a narrow violet band near the shadow and a slender red band away from the shadow. Grimaldi cautioned that these color bands must be observed carefully to avoid mistaking the series for alternating stripes of light and dark.

Next, he examined the effect of varying the shape of the opaque object by replacing the rod with a step-shaped object with two rectangular corners. He meticulously recorded how the bands curved around the outer corner and continued to follow the shadow's edge. He also described that when the two series of bands from each edge of the inner corner approach, they intersect perpendicularly to create regions of brighter color separated by darker areas.

Grimaldi also employed several L-shaped objects of different width to study the color bands produced. His diagrams show two sets of continuous tracks, parallel to the borders, which connect by bending around in a semicircle at the end of the L. He noted that the bands appear only in pairs, the number increasing with the width of the obstacle and its distance from the screen. He also observed that at the corners of the L, an additional series of shorter and brighter colors emerged. He diagrammed these as five feather-shaped fringes radiating from the corner and crossing the paired tracks of light perpendicularly. Grimaldi compared this to the wash behind a moving ship.

GRIMALDI'S APERTURE EXPERIMENTS

Grimaldi's aperture experiment allowed the cone of light to pass through a second hole, about one-tenth of an inch in diameter, before being projected on a wall. The distances between the holes and between the wall and the second hole were equal at about 12 feet. Grimaldi observed that the circle of light cast on the opposite wall was slightly larger than predicted by rectilinear propagation theory, and the border displayed the same red and blue bands. He also mentioned that these diffraction effects were quite small and observable only if extremely small apertures were used.

Grimaldi also discovered that when sunlight entered a room through two small adjacent apertures, the region illuminated by the two beams was darker than when illuminated by either aperture separately. Although he did not understand that he was observing the now well-known principle of "interference of light waves," he regarded this observation as conclusive proof that light was not a material, particulate substance.

Grimaldi's carefully executed experiments convinced him that light had a liquid nature, a column of pulsating fluid that could produce color fringes when the luminous flow was agitated. The colors were inherent in the white light itself and not created by some outside agent. Although the diffraction effect so carefully measured and documented by Grimaldi is an unequivocal indicator that light consists of periodic waves, this notion seems not to have occurred to him. Grimaldi detailed his experiments on diffraction, along with many other optical topics, in his comprehensive treatise *Physico-mathesis de lumine, coloribus, et iride* (1665; physico-mathematical thesis on light, colors, the rainbow; English translation, 1963).

IMPACT

Encouraged by Grimaldi's work, Christiaan Huygens pursued the development of a wave theory of light. He envisioned waves propagating through an invisible all-pervasive medium and established a principle demonstrating how wave fronts progressed through this medium. Using his principle, he derived the well-known laws of reflection and refraction. A consequence of the wave theory is that when light passes obliquely from a less dense to a denser medium, the speed of the wave must decrease to explain the observation that the light refracts to a smaller angle.

Isaac Newton, who was also greatly influenced by Grimaldi's work, favored a particle or corpuscular theory of light in which refraction is explained by the particles increasing their speed when entering a denser medium. He objected to a wave theory because the predicted bending of light around corners was not observed. Grimaldi's diffraction results were explained as being due to refraction; he proposed that the density of a medium decreased near an obstacle, thus causing light to bend. Newton had observed wave interference for water waves and used it to explain anomalous tidal effects, but he did not apply this to optics. Such was the nature of Newton's fame that no one refuted him.

The issue was finally resolved in favor of the wave theory by English scientist Thomas Young (1773-1829), when, in 1802, he published experimental results documenting light interference and proving that Newton's experiments were easily explained by the wave theory. The final nail in the coffin lid of the particle theory was the experimental measurement of the speed of light under water, accomplished in 1850 by the French physicist Léon Foucault (1819-1868). His precise measurements proved that the speed of light under water was considerably less than its speed in air, as predicted by the wave theory.

See also Ionosphere; Optics; X-Ray Crystallography.

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—*George R. Plitnik*

DIPHTHERIA VACCINE

THE SCIENCE: Behring discovered that a toxin produced by the causative agent of diphtheria could be destroyed by blood serum derived from immunized animals, thus leading to the development of a vaccine.

THE SCIENTISTS:

Emil von Behring (1854-1917), German bacteriologist and winner of the first Nobel Prize in Physiology or Medicine
Edward Jenner (1749-1823), English physician who developed the practice of vaccination
Edwin Klebs (1834-1913), German bacteriologist
Friedrich August Johannes Löffler (1852-1915), German bacteriologist
Pierre-Paul-Émile Roux (1853-1933), French bacteriologist
Alexandre Yersin (1863-1943), Swiss bacteriologist
Henry Sewall (1855-1936), American physiologist
Paul Ehrlich (1854-1915), German bacteriologist
Shibasaburo Kitasato (1852-1931), Japanese bacteriologist

The Hunt for Bacteria

During the nineteenth century, there was an enormous growth of knowledge in the field of bacteriology. Much of the expansion resulted from discoveries by German bacteriologist Robert Koch and French chemist Louis Pasteur. The two scientists are considered the founders of modern medical bacteriology and were instrumental in demonstrating the relationship between exposure to bacteria and specific human and animal diseases. These diseases involved causative agents (pathogens) such as bacteria, which would interact with human and animal hosts and induce illness caused by infection or toxicity. The illnesses were collectively classified as "communicable diseases" because they could be transmitted from one host to another.

The disease is caused by a bacterium called *Corynebacterium diphtheriae*, but this causative agent was not discovered until 1883, when a German bacteriologist, Edwin Klebs, isolated the bacterium from people with diphtheria. The discovery was confirmed in 1884, when German bacteriologist Friedrich Löffler demonstrated that pure cultures of these organisms would induce diphtheria in experimental animals. Indeed, the original name of the causative agent of diphtheria was Klebs-Löffler bacillus, later renamed to *C. diphtheriae*.

Five years later, two other scientists, French bacteriologist Pierre-Paul-Émile Roux and Swiss bacteriologist Alexandre Yersin, were able to separate a chemical toxin from *C. diphtheriae* and demonstrate that the chemical was the actual factor that caused diphtheria. Thus, the foundation was established for development of a means for rendering the toxin innocuous in order to prevent the onset or eradicate the symptoms of the disease in people who were exposed to the toxin-producing bacteria.

A New Vaccine

The German bacteriologist Emil Adolf von Behring and his assistant, Japanese bacteriologist Shibasaburo Kitasato, focused on immunization of animals via vaccination. The scope of their research was influenced by concepts established by several other scientists, including an English physician named Edward Jenner, Pasteur, and the American physiologist Henry Sewall. Jenner developed the concept of vaccination during the late 1790's. Jenner knew that people who had acquired cowpox and survived were immunized against future outbreaks and the more dangerous and typically fatal smallpox. Based on this premise, Jenner demonstrated that smallpox could be prevented in humans if they were injected with a small dose of fluid from an active cowpox lesion. He named this process "vaccination" after the Latin word *vaccinia*, which means cowpox.

Pasteur applied Jenner's concept to other diseases and developed vaccinations consisting of attenuated bacteria for the prevention of anthrax and rabies during the 1880's. In turn, based on Pasteur's success, Sewall applied the concept to develop a vaccine that would induce immunity against toxic snake venoms. In 1887, he was successful in demonstrating that an animal could be protected from the toxic venom if previously vaccinated with sublethal doses of the toxin.

The Scourge of Diphtheria

To appreciate the significance of the hard work and great discoveries of Emil von Behring and other scientists of his era who worked to find cures for communicable diseases, it is necessary to understand that life in those days was very different from what it is now.

Infectious diseases were largely uncontrolled and were a constant source of worry. Newspapers routinely reported outbreaks of smallpox, cholera, plague, diphtheria, malaria, anthrax, and other life-threatening illnesses. Today infectious diseases—such as flu, colds, measles, and chickenpox—can often be thwarted by vaccines and antibiotics. In the early 1900's, these diseases often ended in death. In the first ten years of the AIDS epidemic in the United States (1979-1989), approximately seventy thousand people in the United States died of AIDS. In the 1880's, when Behring began his career as a doctor, diphtheria killed approximately seventy thousand children *every* year in Germany.

Diphtheria is transmissible mainly via direct contact with an infected host or by ingestion of contaminated raw milk. During the Industrial Revolution, the prevalence of the disease increased as city populations increased, because the probability of contracting the disease is increased under crowded conditions. The disease is caused by a bacterium, *Corynebacterium diphtheriae*. Certain strains are susceptible to genetic alteration by a virus that causes the organisms to produce a toxin. When humans absorb this toxin, they form lesions in the nasal, pharyngeal, and laryngeal regions of the upper respiratory system. The toxin can also damage the nerves, heart, kidneys, and other organs. If the disease is extensive, diphtheria is fatal.

In one of the small towns in which Behring served after passing his state examination—Winzig, in Silesia—Behring encountered his first diphtheria epidemic. The experience is said to have impressed him so deeply that from then on he believed that his main task was to combat epidemics. In 1894, once the manufacture of serum in sufficient quantity was under way, the death rate from diphtheria began to drop precipitously: to one-half, then to one-third or less of what it had been previously.

Behring and Kitasato attempted to extend the already proven concept of immunization via vaccination and apply the technique for control of diphtheria. Thus, using data generated by Klebs, Löffler, Roux, and Yersin regarding the toxin-producing *C. diphtheriae*, Behring and Kitasato initiated a series of their own experiments. In 1889, Kitasato had discovered the causative agent of tetanus, which was also found to be a toxin-producing bacterium.

Behring's experimental design involved preparing a pure culture of a live, toxin-producing strain of *C. diphtheriae* in a nutrient broth, separating the toxin generated by the bacteria in the broth from the organisms via filtration, injecting graduated sublethal doses of the toxin under the skin of healthy rabbits and mice, and several days later injecting the inoculated animals with live, active *C. diphtheriae* bacteria. Behring's experiment was a success. On December 11, 1890, Behring reported in a journal article that the animals vaccinated with *C. diphtheriae* toxin prior to injection with active *C. diphtheriae* bacteria did not develop diphtheria. Control animals not vaccinated, however, developed the disease subsequent to injection with active organisms.

Emil von Behring. (Library of Congress)

Thus, Behring demonstrated that the experimental animals were able to develop an induced immunity to the *C. diphtheriae* toxin via vaccination because of the formation of a protective toxin-destroying agent produced within their blood sera. (One week earlier, Behring and Kitasato had coauthored a journal article that reported similar findings for experiments using toxin produced by tetanus bacilli.) The two scientists referred to the protective toxin-destroying agent within the blood sera of immunized animals as an "antitoxin."

IMPACT

As a result of Behring's discovery of diphtheria antitoxin, a foundation was established to develop an efficient vaccine and determine an optimal dose for human use. Progress was demonstrated within a year, because of experiments conducted by German bacteriologist Paul Ehrlich, whose work involved determining if serum derived from animals and humans known to contain the antitoxin could be injected in others to induce immunization. This concept became the foundation of what is called "serotherapy" to induce "passive immunity." A person is considered to have been passively immunized when he or she becomes immune to toxin because of injection with serum containing antitoxin from another immunized person or animal. In other words, passive immunity implies the transfer of immunity from one host to another via vaccination with antitoxin instead of active toxin.

Ehrlich's assistance to Behring was also instrumental in establishing some insight into the administration of safe and effective doses of vaccine for clinical use. Within a year of Behring's discovery of the diphtheria antitoxin, clinical trials were established with humans to determine if diphtheria could be prevented and possibly cured. The clinical trials were successful; thus, the era of vaccinating humans, especially children, with diphtheria antitoxin had begun. Although the process was not totally efficient and scientific research continued, immunization to prevent and cure diphtheria via vaccination gained widespread use, and a significant decline in the disease was apparent by the beginning of the twentieth century.

Behring's discovery of the diphtheria antitoxin influenced several major advances in the area of medical science. The concept of serotherapy as a form of vaccination was developed to induce passive immunity against the *C. diphtheriae* toxin. The process was later applied by other scientists to control the impact of other bacterial and viral agents found to be pathogenic to humans and animals. Concomitantly, a greater understanding of the human immune system was gained, especially relative to the concept of antibody (for example, antitoxic protein in blood serum) response to antigen (for example, *C. diphtheriae* toxin). Finally, as a result of the vaccine, countless lives of people who were afflicted with the dreaded disease of diphtheria were saved, while even more people were spared the experience of contracting the illness. In acknowledgment of Behring's discovery and its positive impact, Behring was awarded the first Nobel Prize in Physiology or Medicine in 1901.

See also Schick Test.

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—*Michael S. Bisesi*

DNA FINGERPRINTING

THE SCIENCE: Henry Erlich's DNA fingerprinting technique allowed determination of the identity of an individual from the DNA in a single hair.

THE SCIENTISTS:

Kary B. Mullis (b. 1944), American molecular geneticist who invented the polymerase chain reaction
Alec Jeffreys (b. 1950), English molecular geneticist who first applied the technique of DNA fingerprinting
Henry Erlich, molecular geneticist who helped develop DNA fingerprinting

DNA SIGNATURES

All individuals, with the exception of twins and other clones, are genetically unique. Theoretically it is therefore possible to use these genetic differences, in the form of DNA sequences, to identify individuals or link samples of blood, hair, and other features to a single individual. In practice, individuals of the same species typically share the vast majority of their DNA sequences; in humans, for example, well over 99 percent of all the DNA is identical. For individual identification, this poses a problem: Most of the sequences that might be examined are identical (or nearly so) among randomly selected individuals. The solution to this problem is to focus only on the small regions of the DNA which are known to vary widely among individuals. These regions, termed hypervariable, are typically based on repeat sequences in the DNA.

Imagine a simple DNA base sequence, such AAC (adenine-adenine-cytosine), which is repeated at a particular place (or locus) on a human chromosome. One chromosome may have eleven of these AAC repeats,

KARY B. MULLIS AND PCR

Kary B. Mullis perhaps did more for the development of DNA fingerprinting than any other scientist: He developed the polymerase chain reaction (PCR), which made the practical application DNA fingerprinting possible. In recognition of this achievement, Mullis won the 1993 Nobel Prize in Chemistry (shared with Michael Smith won for his work in site-directed mutagenesis). In its 1993 commendation of Mullis, the Nobel Foundation noted that

> the applications of Mullis' PCR method are already many. It is for example possible using simple equipment to multiply a given DNA segment from a complicated genetic material millions of times in a few hours, which is of very great significance for biochemical and genetic research. The method offers new possibilities particularly in medical diagnostics, and is used, for example, for discovering HIV virus or faulty genes in hereditary diseases. Researchers can also produce DNA from animals that became extinct millions of years ago by using the PCR method on fossil material.

Mullis himself recalled the discovery with characteristic humor:

> I was working for Cetus, making oligonucleotides. They were heady times. Biotechnology was in flower and one spring night while the California buckeyes were also in flower I came across the polymerase chain reaction. I was driving with Jennifer Barnett to a cabin I had been building in northern California. . . . That morning she had no idea what had just happened. I had an inkling. It was the first day of the rest of my life.

Since 2003, Mullis has been developing a method for diverting the body's immune responses (antibodies) from their nominal targets to attack new diseases by means of synthetic chemical linkers. The method aims at making the body temporarily immune to new pathogens by using the body's existing immune reponses. As Mullis puts it:

> Let's say you just got exposed to a new strain of the flu. You're already immune to alpha-1,3-galactosyl-galactose bonds. All humans are. Why not divert a fraction of those antibodies to the influenza strain you just picked up. . . . The concept is actually working now with rodents and their diseases. Hopefully it's going to work in humans.

Source: Nobel commendation and Kary B. Mullis, "Autobiography." Available at The Nobel Foundation, http://nobelprize.org/chemistry. Accessed August, 2005.

while another might have twelve or thirteen, and so on. If one could count the number of repeats on each chromosome, it would be possible to specify a diploid genotype for this chromosomal locus: An individual might have one chromosome with twelve repeats, and the other with fifteen. If there are many different chromosomal variants in the population, most individuals will have different genotypes. This is the conceptual basis for most DNA fingerprinting.

DNA fingerprint data allow researchers or investigators to exclude certain individuals: If, for instance, a blood sample does not match an individual, that individual is excluded from further consideration. However, if a sample and an individual match, this is not proof that the sample came from that individual; other individuals might have the same genoytpe. If a second locus is examined, it becomes less likely that two individuals will share the same genotype. In practice, investigators use enough independent loci that it is extremely unlikely that two individuals will have the same genotypes over all of the loci, making it possible to identify individuals within a degree of probability expressed as a percentage, and very high percentages are possible.

Early Development

Alec Jeffreys, at the University of Leicester in England, produced the first DNA fingerprints in the mid-1980's. His method examined a twelve-base sequence that was repeated one right after another, at many different loci in the human genome. Once collected from an individual, the DNA was cut using restriction enzymes to create DNA fragments that contained the repeat sequences. If the twelve-base sequence was represented by more repeats, the fragment containing it was that much longer. Jeffreys used agarose gel electrophoresis to separate his fragments by size, and he then used a specialized staining technique to view only the fragments containing the twelve-base repeat. For two samples from the

Image Not Available

same individual, each fragment, appearing as a band on the gel, should match. This method was used successfully in a highly publicized rape and murder case in England, both to exonerate one suspect and to incriminate the perpetrator.

While very successful, this method had certain drawbacks. First, a relatively large quantity of DNA was required for each sample, and results were most reliable when each sample compared was run on the same gel. This meant that small samples, such as individual hairs or tiny blood stains, could not be used, and also that it was difficult to store DNA fingerprints for use in future investigations.

Variable Number Tandem Repeats

The type of sequence Jeffreys exploited is now included in the category of variable number tandem repeats (VNTRs). This type of DNA sequence is characterized, as the name implies, by a DNA sequence which is repeated, one copy right after another, at a particular locus on a chromosome. Chromosomes vary in the number of repeats present.

VNTRs are often subcategorized based on the length of the repeated sequence. Minisatellites, like the Jeffreys repeat, include repeat units ranging from about twelve to several hundred bases in length. The total length of the tandemly repeated sequences may be several hundred to several thousand bases. Many different examples have since been discovered, and they occur in virtually all eukaryotes. In fact, the Jeffreys repeat first discovered in humans was found to occur in a wide variety of other species.

Shorter repeat sequences, typically one to six bases in length, were subsequently termed microsatellites. In humans, AC (adenine-cytosine) and AT (adenine-thymine) repeats are most common; an estimate for the number of AC repeat loci derived from the Human Genome Project suggests between eighty thousand and ninety thousand different AC repeat loci spread across the genome. Every eukaryote studied to date has had large numbers of microsatellite loci, but they are much less common in prokaryotes.

Erlich's Experiments

In 1988, Henry Erlich used a technique newly developed by Kary B. Mullis—the polymerase chain reaction, or PCR—to develop a method of DNA fingerprinting so sensitive that it could be used to obtain a DNA fingerprint from a single hair cell, badly degraded tissue, or less than a millionth of a gram of dried blood thousands of years old. Using the PCR, Erlich was able to amplify trace amounts of DNA up to a million times to generate quantities large enough for DNA fingerprinting.

Erlich and his colleagues used the amplified DNA from a single hair to analyze a histocompatibility gene. Histocompatibility genes code for the tissue-type markers that must be matched in organ transplants because they stimulate attacks from the immune systems of individuals with different tissue types. Histocompatibility sequences are highly variable from one person to the next, which is why they are so useful for DNA fingerprinting, since the probability that two unrelated individuals will have the same tissue type is extremely low. DNA fingerprints that are as unique as 1 in 10,000 or even 1 in 100,000 can be obtained by analyzing these sequences. Adding other sequences to the analysis can generate DNA fingerprints that have nearly a zero probability of matching with another person, except for an identical twin. Differences in the histocompatibility sequence chosen by Erlich for typing were identified by matching DNA probes constructed for each histocompatibility sequence.

DNA sequences have the property of self-recognition, and Erlich used this property by preparing samples of the known variants of the histocompatibility sequences. Each variant form can recognize matching forms identical to itself in an unknown sample and bind to them but will not bind to any of the other forms. Erlich took the samples of amplified DNA from the hair cells and applied each probe to each unknown sample. The probes—representing the different variants of the histocompatibility sequence—stick only to their own form and have a stain attached to them so that the high concentrations of probe molecules that stick to a matching sample can be located visually. Erlich was able to identify the differences in histocompatibility sequences from the amplified hair-cell DNA samples by determining which probes remained attached to each sample.

Erlich and his colleagues showed that the results obtained from single hairs were confirmed by results obtained from blood samples taken from the same people who donated the hair. The technique was also successfully used on seven-month-old single hair samples. One of the first forensic applications of the PCR-DNA fingerprinting technique took place in Pennsylvania. In a homicide case, a one-year-old body was exhumed to be examined for evidence, a previous autopsy having been deemed suspicious. The prosecution had accused the defendants of tampering with the body by switching some of its internal organs with those of another body to conceal the cause of death. The PCR-DNA fingerprinting technique was used to show that the child's embalmed organs, exhumed with the body, did in fact match the victim's tissue type, and the defendants were acquitted of the tampering charge.

IMPACT

DNA fingerprinting has been refined to the point where an individual can be identified from the DNA in a single hair, which means that one hair, or even microscopic samples of dried blood, skin, or other body fluids found at the scene of a crime, can be analyzed to determine whose body it came from with nearly 100 percent accuracy, with the exception of twins. Properly used, DNA fingerprinting can be so precise that the margin of error in making a match between biological evidence and a suspect's DNA is less than one in ten thousand, with tests based on tissue-type genes from a single hair, and less than one in a billion with more extensive testing.

Erlich's method of DNA typing from a single hair was a dramatic refinement of DNA fingerprinting. Hair is one of the most common types of biological evidence left behind at crime scenes, so Erlich's improvement over traditional methods of analyzing hair color, shape, and protein composition can be widely applied. Erlich's technique also allows substitution of hair samples for blood or skin when DNA fingerprints are taken; the technique can be automated, making it easier to apply DNA fingerprinting to large populations along with traditional fingerprinting.

The DNA fingerprinting technique developed by Erlich and his colleagues at Cetus Corporation was made commercially available in early 1990 in the form of a DNA-typing kit, allowing more widespread application of the polymerase chain reaction to DNA fingerprinting. Initially, the main disadvantage to DNA fingerprinting was the practical difficulty of transferring a new, highly technical procedure from the research laboratory to routine application in the field. While DNA fingerprinting is virtually 100 percent accurate in theory, and works in the hands of highly trained scientists, methods for reliable and economical mass application had to be developed and proved before DNA fingerprinting became routine.

Evidence based on DNA fingerprinting was introduced for the first time in several dozen court cases in the late 1980's and played a key role in many of them. Since then it has become widely applied—even to cold cases—and has been introduced into evidence in criminal cases. As juries have become more accustomed to the use of this evidence and educated about its accuracy, they have learned to take it very seriously in their deliberations. Moreover, DNA evidence applied to long-running cases and even cold cases have unmasked guilty persons years after their crimes were committed. Perhaps more important, in several instances DNA evidence has revealed several imprisoned individuals wrongly convicted of crimes and finally set free after years of incarceration.

The technique has also been widely applied to paternity testing, to cases (such as wildlife poaching) involving identification of animals, in immigration cases to prove relatedness, and to identify the remains of casualties resulting from military combat and large disasters. The technique's ability to identify paternity has led to its use by those who study breeding systems and other questions of individual identification in wild species of all kinds: plants, insects, fungi, and vertebrates. Researchers now know, for example, that among the majority of birds which appear monogamous, between 10 and 15 percent of all progeny are fathered by males other than the recognized mate. DNA fingerprinting also has many applications to agriculture, helping farmers identify appropriate plant species.

The fact that DNA can provide so much information about an individual, besides simply personal identity, raises ethical questions about the use of DNA fingerprinting that have not been encountered with the use of traditional fingerprinting. Laws regarding the collection and use of DNA data must be carefully considered: For example, should such data be routinely collected from anyone arrested for any sort of offense, or restricted to those charged with certain crimes or who have advanced to a certain stage in the criminal justice system? However, the fact that such absolute certainty can exonerate criminal suspects who are innocent as well as help convict those who are guilty makes the responsible use of DNA fingerprinting the most important advance in forensic science since the advent of traditional fingerprinting.

See also DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Recombinant DNA Technology.

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—Paul R. Cabe and Bernard Possidente, Jr.

DNA SEQUENCING

THE SCIENCE: The development of techniques for sequencing and manipulating DNA initiated a new field of biochemical research.

THE SCIENTISTS:

Walter Gilbert (b. 1932), American biochemist who was a cowinner of the 1980 Nobel Prize in Chemistry
Allan Maxam, a colleague of Gilbert
Andrei Mirzabekov, a colleague of Gilbert and Maxam
Frederick Sanger (b. 1918), English biochemist who was a cowinner of the 1980 Nobel Prize in Chemistry
Paul Berg (b. 1926), American biochemist who was a cowinner of the 1980 Nobel Prize in Chemistry

A CHAIN OF NUCLEOTIDES

Deoxyribonucleic acid (DNA) is often called an information-containing molecule. Genes, which are made of DNA, reside in the nucleus of a cell and directly control the functioning of that cell. Thus, to understand how cells function and to manipulate genes, it is necessary to understand how the information is contained in DNA.

Every DNA molecule is built up by linking, in end-to-end fashion, a large number of smaller molecules into two chains. Only four different subunits, called nucleotides, are used to construct DNA. These nucleotides are called adenine (A), thymine (T), guanine (G), and cytosine (C). Every A in one chain is matched with a T in the other. Likewise, C's are always matched with G's. Thus, the enormously complex human chromosome, which consists of a single long DNA molecule containing hundreds of millions of nucleotides, can be viewed as nothing more than two chains that consist of a linear sequence of A's, C's, T's, and G's.

In the 1960's and 1970's, techniques were developed that made it possible to determine, laboriously, the nucleotide sequence of a very small piece of ribonucleic acid (RNA), which is found in cells and is similar to DNA.

Given that the DNA in a single human cell contains more than five billion nucleotides in forty-six long strands called chromosomes, however, it soon became clear that more powerful techniques for the analysis of DNA molecules would be needed if biologists were to make sense of this incredibly complex structure and gain the ability to manipulate genes directly.

Walter Gilbert and his colleague Allan Maxam had been using the techniques of bacterial genetics to try to understand how the bacterium *Escherichia coli* was able to turn on its ability to use milk sugar as a source of energy. Gilbert realized that he would have to know the DNA sequence—that is, the linear sequence of nucleotides—of the genes that controlled this process in order to understand fully how the bacterium was able to produce this switch in metabolism.

In early 1975, Gilbert, Maxam, and visiting scientist Andrei Mirzabekov began to experiment with various chemical treatments that could cut DNA molecules after specific nucleotides as a way to sequence the molecule. DNA to be sequenced was divided into four portions. Each portion was treated with a different set of chemical reagents; in one tube, the DNA was cut after adenine, while in the other tubes the DNA was cut after thymine, cytosine, or guanine.

The first nucleotide in a DNA molecule produces a fragment one nucleotide long, which appears in only one of the four chemical treatments and thus is sensitive to that particular chemical cleavage. The second nucleotide in the sequence can be determined by observing which chemical treatment made a radioactive fragment two nucleotides long. This analysis continues until the full sequence is determined. Approximately 250 to 300 nucleotides can be determined from a single set of reactions, and very long stretches of a DNA sequence can be obtained by linking the sequence of overlapping fragments.

From Sequencing to Cloning

By 1980, Frederick Sanger had already made major contributions to an understanding of the mechanisms by which genes control the functions of a cell. He had won the 1958 Nobel Prize in Chemistry for work leading to a practical method for determining the amino acid sequence of proteins. Like Gilbert, however, Sanger realized that a full understanding of the function of a gene would require an easy technique for sequencing DNA.

While Gilbert had used a chemical cleavage technique for sequencing DNA, Sanger chose to use a biological technique. Sanger took advantage of a discovery by Joachim Messing and his coworkers that DNA from any source could be linked end-to-end with the DNA of a small virus called

M13. This technique was called "cloning."

Frederick Sanger. (The Nobel Foundation)

When DNA polymerase, the enzyme responsible for assembling nucleotides into long strands, was added, new DNA was made. DNA polymerase always pairs A's in the template with T's in the newly made DNA and vice versa. Likewise, DNA polymerase always paired C's with G's. The newly made DNA was complementary to the cloned template DNA, and the nucleotide sequence of this new DNA could be used to determine the nucleotide sequence of the cloned DNA. Again, nearly three hundred bases could be sequenced at one time, but Sanger's technique proved to be both simpler and faster than Gilbert's.

While the techniques of Sanger and Gilbert were designed to describe the nucleotide sequence of any piece of DNA, other techniques for manipulating DNA would be required for genetic engineering to be possible. Paul Berg was one of the founders of the technique of cloning genes from two different organisms. These hybrid DNA molecules could then be produced in sufficient amounts to sequence easily. The genes also could be mutated and put back into the cells from which they were obtained to determine the effects these specific changes had on gene function. Genes from one organism could easily be introduced into the cells of another by using the same techniques, thus adding new functions to organisms. These techniques were called "genetic engineering."

IMPACT

The information obtained from the techniques of cloning and DNA sequencing has revolutionized the understanding of how genes, cells, and organisms function. Incredibly complex processes such as the functioning of the nervous system and the brain, the development of embryos, the functioning of the immune system, and the genetic contribution to cancer can now be understood at a molecular level. The science of genetic engineering has become routine.

As a result of the ability to clone and manipulate genes, bacteria can make human proteins such as insulin or growth hormone and plants can be produced that are resistant to herbicides or viral infections. These same techniques have made it possible for researchers to diagnose and treat genetic diseases in animals by replacing a defective gene in a cell with a normal one. These techniques will ultimately prove useful in the diagnosis and cure of common human genetic diseases such as cystic fibrosis and muscular dystrophy.

The DNA sequencing techniques of Gilbert and Sanger are used routinely in laboratories throughout the world. The ultimate achievement of the sequencing, however, would be to lay the foundation for determining the human genome, which was accomplished in the year 2000. This information will be a bonanza for the diagnosis and treatment of other genetic diseases and will provide the ultimate blueprint for the genetic capabilities of human beings.

See also Chromosomes; Cloning; DNA Fingerprinting; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Joseph G. Pelliccia*

Double-Helix Model of DNA

The Science: By showing precisely the double-helix configuration of DNA, James D. Watson and Francis Crick essentially discovered the chemical nature of the gene.

THE SCIENTISTS:

James D. Watson (b. 1928), American molecular biologist who shared, with Crick and Wilkins, the 1962 Nobel Prize in Physiology or Medicine
Francis Crick (1916-2004), English physicist
Maurice H. F. Wilkins (1916-2004), English biophysicist
Rosalind Franklin (1920-1958), English physical chemist and X-ray crystallographer
Linus Pauling (1901-1994), American theoretical physical chemist
Jerry Donohue (1920-1985), American crystallographer

AN ODD TEAM

In 1944, the American bacteriologist Oswald T. Avery and his colleagues published a paper demonstrating that deoxyribonucleic acid (DNA) is the carrier of genetic information. Largely through the work of the English organic chemist Alexander Todd, DNA's construction from nucleotide building blocks was understood in terms of how all its atoms are linked together. Each nucleotide consists of one of four bases (adenine, thymine, guanine, or cytosine).

While he was working out the detailed bonding of the nucleic acids, Erwin Chargaff, a biochemist at the College of Physicians and Surgeons in New York, was investigating the differences in the base compositions of DNA from various plants and animals. By 1950, his careful analyses had revealed that the amounts of various bases in different DNA varied widely, but his data also yielded the significant result that the ratios of bases adenine to thymine and guanine to cytosine were always close to one.

Linus Pauling, along with many other American chemists, was slow to accept DNA as the genetic material. For a long time it seemed to him that the molecule was too simple to handle the formidable task of transferring huge amounts of information from one generation of living things to the next. Proteins, with their large variety of amino acids, seemed much better adapted to this information-carrying role.

Nevertheless, while he was a visiting professor at the University of Oxford in 1948, Pauling discovered one of the basic structures of proteins: the alpha-helix. This three-dimensional structure, which was based on the planarity of the group of atoms holding the amino acids together (the peptide bond), was secured in its twisting turns by hydrogen bonds (links whereby a hydrogen atom serves as a bridge between certain neighboring atoms).

At the Cavendish Laboratory at the University of Cambridge, in the early 1950's, James D. Watson, a young postdoctoral fellow, and Francis

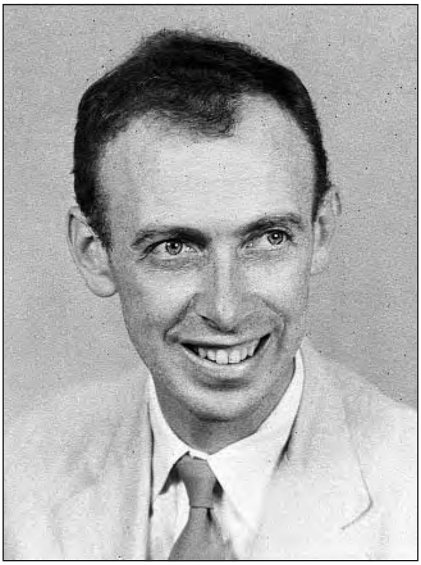
Crick, a graduate student, were trying to work out the structure of DNA. They were deeply impressed by Pauling's work. Crick believed that Pauling's method would allow biologists to build accurate three-dimensional models of the complex molecules in living things, particularly DNA.

At first, Watson and Crick seemed an odd team for this task. Neither had much knowledge of chemistry. Crick's previous training was in physics and work on mines during World War II (1939-1945). Watson's education in ornithology and zoology did not prepare him for dealing with the daunting complexities of the DNA molecule.

X Rays and Cardboard Models

At King's College of the University of London, Maurice H. F. Wilkins and Rosalind Franklin were engaged in an experimental approach to the same problem: They were trying to determine DNA's structure through improved X-ray diffraction photographs of a carefully prepared DNA sample. They were able to show that DNA exists in two forms, which they called the B form and the A form.

Chargaff visited Cambridge in 1952. After talking with Watson and Crick about DNA, he was shocked to learn that neither of them had precise knowledge about the chemical differences among the four bases. He explained to them his findings about the base ratios, but he did not see them as skilled chemists who could solve the problem of DNA's three-



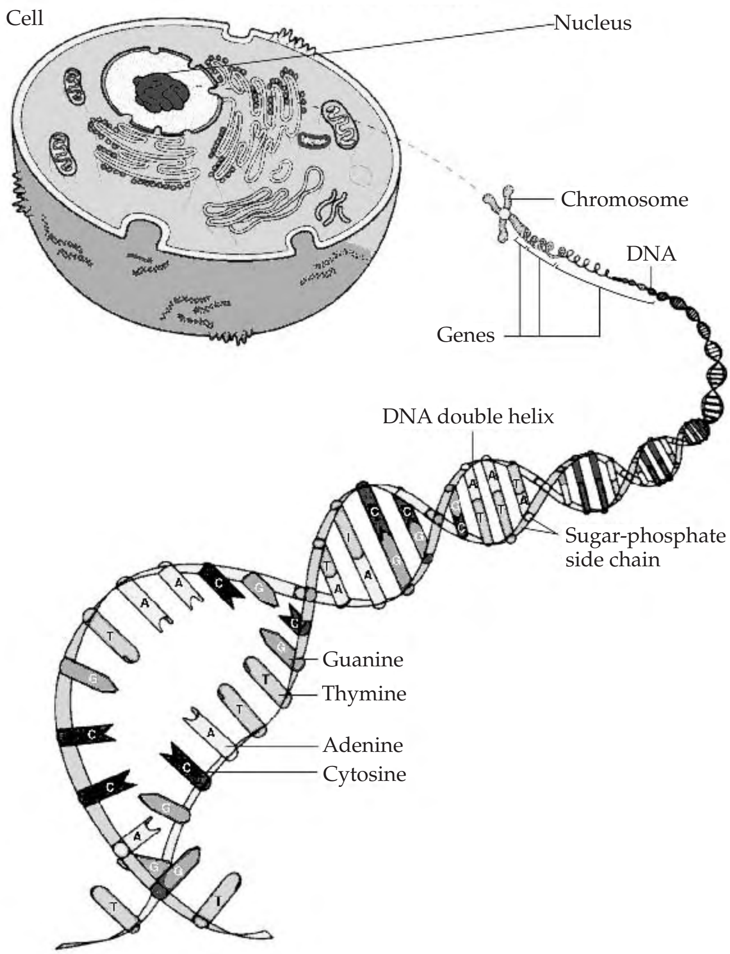
James D. Watson. (The Nobel Foundation)

Francis Crick. (The Nobel Foundation)

dimensional structure. Although Crick had not been aware of Chargaff's discovery, he had been thinking about piling complementary bases on top of one another in a DNA model, so he was fascinated by Chargaff's information. By pairing adenine with thymine, and guanine with cytosine, a rational explanation for the ratios emerged.

Wilkins showed Watson the X-ray picture of the B form, which clearly revealed the presence of a helix. On his return to Cambridge, Watson began building models of DNA. Like Pauling, he began arranging the phosphoric-acid groups in the center.

Fortunately, Jerry Donohue, an American crystallographer and protégé



The Structure of DNA

of Pauling, was sharing an office with Watson. He saw from Watson's cardboard cutouts that Watson did not understand the proper chemical structures of the four bases. When Watson—following Donohue's advice—put the bases into their correct forms, he was able to pair adenine and thymine as well as guanine and cytosine by means of hydrogen bonds whose locations were natural, not forced. Watson immediately sensed that something was right about these pairings, since both pairs (adenine-thymine, guanine-cytosine) had nearly the same size and shape and could be neatly stacked, like a pile of plates, in the interior of a double helix, while the regular sugar-phosphate backbone at the molecule's exterior could account for its acidity and its interactions with water. It turned out that this pairing of bases is the pivotal feature of DNA's structure and the reason for its complementary nature.

In March of 1953, Watson and Crick constructed a detailed model of their double helix to show that all the atoms were in sensible locations. They published their model in *Nature* on April 25, 1953. Their brief paper, which quickly achieved classic status, succinctly described their discovery and noted its implications, especially as a mechanism for transferring genetic material.

Impact

Scholars have compared the discovery of the double helix with Charles Darwin's discovery of natural selection and Gregor Mendel's discovery of the laws of heredity. The importance of the double helix also can be measured by the proliferation of significant discoveries in molecular biology that followed it. Pauling stated that the double helix was "the most important discovery in the field of biology that has been made in the last hundred years." He saw it as a culmination of molecular biology, since no problem is more fundamental than the mechanism of heredity. The double helix did not disappoint scientists eager to understand this mechanism. In the years after the model was unveiled, it proved surpassingly suitable for explaining molecular details about how cells replicate.

The most obvious feature of the model was its natural explanation of how DNA could make an exact copy of itself. In this process of replication, DNA's two complementary strands "unzip" and separate, and each half takes on a new "partner." Thus, both halves of the separated double helix act as the templates or molds on which complementary strands are then synthesized. When the process is completed, two identical double helices appear where one previously existed. This explanation of how, at the molecular level, genes can duplicate themselves exactly would eventually lead to our current understanding of many things, from genetic diseases to genetic “engineering”: the ability to clone and genetically manipulate living organisms.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Robert J. Paradowski*

EARTH ORBIT

THE SCIENCE: By becoming the first American to orbit Earth, John H. Glenn gave a boost to the prestige of the United States space program.

THE ASTRONAUTS:

John H. Glenn (b. 1921), lieutenant colonel in the U.S. Marine Corps and pilot of the *Friendship 7* spacecraft

M. Scott Carpenter (b. 1925), U.S. Navy lieutenant commander, backup pilot for the mission, and pilot of the next Mercury-Atlas 7 flight

Alan B. Shepard (1923-1998), U.S. Navy lieutenant commander who was the first American in space

Virgil I. “Gus” Grissom (1926-1967), U.S. Air Force captain and the capsule commander at the Bermuda tracking station

L. Gordon Cooper (b. 1927), U.S. Air Force major and the capsule communicator at the Muchea, Australia, tracking station

Walter M. "Wally" Schirra (b. 1923), U.S. Navy lieutenant commander and the capsule communicator at the Point Arguello, California, tracking station

Donald K. "Deke" Slayton (1924-1993), U.S. Air Force major and the blockhouse capsule communicator at Cape Canaveral

Soviet Competition

Stunned by the Soviet accomplishment of putting cosmonaut Yuri A. Gagarin in orbit in 1961, and lagging behind the Soviet Union in that respect, the National Aeronautics and Space Administration (NASA) was anxious to get John H. Glenn into orbit. It had been only four years since the United States placed its first, tiny spacecraft into low Earth orbit, but President John F. Kennedy had set a goal for sending astronauts to the Moon within eight years (he became president in 1961).

The program to send Americans into space was originally called the Manned Satellite Project. A shorter name was chosen for the project early in the fall of 1958: Project Mercury. The Olympian messenger Mercury already was a familiar name to most Americans because of the chemical element and automobile bearing his name.

On May 5, 1961, slightly more than three weeks after Gagarin became the first human to fly in space, Alan B. Shepard was launched in the *Freedom 7* spacecraft to a height of 188 kilometers and a distance of 486 kilometers. Two months later, Virgil I. (Gus) Grissom repeated the accomplishment in *Liberty Bell 7*. Less than two weeks later, the Soviets again upstaged the United States by orbiting cosmonaut Gherman Titov for nearly a day.

Spreading Friendship

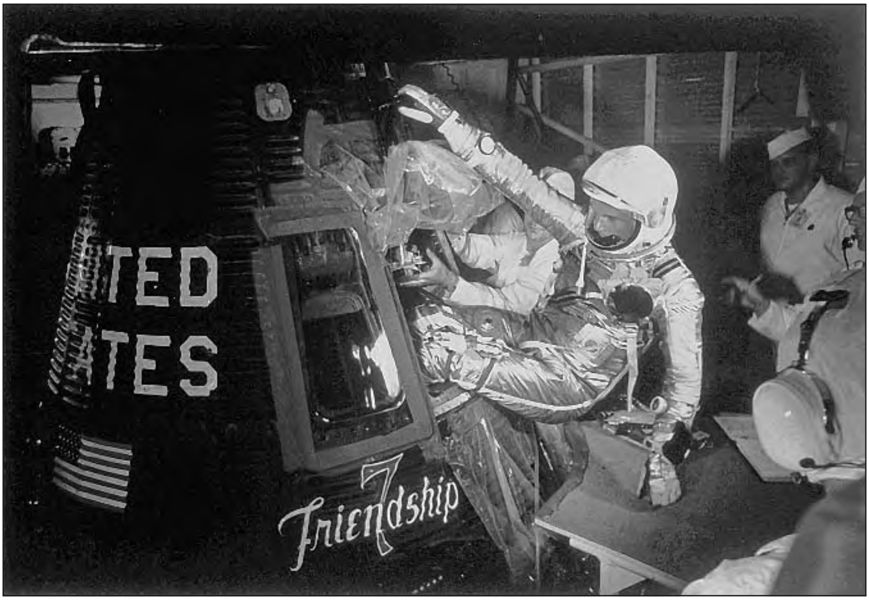
After the launch had been delayed several times, Glenn was awakened at 2:20 A.M. on February 20, 1962. He showered, got dressed, and ate breakfast. He was given a physical examination, had biomedical sensors placed on his body, and then put on his silver-colored pressure suit. At 5:05 A.M., two hours before his scheduled launch, Glenn took a van to Launch Pad 14 at Florida's Cape Canaveral. After the two-minute ride, he rode an elevator to the "white room" that surrounded the tiny *Friendship 7* spacecraft.

In the military tradition, Glenn had been given the privilege of naming his craft. He held a family competition, and the name was chosen because friendship was what he wanted to spread as he circled the Earth. The number 7 was a carryover from Shepard's capsule, *Freedom 7*. Shepard's capsule was production number 7, his booster was Redstone number 7, and his was to be the first of seven manned Redstone suborbital flights. It was only coincidence that there were seven Mercury astronauts, but the group thought they should all name their capsules with a 7.

Glenn climbed into his spacecraft and at 9:47 A.M., after several slight delays, lifted off into the blue Florida sky. "Roger. The clock is operating. We're under way," radioed Glenn in a brisk, businesslike manner. He watched Earth fall away in his rearview mirror, as the vibrations started to build. "Little bumpy along about here," he observed. As the air thinned, the ride began to smooth. Minutes later, Glenn was in orbit.

The planned three-orbit mission went well. Glenn changed the spacecraft's position by moving a hand controller, which operated small hydrogen peroxide jets. He took photographs, checked his craft, and ate some food out of toothpaste tubes. He watched the Sun set and then rise again forty minutes later. Looking out his window, he noticed glowing particles that he described as "fireflies" and that seemed to follow him. The particles are believed to have been snowflakes from water vapor released by the capsule's cooling system, as well as paint and other material from the capsule.

Glenn had some problems with his autopilot and one of his thrusters, but he was able to complete most of his tasks. The ground tracking stations had received a signal showing that the heat shield at the base of the capsule might have come loose. If it were to come off during reentry, *Friendship 7* and its passenger would disintegrate in the intense heat. Ground control-



John Glenn climbs into Friendship 7 *on February 20, 1962.* (NASA)

THE OLDEST ASTRONAUT

In 1974, more than a decade after his historic Earth orbit, John Glenn was elected as a U.S. senator from Ohio. He would be elected to that office three more times. He made an unsuccessful bid for the Democratic presidential nomination in 1984, and on the thirty-fifth anniversary of his historic flight (February 20, 1997), he announced that he would retire from the Senate at the end of his fourth term in 1998.

As senator, Glenn sought additional funding for the National Aeronautics and Space Administration (NASA). After reviewing some documents on the physical changes that happen to astronauts in orbit, he was amazed at the similarities between the effects of zero gravity on the body and the natural aging process on Earth. Consequently, he began petitioning NASA for the opportunity to go back into space to study the effects of weightlessness on older Americans. After much perseverance, on January 15, 1998, he was granted his wish.

After a thirty-seven-year hiatus from spaceflight, Glenn spent months undergoing training and medical tests to become the oldest person to travel into space. As a member of the nine-day space shuttle *Discovery* mission (October 29-November 7, 1998), the seventy-seven-year-old Glenn conducted numerous experiments that focused on osteoporosis and the immune system's adjustments to the aging process. Glenn's contributions demonstrated not only that the elderly can still make important contributions to society but also that they can do so at the highest levels. Glenn stands out as a symbol of courage, honor, and lifelong devotion and service to his country.

lers decided to leave the retropack attached during reentry in the hope that it would keep the shield in place until atmospheric pressure had built up enough to hold it on.

Friendship 7's three retro-rockets ignited, and the spacecraft slowed down enough to be captured by Earth's gravity. Through his window, Glenn saw chunks of the retropack burn off and fly past him. He described the reentry as a "real fireball." Finally, after four hours and fifty-five minutes in flight, *Friendship 7* was bobbing in the Atlantic Ocean. Several minutes later, Glenn, still strapped into his seat, was plucked from the water and placed on board the U.S. Navy destroyer *Noa*.

IMPACT

Glenn became the most celebrated national hero since the American aviator Charles A. Lindbergh and was approached by President Kennedy to run as a Democrat for a Senate seat from Ohio. Glenn had planned to stay with NASA to be part of the Apollo Moon-landing program, but he retired to campaign for the Senate. Remarkably, however, he returned to space in October, 1998, as a member of shuttle mission STS-95 and became, at age seventy-seven, by far the oldest astronaut ever to go into space.

Six of the original seven astronauts selected for Project Mercury flew during the program. Three months after Glenn's flight, M. Scott Carpenter again showed that the United States could orbit a manned spacecraft and that Glenn's journey was not a fluke. In October, 1962, Walter M. (Wally) Schirra flew a six-orbit mission, leading to the final Mercury mission in May, 1963: L. Gordon Cooper's flight, which met the goal of placing a manned spacecraft into orbit for twenty-four hours. Donald K. (Deke) Slayton, scheduled to pilot the Mercury-Atlas 7 mission, was grounded from flight because of problems with his heart. In March, 1972, he was returned to flight status. Slayton flew as docking module pilot on the joint Soviet/American Apollo-Soyuz mission in 1975.

The Mercury spacecraft was a marvel of compactness. The geniuses behind the program developed the technological roots for every American manned spaceflight that followed and quite a few unmanned ones. It had taken humans more than fifty years to get from the Wright brothers' first powered airplane, in 1903, to the launching of Sputnik 1, the world's first artificial satellite, in 1957. That was far longer than it took for civilization to go from putting small satellites in space to launching manned spacecraft.

See also Cassini-Huygens Mission; Galileo Mission; International Space Station; Mars Exploration Rovers; Moon Landing; Space Shuttle; Voyager Missions; Wilkinson Microwave Anisotropy Probe.

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—*Russell R. Tobias*

EARTH'S CORE

THE SCIENCE: Inge Lehmann hypothesized that Earth had an inner and an outer core, and her new theory was confirmed by subsequent investigations.

THE SCIENTISTS:
Inge Lehmann (1888-1993), Danish seismologist
John Milne (1850-1913), English engineer
Beno Gutenberg (1889-1960), German American seismologist

SEISMIC WAVES

Prior to the development of the seismograph, an instrument that records Earth vibrations or earthquakes, very little was known about the composition of the inner parts of the Earth. In the late 1800's, a basic knowledge of vibrations generated by a seismic source evolved. It was found that these vibrations, or waves, travel outward through the Earth at measurable speeds.

The science of geophysics recognizes two major types of "elastic" waves, which were defined by the British geologist Richard Dixon Oldham. The first type is called a "P wave" because it causes a "primary" disturbance that deforms the Earth by means of alternately lengthening and shortening in the direction of the source of the wave. P waves are also called "compressional waves" because the volume of Earth that is affected is alternately compressed and expanded. The second type of elastic wave is the "S wave," which produces a "secondary" disturbance. The S wave is a transverse body wave that travels through the interior of an elastic medium. S waves do not change the volume of the medium, but they do change its shape; for this reason, they are also called "distortional waves" or "shear waves." Both P waves and S waves pass through the interior of the Earth; for this reason, they are called "body waves."

When an earthquake occurs, its waves travel through the body of the Earth and are recorded by seismographs at earthquake observatories. These seismic waves carry to the surface information about the material through which they have passed. In 1883, the English engineer John Milne surmised that every large earthquake at any point of the globe could be recorded if there were an instrument designed for that purpose; however, it was not until 1893 that he perfected the first clockwork-powered seismograph.

In later years, when extremely sensitive seismographs had been developed, it was found that some weak P waves actually were penetrating a shadow zone, an area opposite the projected core of the Earth. The shadow zone, discovered in the research of the Croatian geophysicist Andrija Mohorovičić, was left unexplained in earlier research conducted by pioneers in the use of seismographs to map the interior. Inge Lehmann postulated the existence of an inner core that could reflect the rays back into the shadow zone.

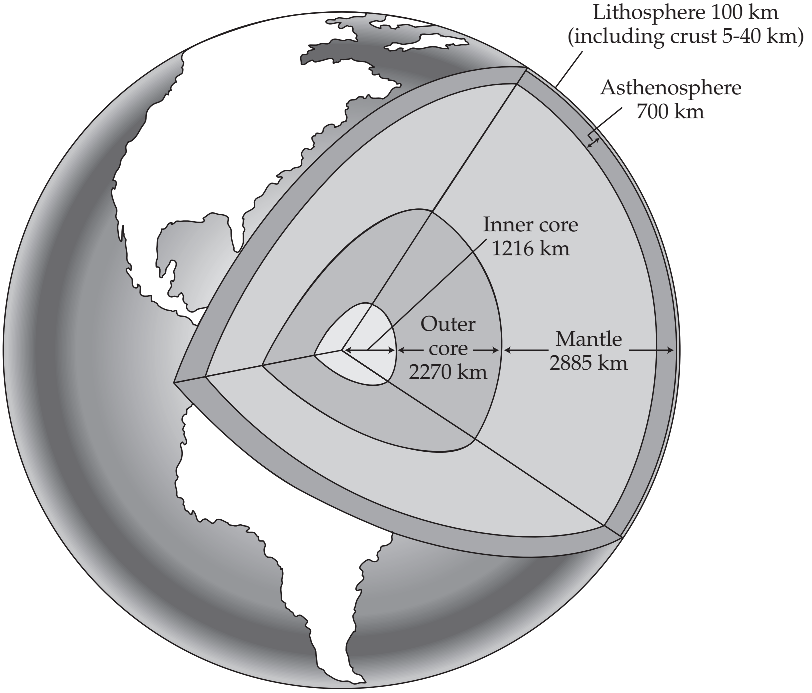
AN INNER CORE

At the Copenhagen Seismological Observatory, Lehmann had for a number of years been clearly observing, through the core, seismic waves caused by earthquakes in the Pacific Ocean. Among these were the shocks that occurred at Murchison and Hawke's Bay in New Zealand in 1928 and 1931, respectively. It was evident from these records that a P-type wave that should have been within the shadow zone was arriving at seismological stations. This phenomenon could be explained only by the existence of an inner core that was about 1,250 kilometers in radius and was denser than the outer core.

Lehmann believed that core waves could be classified into three separate types of P wave. The standard explanation for the first two of these wave types was that their rays were refracted at the boundary between the mantle and core and focused toward the antipodes, placed opposite each other on the globe. She explained that waves of the third type were reflections from another sharp discontinuity within the core itself. This family of waves is made up of the core refractions. Beyond about 103°, the direct P wave cannot be recorded because of the shadow effect of the core. Beyond this distance, the first wave to appear on long-period instruments is often a PP wave, which does not penetrate so deeply and therefore is able to avoid the obstacle. Short-period instruments show a refracted wave arising from complexities within the core, but it is not quite as prominent as P when it makes its reappearance at 142°. Because it is deflected from its path and disappears altogether for nearly 40°, it is called a "PKP wave" (K stands for *Kern*, the German word for "core").

In 1936, after ten years of interpreting seismograms (records made by a seismograph) and using a well-established scientific method, Lehmann was prepared to discover the inner core. Her first step was to calculate a direct problem. She assumed an Earth model that was particularly simple. It had constant velocities in the mantle (10 kilometers per second) and in the core (8 kilometers per second). These were reasonable average values for both regions. She then introduced a small central core, which again had a constant velocity. These simplifications enabled her to view the seismic rays as straight lines; therefore, their travel times could be calculated by using elementary trigonometry. She then showed by making successive adjustments that a reasonable velocity and radius of the inner core could be found that predicted a travel-time curve close to the observations of the third type of P wave. In effect, she proved an existence theorem: A plausi-

Earth's Interior



ble three-shell Earth structure could be defined that explained the features of the observed waves.

Lehmann's discovery of the inner core was very complicated, but it convinced Beno Gutenberg in the United States and Harold Jeffreys in England that her hypothesis was a viable one. Within two years, they had independently carried out more detailed calculations involving many observed travel times of P waves and calculated by means of an inverse method both the radius of the inner core and the P-velocity distribution in it.

Impact

After the discovery of Earth's inner core, the measured travel times could be transformed, using inverse theory, into plausible P velocities in the mantle and the outer core. In late 1938 and 1939, Gutenberg and Jeffreys computed, independently, the average velocity based on thousands of observed travel times of P and S waves. Their agreement was extremely close; in fact, their calculations were so well developed that they have not been seriously altered since.

As a result of the development of sensitive seismographs, an increase in the number of seismographic stations around the world, and the availability of large-capacity computers, a better understanding of the Earth has become possible. The core has a role in many geophysical studies, and the way it is affected during great earthquakes is being probed actively. If the physical properties inside the Earth were better known, the frequencies and amplitude patterns of the resonant vibrations could be calculated, thereby making it possible to prevent loss of life.

See also Continental Drift; Earth's Structure; Fossils; Geologic Change; Geomagnetic Reversals; Hydrothermal Vents; Microfossils; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating; Seafloor Spreading; Uniformitarianism.

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—*Earl G. Hoover*

EARTH'S STRUCTURE

THE SCIENCE: Richard Dixon Oldham, Andrija Mohorovičić, and other seismologists, using data from earthquakes, revealed the layered internal structure of the Earth.

THE SCIENTISTS:

Richard Dixon Oldham (1858-1936), Irish seismologist
Beno Gutenberg (1889-1960), German American seismologist
Andrija Mohorovičić (1857-1936), Croatian meteorologist and seismologist
Inge Lehmann (1888-1993), Danish seismologist

EARTH TIDES

The scientific picture of the deep interior of the Earth must rely upon indirect evidence. This picture has thus changed over time as new evidence becomes available. Only in the twentieth century, with the development of new measurement techniques, did a clear picture begin to emerge.

The preeminent geological text of the later half of the seventeenth century, German Jesuit and scholar Athanasius Kircher's *Mundus Subterraneus* (1664), described the Earth with a fiery central core from which emerged a web of channels that carried molten material into fire chambers or "glory holes" throughout the "bowels" of Earth. The "contraction" theory, popular through the first half of the nineteenth century, held that the Earth had formed from material from the Sun and had since been slowly cooling, creating a solid crust. As the fluid cooled, it would contract, and the crust would collapse around the now smaller core, causing earthquakes and producing wrinkles that formed the surface features of mountains and valleys.

Physicists in the 1860's, however, pointed out several physical consequences of the contraction model that appeared to be violated. For example, the gravitational force of the Moon, which creates tides in the ocean, would produce tides also in a fluid interior. The resulting effect should either cause the postulated thin crust to crack and produce earthquakes whenever the Moon was overhead or, if the crust were sufficiently elastic, cause tides in the crust as well. Instruments were developed to detect crustal tides, but no such tides were discovered.

By the beginning of the twentieth century, geologists were forced to abandon the contraction theory and conclude that the Earth probably was completely solid and "as rigid as steel." Thus, when the German geophysicist and meteorologist Alfred Lothar Wegener suggested the idea of continental drift in 1912, it was dismissed on this basis as being physically impossible. Ironically, the very measuring instruments that overturned the simple liquid interior contraction theory would, in turn, disprove the solid Earth view that had challenged and replaced it. Seismographs—such as the inverted pendulum seismograph invented in 1900 by German seismologist Emil Wiechert—would provide a completely new source of information about the internal structure of the Earth.

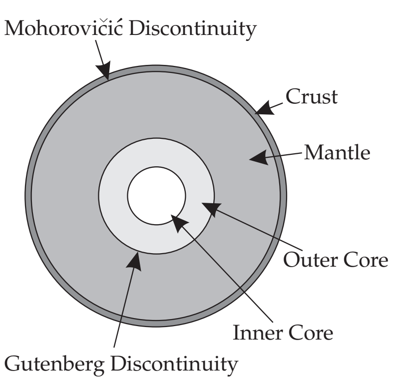
An X Ray of the Earth

In 1900, Richard Dixon Oldham published a paper that established that earthquakes give rise to three separate forms of wave motion that travel through the Earth at different rates and along different paths. When an earthquake occurs, it causes waves throughout the Earth that fan out from the earthquake's point of origin or "focus." Primary (P) waves emanate like sound waves from the focus, successively compressing and expanding the surrounding material. While P waves can travel through gases, liquids, and solids, secondary (S) waves can travel only through solids. S waves travel at about two-thirds the speed of P waves. Surface waves, the third type of seismic wave, travel only near the Earth's surface.

Seismologists now speak of seismic data as being able to provide an X-ray picture of the Earth. In his groundbreaking 1906 article, "The Earth's Interior as Revealed by Earthquakes," Oldham analyzed worldwide data on fourteen earthquakes. He also observed that within certain interior earth zones, P waves behaved differently from what he expected. In 1912, Beno Gutenberg was able to establish that at a certain depth the velocity at which the seismic waves traveled changed sharply. He estimated this depth to be about 2,900 kilometers (almost half of the Earth's radius).

Oldham had also recognized in his own data the suggestion of a thin outer crust, but his data were insufficient to determine its depth. This estimation was to be made by Andrija Mohorovičić, a professor at the Univer-

Earth's Discontinuities



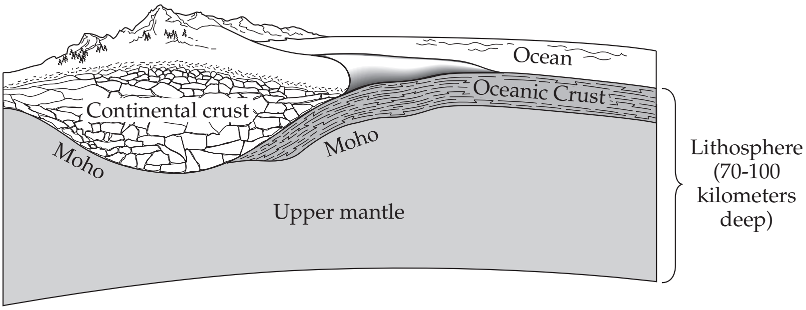
sity of Zagreb, from an analysis (published in 1910) of an earthquake that had hit Croatia's Kulpa Valley in late 1909. Mohorovičić had noticed that at any one seismic station, both P and S waves from the earthquake appeared in two sets, but the time between the sets varied according to how far away the station was from the earthquake's focus.

Based upon these different arrival times, Mohorovičić reasoned that waves from a single shock were taking two paths, one of which traveled for a time through a "faster" type of rock. He calculated the depth of this change in material. His estimate fell within the now-accepted figure of 20 to 70 kilometers (the crustal thickness varies under the continents and shrinks to between 6 and 8 kilometers under the ocean). This boundary between crust and mantle is now called the Mohorovičić Discontinuity, or the Moho.

IMPACT

The use of seismic data to plumb the Earth's interior produced an outpouring of research, both theoretical and experimental. By the mid-1920's, seismologists had learned to make subtler interpretations of their data and realized that no S waves had been observed to penetrate through the core.

The Mohorovičić Discontinuity



Since S waves cannot pass through liquid, there was reason to think that the core was liquid.

Independent support for this hypothesis came from rigidity studies. Seismic waves could be used to determine the rigidity of the mantle; it was revealed to be much greater than the average rigidity of the Earth as a whole (the existence of a low-density fluid region would account for this discrepancy). In 1936, however, Inge Lehmann was able to show that P waves passing close to the Earth's center changed velocity slightly, and she correctly inferred the existence of an inner core to account for this phenomenon. The current picture of the Earth now includes a liquid outer core surrounding a solid inner core about 1,200 kilometers in radius.

See also Continental Drift; Earth's Core; Fossils; Geologic Change; Geomagnetic Reversals; Hydrothermal Vents; Mid-Atlantic Ridge; Plate Tectonics; Seafloor Spreading; Uniformitarianism.

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—*Robert T. Pennock*

ELECTRIC CHARGE

THE SCIENCE: In extending the electrical experiments of Stephen Gray, Charles Du Fay discovered two kinds of electric charge: "vitreous" and "resinous" electricity. He demonstrated that like charges repel and unlike charges attract. This two-fluid theory of electricity was modified by Benjamin Franklin's one-fluid theory, in which an excess or deficiency of the electric fluid was designated positive or negative in place of Du Fay's two kinds of electricity.

THE SCIENTISTS:

Charles-François de Cisternay Du Fay (1698-1739), French scientist at the Academy of Sciences in Paris

Stephen Gray (1666-1736), English pensioner who discovered electrical conduction

Benjamin Franklin (1706-1790), American scientist, statesman, and diplomat

Francis Hauksbee (1666-1713), English instrument maker at the Royal Society of London

ELECTRICAL PHEMONENA: EARLY STUDIES

The Greek natural philosopher Thales discovered the attractive effect of rubbed amber, hence the terms *elektron* (amber), which developed into the term "electricity." English physician William Gilbert began the modern study of electric phenomena in the late sixteenth century when he demonstrated that about thirty materials could be electrified. During the seventeenth century, the study of electrical phenomena was often considered practice in the occult, and so was generally neglected. Electrical studies received impetus when the English pensioner and electrical experimenter Stephen Gray discovered the conduction of "electric virtue" in 1729 and found a distinction between conductors and insulators. This led directly to the work of the French scientist Charles-François de Cisternay Du Fay and his two-fluid theory of electricity, in which like fluids repel and unlike fluids attract. Du Fay's work led to the experiments of Benjamin Franklin and his one-fluid, or single-fluid, theory of positive and negative electricity.

Francis Hauksbee, an uneducated instrument maker and demonstrator at the Royal Society of London, revived interest in electricity in eighteenth century England. Encouraged by Sir Isaac Newton, who was serving as the new president of the society, Hauksbee enhanced his electrical experiments in 1705 by using a long glass tube in place of amber, observing electrostatic repulsion. When he rubbed a glass tube, the rubbing not only attracted bits of matter; it also would sometimes adhere to and be thrown from the tube.

Gray, a dyer by trade, followed up on these electrical experiments. In 1708 he transmitted to the Royal Society the results of his experiments with a glass tube, which were similarly performed by Hauksbee. Gray's first paper, which appeared in the society's *Philosophical Transactions* in 1720, described light and sparks from a glass tube when rubbed in the dark and identified several new materials that could be electrified. A second paper in 1729 described his discovery of electrical conduction. After placing corks in the ends of a glass tube to keep out dust, he found that the cork attracted and repelled a down feather. He concluded that there was an attractive "virtue" communicated to the cork by the "excited" tube.

In his 1729 paper, Gray described a series of experiments on the conduction of electric virtue. He inserted a rod into one of the corks and observed attraction to an ivory ball on the other end of the rod. He then found that metal wire from the cork in the glass tube would conduct electricity to the ivory ball. Working with friends, he was able to observe attraction by the ivory ball suspended on 34 feet of packthread from the glass tube. He then made several attempts to pass the electric virtue along a horizontal line suspended by packthread from a roof beam, but his lack of success led him to conclude that the electricity escaped through the beam (grounding). He finally succeeded by using silk thread to support his horizontal line.

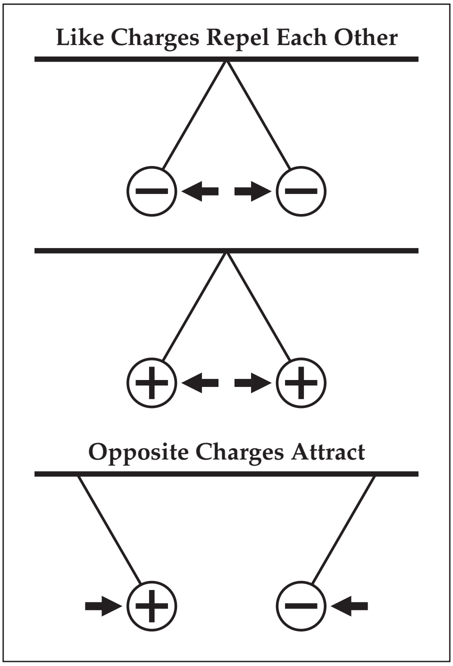
Gray continued his experiments in a barn, succeeding with a packthread line up to 293 feet; when he used metal wire to support a longer line, however, the experiment failed. Using silk supports again, he succeeded in transmitting electricity up to about 650 feet. Thus, he finally recognized the basic distinction between insulators such as silk and glass, and conductors such as metals and packthread. In a 1732 paper, he reported on the electrification of materials by the influence of an electrified glass tube without direct contact.

Two-Fluid and One-Fluid Theories

Electrical studies were soon begun in Paris at the French Academy of Sciences by Du Fay, a self-trained scientist who published papers in all the sciences recognized by the academy and became superintendent of the Royal Gardens. In 1732, Du Fay heard of Gray's experiments and reviewed the existing literature in his first memoir on electricity for the academy. In a half dozen other memoirs on electricity, Du Fay reported his experiments and discoveries. He showed that all materials could be electrified: solids by friction if properly dried and liquids by electrical influence. He repeated Gray's experiments on conduction, obtaining better results by using wet packthread supported on glass tubes up to a distance of 1,256 feet.

In 1733, Du Fay found that gold foils could be attracted to an electrified glass tube, but they would repel each other when approached or touched by the tube. This appears to be the first clear demonstration of electric repulsion. However, to his surprise, when a rod of gum resin electrified one of the gold foils, it attracted the other gold foil. This led him to recognize the existence of two kinds of electricity and to determine how they behave.

Du Fay's experiments led him to distinguish "vitreous" electricity—



hard materials such as glass, rock crystal, and precious stones—and "resinous" electricity, softer materials such as amber, gum resin, and paper. He then described how electrified vitreous objects attract resinous objects, but two vitreous objects or two resinous objects repel each other. Although Du Fay never referred to "fluids," his discovery was called the two-fluid theory of electricity, that bodies with like "electric fluids" repel and those of unlike fluids attract. Du Fay sent his results to the Royal Society, where they were translated into English and published in the *Philosophical Transactions* for 1734. Transferring electric fluid to an object came to be viewed as loading or charging the object, leading to the term "electric charge."

At Boston in 1746, Benjamin Franklin was introduced to electrostatic phenomena and began to experiment with them. In 1747 he stated his one-fluid theory of electricity, in which transferring electricity causes one object to lose electric charge, becoming negative, and the other object to gain charge, becoming positive. Later he identified positive and negative charge with Du Fay's vitreous and resinous fluids, respectively, which he viewed as a surplus or deficiency of a single electric fluid. Franklin's assumption that electrification does not create or destroy charge, but only transfers it from one body to another, implies the law of conservation of electric charge.

IMPACT

The identification of positive and negative electric charge and their properties led to the modern science of electricity. By using the mathematical terms "plus" and "minus," Benjamin Franklin suggested the possibility that electricity is quantitative and measurable. Franklin's theory led to development of the law of electric force by French engineer Charles Coulomb in 1785. The discovery of ways to maintain the flow of electric charge as an electric current opened up the field of practical electricity for heating, lighting, electromagnetism, telegraphy, and many other applications in the nineteenth century.

Ironically, Franklin's choice of positive and negative charges turned out to be mistaken. The discovery of the electron by the English physicist J. J. Thompson at the end of the nineteenth century made it evident that vitreous materials tend to lose electrons and thus should have been called negative, while resinous materials gain electrons and should have been called positive. To accommodate this mistake, electrons are designated as negative and are the basic unit of negative charge. The corresponding positive unit of charge was discovered early in the twentieth century with an equal and opposite charge, but the proton was found to have a mass nearly two thousand times larger than that of the electron.

The atomic number of an element corresponds to the number of protons in the atomic nucleus, with an equal number of electrons surrounding the nucleus. Electric current in most conductors consists of the flow of only electrons, reflecting Franklin's one-fluid theory, but both electrons and protons flow in gaseous discharges, matching Du Fay's two-fluid theory. The existence of both electrons and protons seems to favor Du Fay's theory.

See also Conductivity; Electrodynamics; Electromagnetism; Electrons; Lightning; Magnetism.

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—*Joseph L. Spradley*

ELECTRODYNAMICS

THE SCIENCE: André Ampère, a professor of mathematics, was the first person to describe the mathematical relationships between electricity and magnetism, which led to the modern understanding of light and radio waves and the development of the telegraph.

THE SCIENTISTS:

André-Marie Ampère (1775-1836), French mathematician and physicist whose work led to the new field of electrodynamics
Félix Savart (1797-1841), French scientist who assisted Ampère in his work on electrodynamics and then became a professor of astronomy
Hans Christian Ørsted (1777-1851), Danish physicist who showed that a wire carrying a current deflected a magnetized compass needle
François Arago (1786-1853), French physicist and astronomer

ELECTRICITY AND MAGNETISM

The magnetic compass was invented by the Chinese, who used loadstone, a naturally occurring magnetic material, in water compasses to guide ships as early as the eleventh century. But only naturally occurring iron or lodestone was known to be magnetic until the nineteenth century.

This changed in 1820, when a Danish physicist, Hans Christian Ørsted, performed a series of science demonstrations in his home for a group of his friends and students. First Ørsted demonstrated that an electric current caused a wire to heat up. He also planned to demonstrate magnetism, and he had a compass needle mounted on a wooden stand. While performing his heating demonstration, Ørsted noticed that every time the electric current was turned on, the compass needle moved. Ørsted had discovered that the electric current in a wire caused the deflection of a magnetic needle. This experiment provided the first demonstration that there was a relationship between electricity and magnetism.

ARAGO'S ELECTROMAGNET

François Arago, a French physicist and astronomer, reported on Ørsted's discovery at a meeting of the French Academy of Sciences in Paris on September 4, 1820. Arago repeated Ørsted's experiments at a meeting and began his own research on the relationship between electricity and magnetism. A mere week later, Arago showed that the passage of an electric current through a cylindrical spiral of copper wire caused it to attract iron filings as if it were a magnet. As soon as the current was turned off, the iron filings fell off the copper. Arago's demonstration was the first use of an "electromagnet," a magnet that works due to the passage of current through a coiled wire.

AMPÈRE'S GALVANOMETER

Another French physicist, André Ampère, a professor of mathematics at the École Polytechnique in Paris, was fascinated by Arago's report of Ørsted's research. Although Ampère was a mathematics professor, he worked on a wide variety of topics, including metaphysics, physics, and chemistry. Ampère tried not only to repeat and extend Ørsted's experiments but also to develop mathematical laws describing the relationship between electricity and magnetism.

Ampère is not recognized as a methodical experimentalist. Rather, he is known for having had brilliant flashes of insight, which he would pursue to their logical conclusion. Within a few weeks, Ampère had demonstrated various electrical and magnetic effects to the French Academy. Ampère had the insight to recognize that that if a current in a wire exerted a magnetic force on a compass needle, then two current-carrying wires should each produce a magnetic field, and the magnetic fields of these wires should interact. By the end of September, 1820, Ampère had demonstrated these interactions, observing that two parallel, current-carrying wires are attracted to each other if both currents are in the same direction, but they repel each other if the two currents flow in opposite directions.

Ampère's discoveries allowed him to design and build an instrument, called a galvanometer, to measure the flow of electricity. A simple galvanometer is a compass with a conducting wire wrapped around it. If the wire carries an electrical current—for example, by connecting it across the terminals of a battery—then the current that flows in the wire will produce a magnetic field that deflects the compass needle. The stronger the current, the larger the deflection of the needle, so the position of the needle indicates the amount of current flowing in the wire. Ampère's invention of the galvanometer allowed him to perform quantitative experiments on the relationship between the amount of current that was flowing in a pair of wires and the strength of the magnetic force between them. This development was critical in the formulation of the equations that relate electricity to magnetism.

THE BIOT-SAVART LAW

Ampère was not the only person who reacted quickly to Arago's report of Ørsted's discovery. Jean-Baptiste Biot and his assistant, Félix Savart, conducted experiments on electromagnetism and reported to the Academy in October, 1820. This led to the Biot-Savart law, which relates the intensity of the magnetic field set up by a current flowing through a wire to the distance from the wire.

Another French experimenter who worked on magnetism at this time was Siméon-Denis Poisson, who treated magnetism as a phenomenon completely separate from electricity. Ampère continued his work as well, describing his law for the addition of "electrodynamical forces" to the Academy on November 6, 1820.

AMPÈRE'S LAW

Over the next few years Ampère was assisted by Savart, who performed many experiments and helped Ampère write up the results. Ampère's most important publication on electricity and magnetism, his *Mémoire sur la théorie mathématique des phénomènes électrodynamiques, uniquement déduite de l'expérience* (1827; notes on the mathematical theory of electrodynamic phenomena deduced solely from experiment), describes four of his experiments and contains the mathematical derivation of the electrodynamic force law. Physicists now refer to one of Ampère's mathematical relationships as Ampère's law, an equation relating the electric current flowing through a wire to the strength of the resulting magnetic field at any distance from the wire.

Ampère even attempted to explain the natural magnetism of the compass needle. He knew that if a current flowed through a circular loop of wire it created a magnet very much like the magnetic compass needle. Ampère proposed that each atom of iron contained an electric current, turning the atom into a small magnet. In an iron magnet, all these atomic magnets were lined up in the same direction, so their magnetic forces would be combined.

IMPACT

Ampère's discoveries, as well as the work of Arago, had immediate and practical applications. Once it was discovered that a current-carrying wire generated magnetism, it was a simple matter to bend that wire into a coil to stack many loops of wire on top of each other and strengthen the magnetic effect. The development of the electromagnet was the immediate result. In 1823, William Sturgeon wrapped eighteen turns of copper wire around a bar, producing an electromagnet that could lift twenty times its own weight.

In 1829 Joseph Henry used insulated wire on his electromagnet, allowing the wires to come closer together without shorting, and by 1831 Henry had demonstrated an electromagnet that could lift a ton of iron. The electromagnet is also the basis for the operation of the telegraph, the first practical means for instant communication over long distances. Samuel Morse developed the idea of an electromagnetic telegraph in 1832. Although Morse constructed an experimental version in 1835, the first practical telegraph system was a line from Baltimore to Washington, D.C., put into operation in 1844.

Ampère's discovery also provided an explanation for the Earth's magnetic field, which could not be caused by a natural lodestone in the Earth (as once proposed) because lodestone loses its magnetism at high temperatures and temperature is known to increase with depth in the Earth. Instead, Ampère's work opened the possibility that a circulating electric current in the Earth's core generates the Earth's magnetic field.

The discovery of the link between electricity and magnetism was also fundamental to the later understanding of electromagnetic waves, including light waves and radio waves. In 1864, James Clerk Maxwell demonstrated that the connection between the electric and the magnetic forces involved a constant, the velocity of light in a vacuum. The idea that light was an electromagnetic phenomenon evolved from Maxwell's work and in turn led to the discovery of radio waves, the development of the theory of relativity, and much of twentieth century physics.

Ampère's work was thus fundamental to a broad array of both theoretical and applied physics. The fundamental unit of electric current was named the "ampere" in honor of Ampère's contributions to electromagnetism and electrodynamics.

See also Conductivity; Electric Charge; Electromagnetism; Electrons; Lightning; Magnetism.

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—*George J. Flynn*

ELECTROMAGNETISM

THE SCIENCE: Michael Faraday converted magnetic force into electricity through experiments that reinforce the belief in field theory, arguing that light, electricity, and magnetism are interrelated.

THE SCIENTISTS:

Michael Faraday (1791-1867), British scientist who became director of London's Royal Institution laboratory in 1825

André-Marie Ampère (1775-1836), French scientist who studied the connection between electricity and magnetism

Humphry Davy (1778-1829), British scientist and director of London's Royal Institution

Hans Christian Ørsted (1777-1851), Danish scientist who sought a connection between electricity and magnetism

A FIELD OF FORCES

Early in the nineteenth century, scientists who studied heat, light, electricity, and magnetism were finding that some of their experimental evidence contradicted the established principles of Newtonian science. According to the classic physics of Sir Isaac Newton, these phenomena should behave as separate and distinct, acting as straight-line forces between centers of bodies. However, later experiments suggested that these forces exerted their influence as waves acting through some medium.

With this evidence, physicists began to think in terms of a "field" of forces rather than straight-line effects. This growing belief in a field theory benefited from the influential nineteenth century German *Naturphilosophie* (natural philosophy) school, which sought a unity in nature to prove that a *Weltseele* (a world spirit or force) was the sole power in nature.

Naturphilosophie heavily influenced the Danish scientist Hans Christian Ørsted during his graduate studies in Germany. When he returned to Denmark, Ørsted embraced this belief in the unity of forces and sought demonstrable evidence of a link between electricity and magnetism. In 1813,

THE MAGNETIC MICHAEL FARADAY

Considered the greatest British physicist of the nineteenth century, Michael Faraday was the son of a poor Yorkshire blacksmith. Michael received only a rudimentary education and never mastered mathematics. As a teenager, he was inspired to become a scientist by reading an article on electricity in the *Encyclopaedia Britannica*.

(National Archives)

By 1825 Faraday was the director of the Royal Institution's laboratory as well as a beloved educator. His Friday Evening Discourses and Christmas Courses of Lectures for Juvenile Audiences exercised a magic on his audience, especially children: As they listened, a sense of drama and wonder unfolded among them, and they delighted in the marvels of Faraday's experiments.

In 1831, Faraday made his most famous discovery, reversing Hans Christian Ørsted's experiment by converting magnetism into electricity—which he called electromagnetic induction—and elaborating a conception of curved magnetic lines of force to account for the phenomenon. He then devised variations and extensions of the phenomenon, the most famous one being the invention of the dynamo. He converted mechanical motion into electricity by turning a copper disc between the poles of a horseshoe magnet, thereby producing continuous flowing electricity. This discovery laid the foundation for the entire electric-power industry.

In 1833, Faraday studied the relationship between electricity and chemical action to reveal the two laws of electrochemistry. He then devised a beautiful, elegant theory of electrochemical decomposition which, totally at odds with the thinking of his contemporaries, demanded a new language for electrochemistry: electrode, anode, cathode, anion, cation, electrolysis, and electrolyte—terms in use to this day.

In 1838, Faraday's stupendous labors led to a serious mental breakdown that prevented him from working for five years. After recuperating, he responded to a suggestion by William Thomson (Lord Kelvin) to experiment with the relationship between light and electricity. This stimulated Faraday to discover the effect of magnetic force on light: magneto-optical rotation. The fact that the magnetic force acted through the medium of glass further suggested to Faraday a study of how substances react in a magnetic field. This study revealed the class of diamagnetic substances. Faraday listed more than fifty substances that reacted to magnets not by aligning themselves along the lines of magnetic force (paramagnetics) but by setting themselves across the lines of force. This attracted more attention from scientists than any of his other discoveries.

Faraday's theorizing led in the 1850's to the idea that a conductor or magnet causes stresses in its surroundings, a force field. The energy of action lay in the medium, not in the conductor or magnet. Faraday came to envision the universe as crisscrossed by a network of lines of force, and he suggested that they could vibrate and thereby transmit the transverse waves of which light consists. These speculations contradicted Newtonian physics and led to field theory, which would have an immeasurable influence on physics.

Faraday's mental faculties gradually deteriorated after 1855. Concern for his health reached Prince Albert; at his request, Queen Victoria in 1858 placed a home near Hampton Court at Faraday's disposal for the rest of his life. There, he sank into senility until his death in 1867. Like his life, his funeral was simple and private. His legacy, however, was richly complex and for all the world.

he published results of an experiment which demonstrated that an electrical current moving through a wire deflected a compass needle.

A few years later, in the early 1820's, French scientist André Ampère found that a circular coil of wire carrying a current acted like a magnet. He also found that current moving in parallel wires caused an attraction or repulsion depending on the direction of the current in those wires. Clearly, electricity and magnetism were somehow related.

Faraday's Search for Unity

These experimental results intrigued two members of London's Royal Institution, founded in 1799 to spread scientific knowledge and conduct scientific experiments. Humphry Davy, its director, and his assistant, Michael Faraday, repeated and extended Ørsted's work in 1820 and 1821. Befitting his role at the Royal Institution, Faraday conducted a series of experiments treating electromagnetism and published a compendium of existing knowledge about the field in his "Historical Sketch of Electromagnetism" in late 1821 and early 1822. This review of the subject heightened Faraday's interest in seeking a unity of nature's forces.

In his search for unity, Faraday brought a theoretical construct shaped by *Naturphilosophie* and his theological beliefs grounded in the fundamentalist sect known as the Sandemanians. His religious beliefs instilled in him the notion that nature derived from a single force, God; hence, as he investigated nature, he sought an economy to and unity of nature that would endorse those beliefs. During the 1820's, he conducted experiments to confirm the relationships between and among electricity, heat, light, and magnetism.

At the Royal Institution, Faraday had a basement laboratory where he investigated many developing scientific concepts. There, in 1821, he demonstrated that a bar magnet rotated around a wire carrying a current and postulated that circular lines of force accounted for the path of that motion. These results, producing electromagnetic rotation, set in place a continuing effort by Faraday over many years to use experimental methods to discover the connections between electricity and magnetism. In doing so, he held steadfast to the principle that viable scientific theories must rely on strong experimental evidence. Faraday constantly revised his theories through experiment with a superb talent that combined preceptual, conceptual, and laboratory-based information to generate new knowledge. He recorded his laboratory investigations meticulously in a diary he kept over a forty-year period. It is a rich source of information about his speculations in the world of science and his ingenuity in explaining theories with elegant and carefully planned public demonstrations and lectures.

Experiments and More Experiments

Faraday, a skilled experimentalist, continually addressed the issue of electromagnetism during the 1820's. By 1824, he believed a magnet should act on a current, just as Ørsted had demonstrated that a current acted on a magnet. With Faraday's many duties at the Royal Institution, where he became director of the laboratory in 1825, and his private work as a consulting scientist, he turned to the issue repeatedly but sporadically for years. Finally, in 1831, he began a series of experiments over the course of four months, from August to November, in which he focused on electromagnetic induction.

During those four months, Faraday conducted 135 experiments to test his hypothesis that electricity can be induced by magnetic substances. His first success came in late April, when he arranged two separate coils of wire, insulated from each other, around opposite sides of an iron ring and suspended a magnetic needle over this ring. He then introduced a current in one wire coil and detected an induced current in the second wire coil on the ring—the magnetic needle oscillated. This experimental evidence confirmed his long-held belief that electricity was related to magnetism: The movement of electrical current in a coil of wire produced a current in another coil when these two coils were linked by a magnetic material.

ELECTROMAGNETIC INDUCTION

Although this experiment had confirmed much of his expectations, it had one surprising result. Faraday had assumed that the induced current in the second coil would be continuous; instead, he discovered that it was transient: He obtained a pulse of current, not a continuous flow. Yet the evidence of his August, 1831, experiment convinced him electromagnetic induction was a fact, and he conducted several more tests over the next few months building on the evidence of his first researches. By mid-October of 1831, he was producing an electric current directly from a magnet itself by the reciprocal motion of a magnet in and out of a cylindrical helix. The key to this process lay in his strong belief in a field composed of lines of force: Continuous electricity was produced only when a conductor was moved through a magnetic field cutting the lines of force.

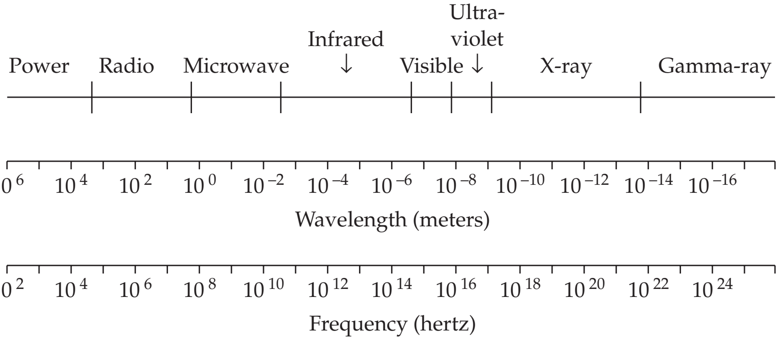
An experiment conducted in late October, 1831, confirmed this: Faraday rotated a copper disc between the poles of a powerful electromagnet and obtained a continuous current. These results provided Faraday with the experimental evidence he needed to prove his theory of the unity of forces between electricity and magnetism. On November 24, 1831, he presented those findings to the Royal Society in a series entitled *Experimental Researches in Electricity*. In this public setting, Faraday had demonstrated the reciprocal linkage between magnetism and electricity.

IMPACT

Faraday's work represents the importance of careful, thorough experimentation in nineteenth century physics. Although Faraday held strong convictions about the nature of forces, he tested those notions in the laboratory and constantly revised his interpretations of events based on his experimental results. The Royal Institution, his scientific and personal home for almost forty years, provided the framework and facilities for his ongoing research. His special skill in devising definitive experiments allowed him to discover electromagnetic induction and to explain it to the scientific community in elegant ways. In doing so, he was a founder of the scientific world of field theory and the technological world of electrical power.

With his brilliant experimental work, Faraday established the scientific principles that resulted in the development of electric generators or dynamos. These devices became the foundation of a new electrical technology using generators and motors as a new power source in the latter half of the nineteenth century. His work also reinforced the unity principles of

THE ELECTROMAGNETIC SPECTRUM



Naturphilosophie and convinced many nineteenth century physicists that electricity, magnetism, and light were interrelated.

Faraday's experimental evidence provided a foundation for James Clerk Maxwell, a distinguished British physicist, to analyze electromagnetic forces propagated through space. The result, Maxwell's equations, became the basis for field theory and provided unifying mathematical statements for the observations of electromagnetic forces studied by experimentalists such as Ørsted and Faraday.

See also Conductivity; Electric Charge; Electrodynamics; Electrons; Lightning; Magnetism; Speed of Light; Wave-Particle Duality of Light; X Radiation.

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—*H. J. Eisenman*

ELECTRON TUNNELING

THE SCIENCE: Japanese physicist Leo Esaki demonstrated tunneling effects in electronic systems, a discovery that would help to revolutionize the field of electronics.

THE SCIENTISTS:
Leo Esaki (b. 1925), Japanese physicist
Ivar Giaever (b. 1929), Norwegian physicist
Brian Josephson (b. 1940), British physicist
William Shockley (1910-1989), American physicist
Walter H. Brattain (1902-1987), American physicist

THE SEMICONDUCTOR REVOLUTION

Electrical and electronic devices rely on electrons to perform work, such as generating heat, creating sound waves, or moving a machine part. In a simple electrical device (a lightbulb, for example), the flow of electricity is controlled by a manual switch; in an electronic device, one electrical signal controls others. The advances that make up the electronic revolution may be thought of in simple terms as the creation of ever smaller, cheaper, and more sensitive switches for controlling electrical current.

In the 1920's and 1930's—the period between the two world wars and before the invention of the transistor—electronic switching was done by using electron beams enclosed in vacuum tubes the size of small lightbulbs. These devices needed to be heated and required substantial current to run. The earliest computers, which were built with this technology, occupied entire rooms and were less powerful than a modern hand-held calculator.

The invention of the transistor by William Shockley, John Bardeen, and Walter H. Brattain in 1948 profoundly changed electronics engineering. A transistor uses the properties of a semiconductor, such as silicon, for switching. A semiconductor is a substance in which low-energy electrons are not free to move but higher-energy electrons are. Therefore, when voltage (a measure of electron energy) increases past a certain point, a semiconductor will conduct current. Thus, it acts as a voltage-sensitive switch, performing all the functions of a vacuum tube in much less space and with much less energy. Furthermore, the sensitivity of a silicon switch and the direction in which it passes current can be modified quite precisely by the addition of impurities (materials other than silicon). An entire new industry was created, in which the Japanese took the lead in applying the new technology to consumer products.

Improving Semiconductor Diodes

In 1956, Leo Esaki was a doctoral student at Tokyo University who also worked for the Sony Corporation. He was looking for ways of improving semiconductor diodes with p-n junctions ("p-n" stands for positive-negative). A p-n junction is formed when half of a piece of a semiconductor, such as silicon, is "doped" with impurities (that is, has impurities added to it) that have fewer electrons than the silicon does, creating a net positive charge, and the other half of the piece contains impurities with excess electrons, creating a net negative charge. P-n junctions are fundamental to modern electronics; much of the process of manufacturing a silicon chip consists of selectively introducing impurities into microscopic regions on the chip to create thousands of p-n junctions.

Esaki experimented with various levels of impurities in silicon and another semiconductor, germanium, taking advantage of improving technology for doping semiconductors to produce junctions that were far narrower and more clearly defined than had been possible a few years earlier. He then drew current across the junction as a function of increasing voltage. At the junction, a potential barrier exists that classical physics theory predicted electrons must surmount in order to flow through the semiconductor. Previous experiments had demonstrated current flow only at voltage levels greater than the potential barrier, but in heavily doped germanium crystals, current flow occurred at lower levels. This, Esaki showed, was the result of a tunneling effect.

The tunneling of electrons through a potential barrier, which is predicted by Albert Einstein's theory of general relativity, is related to the dual nature of an electron as both a particle and a wave. A relativistic particle (that is, a particle whose behavior is described by Einstein's theory) has a certain probability of being found in a region that is forbidden to it by classical physics. As long as the potential barrier region was broad (as it had been in earlier experiments), too few electrons tunneled through the barrier to be detected, but with the improved technology that made it possible

Leo Esaki: Tunneling Through Barriers

It would perhaps not be overstating the case to observe that there is a poetic consistency between the nature of Leo Esaki's extremely technical research as an atomic physicist and his philosophy as an international scientist. Esaki himself suggested the connection in the conclusion to his 1973 Nobel Prize lecture, when he noted that although his scientific research had made tunneling through a barrier possible, other barriers still existed:

> I would like to point out that many high barriers exist in this world: Barriers between nations, races and creeds. Unfortunately, some barriers are thick and strong. But I hope, with determination, we will find a way to tunnel through these barriers easily and freely. . . .

The Nobel Prize immediately gave him the opportunity to do so. Responding to the mild confusion about the nationality of the person winning the prize, Esaki observed in an interview for *The New York Times* (October 24, 1973), "Americans think an American Esaki won the award. On the other hand, the Japanese think a Japanese Esaki won it, and that's fine with me because science is international and the Nobel prize is international." It seems a characteristic of this international scientist that when he took a break from his work of penetrating microcosmic physical barriers, he was breaking down barriers of a different kind.

to construct narrow p-n junctions, Esaki was able to demonstrate the tunneling phenomenon that had been predicted in mathematical models.

Image Not Available

Impact

The techniques for the precise introduction of impurities into semiconductors developed by Esaki and his colleagues in the Sony laboratories are key to the production of silicon chips that form the basis of modern electronics. Esaki "tunnel diodes" have both advantages and disadvantages when compared with nontunneling semiconductor transistors. Tunnel diodes are used together with transistors in computers, and they have been found to be particularly useful in sensitive microwave detectors, such as those used in radio telescopes.

The demonstration of electron tunneling across p-n junctions in semiconductors stimulated investigation in other areas—notably, superconductivity. The work of Brian Josephson and Ivar Giaever, who shared the 1973 Nobel Prize in Physics with Esaki, also concerned tunneling in superconductors.

The silicon revolution has transformed manufacturing, communications, and information processing, and it has allowed virtually every task that can be done by electricity to be done with an efficiency and an economy that was not dreamed of before World War II. Its discoveries are not the product of a single person, laboratory, or nation; the silicon revolution is worldwide. The discoveries of Shockley, Esaki, Josephson, Giaever, and others who built upon their work helped to reshape the modern world.

See also Alpha Decay; Heisenberg's Uncertainty Principle; Quantized Hall Effect; Superconductivity.

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—*Martha Sherwood-Pike*

ELECTRONS

THE SCIENCE: Sir Joseph John Thomson's discovery of the electron explained the nature of the cathode rays, provided explanations for problems with currents in gases, and paved the way for the understanding of atomic structure.

THE SCIENTISTS:

Sir Joseph John Thomson (1856-1940), English physicist, director of the Cavendish Laboratory, and winner of the 1906 Nobel Prize in Physics

Charles Thomson Rees Wilson (1869-1959), Scottish physicist who developed the cloud chamber and cowinner of the 1927 Nobel Prize in Physics

Wilhelm Conrad Röntgen (1845-1923), German physicist who discovered X rays and winner of the 1901 Nobel Prize in Physics

Philipp Lenard (1862-1947), Hungarian-born, German-educated physicist who won the 1905 Nobel Prize in Physics

CATHODE RAYS: WAVES OR PARTICLES?

In his celebrated work *Treatise on Electricity and Magnetism*, published in 1873, James Clerk Maxwell stressed the need to study the complex processes involved in electric discharge in gases in order to understand the nature of the charge and the medium. In 1879, the English chemist Sir William Crookes—who had invented the Crookes tube and was the first to observe radiations emitted from a cathode in an evacuated glass tube through which electric discharges occurred—published an extensive study of the attributes of these rays. Among other properties, Crookes noted that cathode rays cast shadows and were bent by a magnetic field. He concluded that they were made up of particles.

On the suggestion by Hermann von Helmholtz, Eugen Goldstein of Berlin studied the cathode rays exhaustively and published an impressive paper in the English *Philosophical Magazine* in 1880, firmly convinced that these rays were a form of waves. Thus, in 1880, the divergence of opinion regarding the nature of cathode rays became the central problem. Crookes and the leading English physicists believed that the cathode rays consisted of electrified particles, while the German physicists, led by Heinrich Hertz, were certain that these rays were waves.

In 1883, Hertz found that the cathode rays could be bent if one applied a magnetic field outside a discharge tube. He attempted to determine the relation between the magnetic field and the direction of the discharge inside the tube (between two parallel glass plates, which enabled him to determine the current distribution therein) but found no significant correlation. Hertz applied static electric fields both inside and outside the tube via parallel conducting plates connected to batteries up to 240 volts. He hypothesized that this would produce a force perpendicular to the direction of the rays, deflecting them if they were composed of charged particles. In both situations, he obtained a null result. His long series of experiments seemed to confirm the basic premise with which he had started: that cathode rays were waves, not particles.

His pupil, Philipp Lenard, continued the study of cathode rays, concentrating on their properties outside the tube, which made them easier to handle. He showed that once out of the tube, the rays rendered the air a conducting medium and blackened the photographic plates; moreover, the distance they traveled depended on the weight-per-unit area of matter, not on its chemical properties, and the magnetic deflection was independent of the gas inside the tube. Like Hertz, Lenard believed that he was dealing with a wave phenomenon.

In 1895, Jean-Baptiste Perrin, repeating Crookes's experiment with improved equipment, succeeded in collecting from cathode rays negatively charged particles in an insulated metal cup. This result cast doubt on the wave nature of cathode rays. Consequently, by late 1895, two divergent views prevailed among the leading physicists as to the nature of electric charges. One group thought of them as portions of fluids consisting of large numbers of "molecules of electricity," or electrons. The other group regarded the "charge" as a result of an unknown form of stress in ether, attached to matter being rendered visible. The nature of the cathode rays remained unresolved.

From X Rays to Electrons

In 1895, at the University of Würzburg, while studying discharges produced by an induction coil in an evacuated Crookes tube, Wilhelm Conrad Röntgen accidentally discovered X rays, which were produced by cathode rays as they impacted a platinum target. X rays were found capable of penetrating matter and ionizing a gaseous medium, making it conduct. This property of X rays accelerated the study of conductivity in gases. Sir Joseph John Thomson's use of this property of X rays proved to be the pivotal point in guiding him toward the discovery of the electron.

In the hope of resolving the controversy on the nature of cathode rays, Thomson repeated Perrin's experiment with minor modifications in the collection and measurement of the charges. Using a magnetic field to bend the rays, he collected them in a metal cup placed away from the direct line. He found that the charge in the cup reached a steady state after attaining a maximum value, which he correctly explained as caused by leakage into surrounding space. Hertz had failed to observe electric deflection of the cathode rays. Thomson—using two conducting plates between the cathode rays within the tube, applying an electrostatic field between the plates, and utilizing a better vacuum technique compared to that available to

J. J. THOMSON AND THE BIRTH OF PARTICLE PHYSICS

In a lecture given at England's Royal Institution on April 30, 1897, J. J. Thomson gave his first public account of his discoveries regarding cathode rays. Thomson's conclusion about the mass of the electron was not regarded by the physics community as entirely new. However, physicists were slow in recognizing the implications of Thomson's results. In addition, Emil Wiechert and Walter Kaufmann had independently inferred a similar conclusion from their earlier experiments. Nevertheless, neither Wiechert nor Kaufmann could be credited with the discovery of the electron, because both had rejected the existence of such a charged particle.

Within two years, Thomson would verify his findings in other experiments. He later measured the value of the electron's electrical charge by capturing each electrical charge in liquid droplets through condensation. Because he knew the size of the overall charge and the number of separate charges, he could now calculate the value of each electrical charge. A few gaps remained in the theory, however, and other physicists would provide the necessary links before Thomson could claim the discovery of the electron.


(The Nobel Foundation)

In 1899, Thomson published his view that the atom is surrounded by negatively charged particles on the outside. By 1904, he had developed this model of the atom further; it included electrons accelerating on concentric rings surrounding the atom, with the innermost ring containing the fewest number of electrons and the outer rings containing progressively more electrons. Particle and nuclear physics can be dated from this moment, and all work in the field has depended, to some extent, on Thomson's contributions.

After the discovery of the electron, Thomson devoted much of his remaining research years to determining the nature of "positive electricity." This phenomenon was identified by Wilhelm Wien, and by 1913 Thomson had developed an instrument sensitive enough to analyze the positive electron, or positron. It is through this work that Thomson became one of the first scientists to isolate isotopes of elements.

Hertz—was able to observe deflection of the rays, showing that they were composed of negatively charged particles. He correctly explained that Hertz's failure to observe electric deflection of the cathode rays was caused by their ionizing property in the excess amount of gas in the tube, which caused them to be shielded from the very field meant to deflect them.

By the simultaneous application of the electric and magnetic fields to the cathode rays, Thomson obtained the velocity *v* of the cathode-ray particles. On the assumption that the particles carried a charge *e* and had mass *m*, Thomson succeeded in obtaining the crucial ratio of charge to mass, that is, *elm*, showing that it was seventeen hundred times the corresponding value for hydrogen atoms. He further showed that the constant *elm* was independent of velocity *v*, the kind of electrodes used, and the type of gas inside the cathode-ray tube.

Using Charles Thomson Rees Wilson's newly developed "cloud chamber," Thomson was able to obtain the value of the charge *e*; from the ratio *elm*, it was simple to compute the numerical value of *m*. Hence, the smallness of the mass, combined with the relatively large velocity of the cathode-ray particles, also explained Hertz's observation, namely, that the rays penetrated thin sheets of metals. Obviously, massive particles could not do so. From Lenard's finding of the constancy of magnetic deflection of the rays and independence of chemical properties, Thomson soon realized that he had discovered a universal module of atoms found in radioactive substances, in alkali metals bombarded by ultraviolet light, and in a variety of gaseous discharge phenomena. Thomson's discovery that the cathode-ray particle is universal and fundamental to the understanding of the structure of all matter unraveled the puzzling aspect of conductivity of gases, the nature of electricity, and the wave-particle controversy.

Impact

Thomson's discovery of the electron—including the recognition that it carried a natural unit of charge and was a component of all atoms—marked the beginning of a new and exciting period in atomic research. The confirmation concerning the particle nature of cathode rays also came from other quarters. For example, Pieter Zeeman's observation of the widening D lines in the spectrum of sodium, explained by Hendrik Antoon Lorentz's theory, caused by changed electron configurations of the atoms in the presence of a magnetic field, gave a value of *elm*, comparable to those obtained by Thomson.

Based on his discovery and a study of mechanical stability of the electrons under the influence of the electrostatic force, Thomson showed that the electron must circulate about the atom's center, constrained to move in concentric circles. Calling the cathode-ray particles "corpuscles" and speculating that their number increased proportionally to the atomic weight of any given element, Thomson attempted to explain the structure of the chemical elements and their properties.

From this early model, he drew several important conclusions. First, since the electrons must accelerate as they move in circles around the atomic center, they will radiate. Therefore, such an arrangement of electrons cannot be stable since n, the number of electrons, was assumed to be of the order of one thousand times the atomic weight A. Because experimental work on alpha, beta, and gamma scattering—performed under the supervision of Thomson at the Cavendish Laboratory to verify his theory and obtain n of chemical elements—had led to negative conclusions, this served as a basis for Ernest Rutherford's model of the nuclear atom.

Additionally, Thomson's discovery of the order of n fostered the development of the scattering theory, which was to play an important role in future research in atomic and nuclear physics. The instability of his model atom was instrumental in the formulation of the quantum hypothesis and the discovery of the atomic quantum levels.

Finally, Thomson's electron distribution in atoms provided analogies to the behavior of the chemical elements and in particular the population of electrons in the atoms of contiguous elements in the periodic table that differed by unity.

See also Alpha Decay; Atomic Nucleus; Atomic Structure; Compton Effect; Electric Charge; Exclusion Principle; Isotopes; Neutrons; Oil-Drop Experiment; Photoelectric Effect; Superconductivity; Superconductivity at High Temperatures; Wave-Particle Duality of Light; X-Ray Fluorescence.

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—*V. L. Madhyastha*

ELECTROWEAK THEORY

THE SCIENCE: The discovery of three new particles that had been predicted by theoretical physicists provided evidence for the unification of the electrical and weak forces.

THE SCIENTISTS:
Carlo Rubbia (b. 1934), Italian experimental physicist
Simon van der Meer (b. 1925), Dutch physical engineer
Sheldon Lee Glashow (b. 1932), American theoretical physicist
Abdus Salam (1926-1996), Pakistani theoretical physicist
Steven Weinberg (b. 1933), American theoretical physicist

THE STRONG AND WEAK FORCES

During the early decades of the twentieth century, physicists came to realize that they needed to consider additional forces, beyond the familiar gravitational and electromagnetic forces, to understand how the nuclei of stable atoms could hold together and how the nuclei of radioactive atoms could allow some particles to escape. They named the former force "strong" and the latter "weak."

By the second half of the twentieth century, experimental physicists had discovered many previously unknown elementary particles that had to be added to the previously known electrons, protons, and neutrons that make up familiar atoms.

The discovery of such new particles usually required the use of very large, powerful, and expensive "particle accelerators" that hurled high-speed electrons or protons against targets to be broken into fragmentary particles.

Meanwhile, theoretical physicists busied themselves cataloging the new particles and trying to understand how the strong and weak forces involved could be integrated into the established understanding of electromagnetism. They were encouraged to seek unifying principles for the new forms because, in the nineteenth century, the electric and magnetic


Steven Weinberg. (The Nobel Foundation)

forces had been integrated through the recognition that magnetic forces were caused by moving electrical charges or currents of electricity. Also, Sir Isaac Newton had shown much earlier that a single theory of gravitation could explain both the movement of the planets around the Sun and the falling of nearby objects, such as apples, to the Earth.

W AND Z PARTICLES

During the 1960's and 1970's, many theoretical physicists were working toward the goal of unifying the weak force with the electromagnetic force. Three in particular—Sheldon Glashow, Abdus Salam, and Steven Weinberg—made significant progress toward that goal. They did not collaborate with one another directly, but each published his results and knew of the others' work. Their progress was achieved largely through an advanced mathematical technique known as "gauge theory."

In 1979, they shared the Nobel Prize in Physics "for their contribution to the theory of the unified weak and electromagnetic interaction between elementary particles." An important element of their work was the prediction of three new particles, called "bosons," which were designated W^+, W^-, and Z^0. Both W particles were predicted to have the same mass, about eighty times that of a proton, but one would carry a positive charge, the other a negative charge. The more massive Z particle, about ninety times as massive as a proton, would not carry any electric charge.

RESEARCH ACCELERATES

Experimentalists at all accelerator laboratories were already hunting for these new predicted particles. In particular, a large group at the Centre Européen de Recherche Nucléaire (the European Center for Nuclear Research, or CERN) focused its attention on this quest. CERN, located near Geneva on the border between France and Switzerland, is an international research center funded by more than a dozen European nations. In 1976, Carlo Rubbia, a group leader at CERN, designed an experiment that involved a beam of protons and a beam of antiprotons that circulated in opposite directions in the chamber and collided with each other. Antiprotons do not occur in nature. They have a negative electric charge but have the same mass as the more familiar, naturally occurring, positively charged protons. The opposite charges of the protons and antiprotons cause them to travel in opposite directions when a magnetic field is activated in the chamber.

Carrying out such an experiment was difficult, and there was considerable doubt among scientists that it could be accomplished. Rubbia had to convince the directors of CERN to redesign existing equipment to accommodate his proposed experiment. He received their approval in 1978.

STOCHASTIC COOLING

A crucial ingredient in making Rubbia's idea successful in operation was an invention made years earlier by Simon van der Meer: "stochastic cooling." Stochastic cooling made possible the concentration of a large number of artificially produced antiprotons into a beam that would provide a large number of collisions so that W and Z particles might be observed. Also, the collisions had to be energetic enough to allow the large

TOWARD A GRAND UNIFIED THEORY

Ever since Sir Isaac Newton identified the gravitational force, all the forces of nature have come very close to unification in theory. Electricity and magnetism were found to be linked as the same force early in the twentieth century. Then, after gravity and electromagnetism, two more forces were discovered at the beginning of the twentieth century: the "strong" and "weak" nuclear forces of the atomic nucleus.

Whereas the electromagnetic and gravitational forces operate over relatively large distances, the strong and weak nuclear forces operate over distances confined to the diameter of an atom. The strong force holds the individual parts of the nucleus together, and the weak force, through "beta radiation," is responsible for the decay of the nucleus itself. A subatomic particle called a "neutrino" reacts within the core of the atom and participates in some nuclear reactions. Although neutrinos do not react with mass, they interact with other subnuclear particles through the weak force. Most of the neutrinos that affect Earth are generated in the center of the Sun's thermonuclear core.

The theory developed by Sheldon Glashow, Abdus Salam, and Steven Weinberg is called the electroweak theory. For the first time it precisely detailed the interaction of the electromagnetic (large) force and the weak (small) force. It also stated that the neutrino and the electron are members of the same family of particles; in effect, the neutrino is the electron's "little brother." The theory predicted the existence of what are called "neutral currents." When the electron changes its identity to a neutrino and vice versa, the theory predicts that a "charged current" will be manifested in advance of the change of charge. Concurrently, a "neutral current" is present as the neutrino "acts without changing identity."

The unification of all the forces into a single, unified mathematical theory has been a dream of physicists. The development of the electroweak theory brought that "grand unified theory" one step closer to being discovered.

masses of the W and Z particles to be converted from available energy. In other words, the energy involved in the experiment would be transformed into W and Z particles, in accordance with Albert Einstein's mass-energy equation: $E = mc^2$.

Work involving hundreds of scientists and engineers went on at a feverish pace at CERN. An important activity related to the establishment of the colliding beam experiment was the detection of the W and Z particles when and if they were produced. Two devices that could perform this function were put into operation in 1981. By 1983, Rubbia and his team of workers were detecting a small number of W and Z particles.

The results of the work at CERN immediately received much attention from physicists. In 1984, the Nobel Prize in Physics was awarded jointly to Rubbia (for developing the idea of the experiment) and van der Meer (for making the experiment feasible).

Impact

The breakthrough achieved by Rubbia and van der Meer and their colleagues at CERN inspired new confidence among theoretical physicists and set the stage for further investigations, but the search for further unification of fundamental forces continues. Two aspects of modern physics are exemplified in the results achieved by Rubbia and van der Meer: the interplay between theory and experiment, and the conviction that present understanding of natural forces can be increased by detecting the principles that unify those forces. The search for this "grand unified theory" remains one of the most compelling, and elusive, for particle physicists.

See also Grand Unified Theory; Quantum Chromodynamics; Quantum Mechanics; Quarks.

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—*Katherine R. Sopka*

EUCLIDEAN GEOMETRY

THE SCIENCE: Euclid's *Elements*, one of the most influential mathematics texts of all time, set the standard for logical mathematical thought throughout Europe and the Middle East.

THE SCIENTIST:
Euclid (c. 330-c. 270 B.C.E.), Greek mathematician

AN ACADEMY IN ALEXANDRIA

The city of Alexandria was founded by Alexander the Great in 332 B.C.E. After Alexander's death in 323 B.C.E., his empire was divided between his generals. Alexandria came under the power of Ptolemy Soter, who founded a great library and school there. The first of what was to become a long line of mathematicians at that school was Euclid.

The only sources of information on Euclid's life are commentaries in mathematics texts, which discuss his mathematics more than his personal life. The main sources are the commentaries of Pappus, which were written in the third century C.E., and the commentaries of Proclus, which were written in the fifth century C.E., significantly later than Euclid's lifetime. What can be said about Euclid's life is that he flourished about 300 B.C.E. and probably studied mathematics in Athens at the school founded by Plato. What is certain is that he wrote the *Stoicheia* (compiled c. 300 B.C.E.; *Elements*, 1570), an elementary introduction in thirteen books to all of Greek geometry as it was known at the time.

EUCLID'S ACHIEVEMENT

Euclid's great task was not in the creation of that geometry, although some of the proofs of the theorems in the *Elements* are thought to be Euclid's.

Rather, his accomplishment is in the collection, categorization, and simplification of the contemporary knowledge of geometry. Euclid's achievement is twofold.

First, he collected the entire corpus of ancient Greek geometry and arranged it in a logical fashion. Each theorem in the *Elements*, including those of other authors, is proved using theorems that precede it in the text. Thus the theory is built up, theorem by theorem, on a solid logical foundation.

The second, and perhaps more important, of Euclid's accomplishments is the statement of the five axioms forming the logical basis of the entire work. An axiom is an unprovable statement, one that is simply accepted as true and is then used as the basis of a mathematical theory. Euclid's genius lay in recognizing that all of Greek geometry flowed from five simple axioms. All of the theorems in the *Elements* are logically based on just these five axioms.

The Fifth Axiom

Special note must be made of the fifth axiom. It is often called the Parallel Postulate, because in fact, it is a statement about parallel lines: If a line happens to intersect two others, and the sum of the interior angles on neither side of the first line is less than two right angles, then the other two lines do not meet; in other words, they are parallel. This axiom stands out from the others. The first four are all simply stated and quickly understood and believed; the fifth takes some time to state and to understand, and it caused much anxiety among mathematicians, ancient and modern. Many tried to prove the fifth postulate from the other four, to no avail. Finally, in

Euclid's Five Axioms

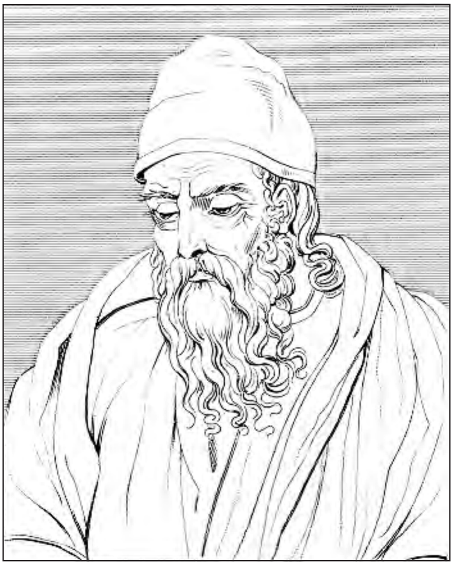
Euclid's genius lay in recognizing that all of geometry flows from five simple axioms. These basic principles form the basis for proofs of all the theorems in Euclid's *Elements*:

(1) A straight line can be drawn between any two points.
(2) A straight line can be extended indefinitely.
(3) Given any center and any radius, a circle can be drawn.
(4) All right angles are equal to each other.
(5) If a line intersects two other lines, and if the sum of the interior angles made on one side of the first line is less than two right angles, then the other two lines, when extended, meet on that side of the first line (the Parallel Postulate).

the nineteenth century, it was shown that the fifth could not be proved from the other four. In fact, one can replace the fifth axiom with certain other axioms and obtain "non-Euclidean" geometries.

BEYOND GEOMETRY

The geometry of Euclid covers more than the modern definition of geometry. In fact, it covers a great variety of mathematical subjects from a modern perspective. For instance, Euclid's geometry does deal with plane and solid figures, but it also deals with the application of these figures to many other problems. Plane figures such as rectangles, triangles, and circles are treated in books 1, 3, and 4 of the *Elements*. These books cover modern geometry. In books 2 and 6, geometric methods are used to solve what today are considered algebraic problems, such as solving linear and quadratic equations. The geometry of ratios of magnitudes, covered in book 5, is in today's terminology the study of rational numbers; book 10 covers the geometry of magnitudes that are not in a simple ratio, or are incommensurable, which is the study of irrational numbers. The geometry in books 7, 8, and 9 is used to do what is now called number theory, including divisibility of one whole number by another, factoring whole numbers, and a treatment of prime numbers. Solid figures also appear prominently in Euclid's geometry, in books 11, 12, and 13. These books hold theorems from the most basic facts about solid figures up to the fact that there are only five regular solid figures all of whose sides are a given regular planar figure. These five figures are known as the Platonic solids.



Euclid. (Library of Congress)

Euclid is thought to have written nine works besides the *Elements*. These other works deal with some more specialized areas of geometry. *Data* (compiled c. 300 B.C.E.; English translation, 1751) is a text that deals further with plane geometry, expanding on books 1 through 6 of the *Elements*. *Peri Diairéson biblion* (compiled c. 300 B.C.E.; *On Divisions of Figures*, 1915) treats the taking of a single plane figure and dividing it according to a rule; for example, dividing a triangle into a quadrilateral and a triangle of certain areas, or dividing a figure bounded by two straight lines and the arc of a circle into equal parts. Parts of these two works are extant.

The rest of Euclid's works are known only because they are mentioned by other mathematicians or historians. Euclid produced a work called the *Pseudaria*, or the "book of fallacies." In it he gives examples of common errors and misgivings in geometry, with the idea that later geometers could avoid these mistakes. The *Porisms* are described by Pappus as "neither theorems nor problems, but . . . a species occupying a sort of intermediate position." An example of this is the task of finding the center of a circle: it can be stated as a problem, or as a theorem proving that the point found is actually the center. Euclid also wrote a work entitled *Conics*, which deals with conic sections, or the shapes obtained when one slices a cone in different ways. *Surface-Loci* deals with figures drawn on surfaces other than a plane, for example, triangles drawn on a sphere. Euclid also produced works in applied mathematics: *Phaenomena*, dealing with astronomy, *Optics*, *Caltropics*, or the theory of mirrors, and the *Elements of Music*.

Impact

The influence of Euclid's *Elements* has been felt across the ages. From the rise of the Roman Empire through the early medieval period, the value of the kind of abstract intellectual thought embodied in the *Elements* was largely ignored in Europe. The Arabian world, however, had inherited Greek intellectualism and continued to study geometry, copying and translating the *Elements* and adding to geometry and mathematics in general.

In the eleventh and twelfth centuries C.E., this intellectual thought was reintroduced to Europe as a result of the Crusades and the Moorish invasion of Spain. Euclid was translated into Latin, first from Arabian copies, then from older Greek copies. The rise of the universities in Europe introduced many to Euclid's *Elements*, and European intellectuals began to add to mathematical knowledge.

The geometry of Euclid is studied to this very day. Although much has been added to mathematical thought in the twenty-three centuries since the writing of the *Elements*, that text remains one of the most published and most revered of mathematical treatises.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Fermat's Last Theorem; Fractals;

Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Andrius Tamulis*

EVOLUTION

THE SCIENCE: In 1859, Charles Darwin's *On the Origin of Species by Means of Natural Selection* set forth the theory that existing plant and animal species evolved from earlier life-forms through selection: survival of those species with traits that were best adapted to their environments. This principle provided an organizing principle for biology and cast doubt on the literal interpretation of biblical Creation.

THE SCIENTISTS:

Charles Robert Darwin (1809-1882), English naturalist

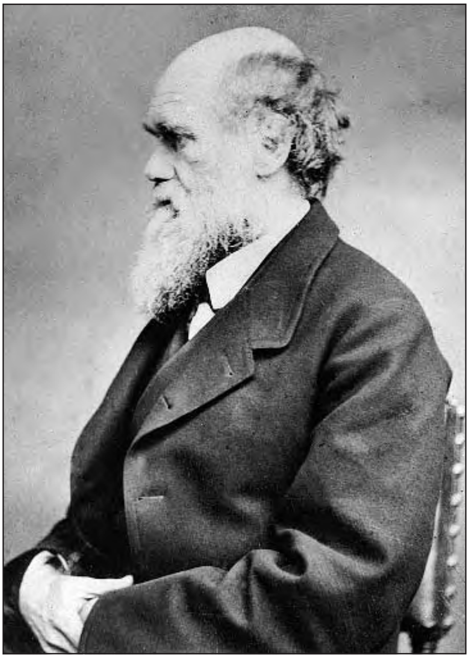
Erasmus Darwin (1731-1802), Charles's grandfather, a physician

Thomas Henry Huxley (1825-1895), English biologist who became Darwin's chief apologist

Sir Charles Lyell (1797-1875), eminent geologist who encouraged Darwin to publish his speculations

Alfred Russel Wallace (1823-1913), Scottish naturalist who in 1858 independently originated the theory of natural selection

THE *BEAGLE* EXPEDITION

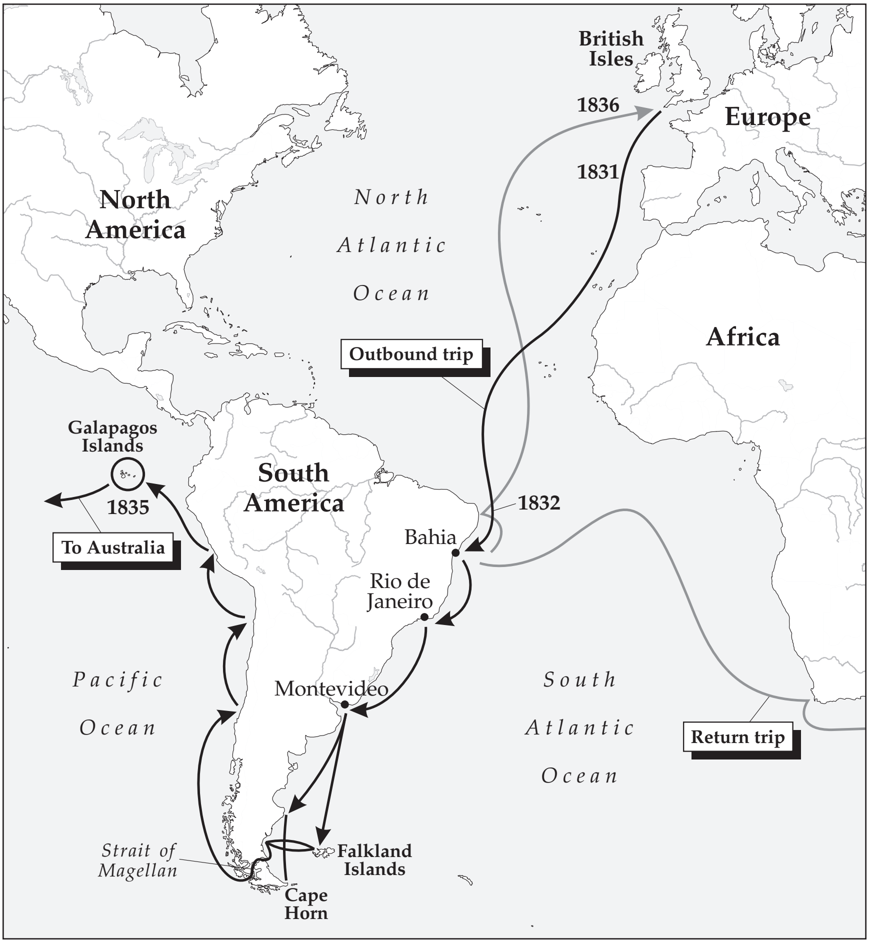


Charles Darwin. (National Archives)

Charles Robert Darwin was born in 1809, the son of a middle-class English family whose heritage included much interest in science. His grandfather, Erasmus Darwin, had earlier speculated about evolution, although, like the French evolutionary theorist Lamarck, who attributed organic changes to the will of the organism seeking to adapt itself to its changing environment. Darwin himself claimed that his grandfather's ideas had little impact on him, and he disputed any comparison between his own work and Lamarck's. It is known, however, that Darwin as a youth read his grandfather's *Zoonomia: Or, The Laws of Organic Life* (1818).

Darwin's first interest was in becoming a physician like his father, but he found this work distasteful. He went to Cambridge University with the intention of becoming a clergyman, but once there he quickly developed his lifelong interest in the natural sciences and came into contact with some of the best naturalists of his day.

Perhaps the most momentous development in Darwin's life came when he traveled as the naturalist on the HMS *Beagle*, which left England in 1831 for South America. Immersed as he was in geological investigations, his primary pursuit at the time, Darwin nevertheless became more interested in flora and fauna as the expedition progressed. The tremendous diversity of life struck him, and the old explanations for this diversity seemed alto-



gether unsatisfactory. His experiences in the Galápagos Archipelago, off the western coast of South America, jolted him into noting that although the climate was essentially the same as the nearby mainland, there were significant differences among the animals on the various islands themselves.

The expedition lasted nearly five years. When he left England, Darwin had no particular ideas about evolution, but he returned convinced that evolution was a fact. This in itself was not unprecedented; there had been earlier theories concerning the evolution of species, but none had received general acceptance. Lamarck's concept had never found favor because it ascribed organic evolution to the will of the organisms themselves—an argument incapable of investigation. The French naturalist Georges-Louis Leclerc, comte de Buffon, had speculated that organic changes were deter-

Charles Darwin and the *Beagle*

In 1831, a twenty-two-year-old Charles Darwin, who had been studying for the ministry at Cambridge, by luck was offered a position as naturalist on the ship HMS *Beagle*, which was about to embark on a round-the-world voyage of exploration. His domineering father was against the trip at first, but he finally relented. The expedition would turn the young man into a scientist. Over the next five years, Darwin recorded hundreds of details about plants and animals and began to notice some consistent patterns. His work led him to develop new ideas about what causes variations in different plant and animal species:

> [The] preservation of favourable individual differences and variations, and the destruction of those which are injurious, I have called Natural Selection, or the Survival of the Fittest. . . . slight modifications, which in any way favoured the individuals of any species, by better adapting them to their altered conditions, would tend to be preserved. . . .
>
> —*On the Origin of Species by Means of Natural Selection*, 1859

Until Darwin and such colleagues as Alfred Russel Wallace, the "fixity" or unchangingness of species had been accepted as fact, and the appearance over time of new species remained a mystery. Darwin's lucky trip laid the foundation for today's understanding of life and its diversity.

mined by climatic and environmental factors. As Darwin noted, flora and fauna in similar climactic conditions were not necessarily similar.

Selective Breeding

Darwin was also familiar with the techniques used by animal breeders to obtain strains of animals with desirable characteristics. It perhaps followed that he would wonder whether any similar process occurred in nature. The answer occurred to him in 1838 after reading *An Essay on the Principle of Population as It Affects the Future Improvement of Society* (1798), by Thomas Malthus. Darwin realized that if a population always tended to outgrow the available sources of food, then there must be a constant struggle for existence in nature. If this were so, then this struggle would play the role of the selective breeder, and animals that had developed variations helpful for their survival would pass those variations on to their progeny; thus the species could gradually evolve into a new species. These thoughts were the beginning of Darwin's theory of natural selection. Darwin's theory did not account for the variations themselves, but it did provide a mechanism by which these variations could be perpetuated.

Darwin was cautious. He first shared his theory with scientifically minded friends, and he performed various experiments to test different aspects of his theory. He did not rush into print but wrote a short account in 1842 for his own use. In 1844, he wrote a somewhat longer statement, but it also remained unpublished. In 1858, however, Darwin received a letter from Alfred Russel Wallace, who had developed essentially the same theory independently. This finally forced Darwin to action, and in 1859 he brought forward what he considered to be an abstract of a much longer intended work. This abstract was the famous *On the Origin of Species by Means of Natural Selection: Or, The Preservation of Favored Races in the Struggle for Life*.

A Sensational Theory

The book was an immediate sensation. All copies in the first printing were purchased on the day of its release. However, the reaction to Darwin's ideas was mixed. A number of church leaders perceived the book to be a challenge to the historical accuracy of the Bible. This was not the first such challenge, since many geologists, including Darwin's friend Sir Charles Lyell, were amassing evidence that the Earth had existed for a much longer time than the Bible, literally interpreted, would allow. Consistent with the geological evidence, the process of natural evolution would require many millions upon millions of years and not the six days described in the book of Genesis. Some scientists accepted the theory quickly, others more slowly; still others resisted for years.

Samuel Wilberforce, an Anglican bishop, became the most outspoken opponent of the theory, while Thomas Henry Huxley, a biologist, took on the task of defending the theory at scientific meetings and in print, a task that did not fit Darwin's temperament. Darwin had not discussed the origin of the *human* species in his book. He later presented his ideas on this topic to the public in a second volume, *The Descent of Man and Selection in Relation to Sex* (1871).

Impact

While the evidence for evolution amassed by Darwin was voluminous and convincing to many, the theory as it first appeared was necessarily incomplete, as neither the mechanism of inheritance nor the means of variation would be understood until the molecular biology of the gene had been fully investigated in the twentieth century. Modern biologists, with access to far more fossil evidence than Darwin had available, generally accept the theory, along with the notion of "punctuated equilibrium," developed to take into account the well-documented "great extinctions" during which large numbers of species disappeared in relatively short periods of time.

Nevertheless, Darwin's theory in its modern form continues to prove a source of controversy between science and religion. Ever since the Middle Ages, philosophers and theologians have taken seriously the possibility of a "natural theology": that is, a body of beliefs about God that could be proven from ordinary experience by reason alone. Prominent within this field was the "argument from design," which inferred from a highly organized universe the necessity for a supreme intelligence. From this point of view, the existence of highly complex organisms extremely well suited to survival, each in its own environment, could hardly be explained as the result of chance processes, even given enormous periods of time.

In response to this, much current evolutionary thinking is concerned with proving that random variation, coupled with natural selection, can give rise to complex structures such as the eye in complex organisms such as humans. Although controversy continues, it is often motivated by a need to reconcile socioreligious values with scientific observation. The overwhelming majority of scientists who accept evolutionary theory—many of whom are deeply committed to a religious faith—perceive no conflict between ideology and scientific fact, and thus no need to align the two.

See also Fossils; Human Evolution; Lamarckian Evolution.

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—*Paul T. Mason and Donald R. Franceschetti*

EXCLUSION PRINCIPLE

THE SCIENCE: Wolfgang Pauli's exclusion principle states that no more than two electrons can occupy the same energy level in an atom at the same time.

THE SCIENTISTS:
Niels Bohr (1885-1962), Danish physicist
Samuel Goudsmit (1902-1978), Dutch physicist
Wolfgang Pauli (1900-1958), Austrian American physicist
George Uhlenbeck (1900-1988), Dutch physicist

THE NEW ATOM

The early 1900's brought revolutionary changes in ideas about the structure of the atom. It began when the German physicist Max Planck proposed that light could be emitted or absorbed by matter only in bundles, called "quanta." Laboratory experiments led the British physicist Ernest Rutherford to propose that the atom was a "planetary" structure in which negatively charged electrons orbited a dense, positively charged nucleus.

The Danish physicist Niels Bohr used these proposals to create a new model for the hydrogen atom. Bohr's model explained the spectral lines of hydrogen. When they are heated, gases such as hydrogen give off a "spectrum" of light. The spectrum consists of a series of sharp lines of certain wavelengths, or colors. In the atom as Bohr conceived it, an electron can orbit only at certain distances from the nucleus; these distances are determined by the electron's energy. The electron can jump from a high orbit to a lower one by losing a quantum of light energy, which is seen as a spectral line. The electron can jump to a higher orbit by absorbing a light quantum. Bohr described the energy required for each electron orbit by means of a set of three quantum numbers. This "quantum theory" of the atom, however, ran into difficulties when it tried to explain the behavior of atoms that had more than one electron.

Beyond Hydrogen

Wolfgang Pauli was a young, energetic physicist who was interested in atomic structure. In 1925, at the University of Hamburg, Germany, Pauli proposed the exclusion principle, which expanded Bohr's quantum theory of the hydrogen atom to include all the elements.

In 1922, Pauli attended a series of lectures by Bohr on the periodic system of elements. The lecture made him aware of the problems that existed in applying the planetary model to atoms of elements other than hydrogen. The electron in the hydrogen atom naturally exists in its lowest energy state unless it receives energy from outside the atom, and electrons in other atoms also seek the lowest energy state. According to Bohr's model, as electrons crowded into the lowest orbit, atoms from helium to uranium became smaller. This occurrence also made it more difficult to remove electrons, thereby forming charged atoms called ions.

However, the inert gases—such as helium, neon, and argon—were composed of very large atoms that did not form ions easily. In addition, the elements fell into distinct chemical families: Those elements whose atoms had more electrons formed ions more easily than did those elements that had fewer electrons. Bohr admitted that his model could not explain these phenomena. It was clear to Pauli, however, that some principle existed that prevented all the electrons from crowding into the lowest orbit, or energy state.

Solving the Zeeman Effect

Pauli found an important clue when he tried to explain the Zeeman effect (which Pieter Zeeman had first observed in 1892): a splitting of spectral lines that occurs when a strong magnetic field is applied to heated gases. Another clue came from the chemical properties of the elements. It was thought that electrons existed in different shells in the atom and that the closing of the shells was related to the arrangement of the periodic system of elements. Pauli suspected that the closing of the shells and the splitting of the spectral lines were related. He continued to study atomic spectra.

In 1924, developments in the quantum theory provided the last clue. It

WOLFGANG PAULI'S LATER CONTRIBUTIONS

In 1928, not long after publishing his work on the exclusion principle, Wolfgang Pauli became professor of theoretical physics at the Federal Institute for Technology in Zurich, Switzerland, his home for the next twelve years. Together with his friend George Wentzel, a professor at the University of Zurich, he taught theoretical physics to many students who later became prominent physicists in their own right.


(The Nobel Foundation)

In Zurich, Pauli also produced one of his most important theories, the neutrino hypothesis. In a letter to physicist Lise Meitner in 1930 (whose work with Otto Hahn would reveal several new elements and pave the way for the discovery of atomic fission), Pauli reported that a neutron is emitted along with an electron when certain subatomic particles decay. Although Enrico Fermi later christened this neutron the "neutrino," it is also called the "Paulino" in honor of Pauli, who made the observation before Sir James Chadwick had discovered the neutron in the atomic nucleus.

Much of Pauli's research in this period was also devoted to the development of relativistic quantum electrodynamics in an effort to explain the infinite self-energy of the electron. This work led Pauli into a study of wave mechanics. In an article Pauli wrote for *Handbuch der Physik* in 1933, he expanded the scope of wave mechanics to include not only a single particle but the interaction of an indefinite number of particles as well.

In the late 1930's, Pauli's work began to take him away from Zurich. Between 1935 and 1936, he was appointed visiting professor of theoretical physics at the Institute for Advanced Study in Princeton, New Jersey. Then, in 1940, the Institute for Advanced Study once again summoned him to Princeton, largely because of the Nazi invasion of Norway and Denmark. In 1945, while he was still a temporary member of the institute's faculty, Pauli received a Lorentz Medal and, later that year, the Nobel Prize in Physics.

In 1946, at the end of the war, Pauli returned to Zurich with his wife, Franciska, whom he had married in April, 1934. He spent the remainder of his life in a heavily forested area called Zollikon, where he often took long walks, reflecting on the meaning of scientific activity. This new interest manifested itself in a number of essays, lectures, and a book coauthored with Carl Jung, *Natureklärung und Psyche* (1952). Pauli had hoped all along that physics would reveal the harmony between God and nature.

was found that the value of the principal quantum number corresponded to the number of electrons in the closed shell of inert gases. Pauli then realized that a fourth quantum number was needed to describe electron energy levels in the atom. Only two electrons could remain at the same energy level; therefore, other electrons were excluded.

At this same time, Dutch physicists Samuel Goudsmit and George Uhlenbeck proposed that the splitting of spectral lines was caused by the electron spinning either counterclockwise or counterclockwise on its axis as it orbited the nucleus. If the two allowed electrons in an excited energy level spin in opposite directions, their jump to a lower state was observed as the Zeeman effect.

Pauli's fourth quantum number related to electron spin. The two electrons in each energy level have opposite spins. Incorporating later refinements of quantum theory, Pauli's principle is often restated in this way: Each electron in an atom has a unique set of four quantum numbers.

Pauli received the Nobel Prize in Physics in 1945 for his contributions to atomic quantum theory. His work expanded Bohr's theory to include the atoms beyond hydrogen. It explained the spectral and chemical properties of all elements and formed the basis of a quantum approach to modern chemistry.

IMPACT

Pauli's exclusion principle states that no more than two electrons can occupy the same energy level in an atom at the same time. This concept made it possible for scientists to make models of atoms from hydrogen to uranium. It explained the size of atoms and predicted which atoms could form ions easily. Years before, the chemical properties of atoms had been observed and classified by the Russian chemist Dmitry Mendeleyev. Pauli's principle explained these chemical properties as one aspect of an atom's electronic structure. The splitting of spectral lines was simply another aspect of atomic structure.

Pauli's publication of the exclusion principle in 1925 facilitated developments in quantum theory over the next few years. Work in such areas as matter waves, by Louis de Broglie; wave mechanics, by Erwin Schrödinger; and quantum numbers and electron spin, by Pauli, Goudsmit, and Uhlenbeck finally combined and evolved into the field of quantum mechanics. This new theory would help to explain the nature of individual atoms and combinations of atoms. It would also be used to understand the nature of the particles that make up atoms. Pauli's ability to recognize that the chemical and spectral properties of elements were different aspects of the same atomic structure was an important step in the development of modern physics and chemistry.

See also Atomic Structure; Atomic Theory of Matter; Electrons.

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—*Pamela R. Justice*

EXPANDING UNIVERSE

THE SCIENCE: Edwin Powell Hubble discovered that distant galaxies are moving away from the Milky Way galaxy at speeds that are determined by their distance from the Milky Way.

THE SCIENTISTS:

Edwin Powell Hubble (1889-1953), American astronomer
Vesto Melvin Slipher (1875-1969), American astronomer
Henrietta Swan Leavitt (1868-1921), American astronomer
Georges Lemaître (1894-1966), Belgian cosmologist
Walter Baade (1893-1960), German American astronomer

EVIDENCE OF EXPANSION

In 1929, Edwin Powell Hubble announced that the greater the distance to a given galaxy, the faster it is traveling away from the Milky Way galaxy. This discovery was of major importance because it implied that the universe was expanding; the discovery, in turn, supported a theory proposed by Georges Lemaître in 1927 that would be developed into the "big bang" theory of the creation of the universe by the American physicist George Gamow in 1948.

Hubble made his discovery by studying photographs of stellar spectra that Vesto Melvin Slipher had taken as a way of measuring the distances to those stars. The initial key in measuring the distances to the galaxies was the work of Henrietta Swan Leavitt. In 1911 and 1912, Leavitt analyzed Cepheid variables, which are stars that change their brightness according to a predictable cycle. Leavitt arranged the stars in order according to the periods (durations) of their cycles. She noticed that arranging them by period placed them in order of actual, or absolute, brightness. She discovered what became known as the "period-luminosity scale," by means of which, once the period of a Cepheid was measured, the star's actual brightness could be determined and compared to its apparent brightness, which in turn would reveal its distance.

The "redshift" measurements that Slipher had begun in 1913 suggested that the farther away a galaxy was, the faster it was receding. (The phenomenon is called "redshift" because, as the galaxy moves away, the light it emits has longer wavelengths; that is, its light moves, or shifts, toward the red end of the spectrum of visible light.) Slipher had no reliable way of measuring distances, however, and thus no means of proving the relationship. It was left to Hubble to put together the redshift results with the measurements of distance, leading to what is now called "Hubble's law."

Hubble began work in 1919 with the 152-centimeter telescope on Mount Wilson, near Pasadena, California, when he returned from service in World War I; he then moved to the 254-centimeter Hooker telescope at the same location. He studied objects within the Milky Way, such as novae (exploding stars), stars associated with gaseous nebulae, and variable stars. By 1922, he had published a paper noting the differences between the gaseous nebulae and those that were suspected of being more remote.

THE HUBBLE CONSTANT

By 1928, using Leavitt's period-luminosity scale, Hubble estimated that the Andromeda nebula was more than 900,000 light-years away (a light-

LEAVITT, SHAPLEY, AND THE PERIOD-LUMINOSITY SCALE

In 1902, Henrietta Swan Leavitt became a permanent staff member at Harvard College Observatory. She studied variable stars, stars that change their luminosity (brightness) in a fairly predictable pattern over time. During her tenure at Harvard, Leavitt observed and photographed nearly 2,500 variable stars, measuring their luminosities over time. She was equipped with photographs of the Large and Small Magellanic Clouds collected from Harvard's Peruvian observatory. The Magellanic Clouds are very small galaxies visible in the Southern Hemisphere and close to the Milky Way. The Small Magellanic Cloud contained seventeen Cepheid variables having very predictable periods ranging from 1.25 days to 127 days. Leavitt carefully measured the brightening and dimming of the seventeen Cepheids during their respective periods. She collected photographs of other Cepheids in the Magellanic Clouds and made additional period-luminosity studies. In a circular dated March 3, 1912, she stated:

> The measurement and discussion of these objects present problems of unusual difficulty, on account of the large area covered by the two regions, the extremely crowded distribution of the stars contained in them, the faintness of the variables, and the shortness of their periods. As many of them never become brighter than the fifteenth magnitude, while very few exceed the thirteenth magnitude at maximum, long exposures are necessary, and the number of available photographs is small. The determination of absolute magnitudes for widely separated sequences of comparison stars of this degree of faintness may not be satisfactorily completed for some time to come. With the adoption of an absolute scale of magnitudes for stars in the North Polar Sequence, however, the way is open for such a determination.

Ejnar Hertzsprung of the Leiden University in the Netherlands and Henry Norris Russell of the Mount Wilson Observatory in Pasadena, California, had independently discovered a relationship between a star's luminosity and its spectral class (that is, color and temperature). Together, their experimental results produced the Hertzsprung-Russell diagram of stellar luminosities, the astronomical equivalent of chemistry's periodic table. According to their classification scheme, most stars lie along the "main sequence," which ranges from extremely bright blue stars ten thousand times brighter than the Sun to very dim red stars one hundred times dimmer than the Sun. Cepheid variables fell toward the cooler, red end of the main sequence.

Leavitt carefully measured the luminosities and cyclic periods of changing luminosity for each of many Cepheid variables from the Magellanic Clouds. From her careful measurements, she graphically plotted Cepheid luminosity against Cepheid period. She noticed "a remarkable relation between the brightness of these variables and the length of their periods. . . . the brighter variables have the longer periods." She had discovered that a Cepheid's apparent luminosity is directly proportional to the length of its period, or the time it takes to complete one cycle of brightening and dimming.

Harlow Shapley, an astronomer at the Mount Wilson Observatory, measured the distances of moving star clusters containing Cepheids, then related the Cepheid distances to Cepheid period-luminosity data. From these experiments, Shapley constructed a Cepheid period-absolute luminosity curve, which made it possible to plot a Cepheid variable having a specific measured period and obtain its absolute luminosity. Knowing the Cepheid's apparent and absolute luminosities, one can instantly calculate its distance and, therefore, the distances of all the stars in the star cluster containing that particular Cepheid variable.

The distances to Cepheid variables in the Milky Way and other galaxies were soon determined. Shapley used Cepheid distances to demonstrate that the center of the Milky Way is directed toward the constellation Sagittarius and that the Sun is located approximately thirty thousand light-years from the galactic center. Edwin Powell Hubble applied the technique to obtain estimates of the distances between our galaxy and others, which led to his monumental astronomical discovery that the universe is expanding.

year is the distance that light, moving in a vacuum, travels in one year—at the rate of 299,000 kilometers per second). This figure was far higher than both the Dutch astronomer Jacobus Cornelis Kapteyn's 50,000 light-year diameter for the Milky Way and the American astronomer Harlow Shapley's estimate of 200,000 light-years. Hubble later adjusted his estimate to 750,000 light-years. It is now known that Hubble's estimates were too small, because, in 1952, Walter Baade was able to demonstrate that there are two types of Cepheid variables with different absolute brightnesses. As a consequence, modern estimates of the distance to the Andromeda nebula are more than 2 million light-years. Hubble had, however, established that Andromeda is outside the Milky Way.

Later, using the Hooker telescope, Hubble was able to resolve some of the fringes of nebulae into stars. By 1929, he had measured twenty-three galaxies out to a distance of about 20 million light-years. By 1931, Hubble and Milton L. Humason had measured some forty new galactic velocities out to a distance of 100 million light-years. Their major contribution to reliable measurement had to do with the fact that twenty-six of these velocities occurred within eight clusters. Because stars in the same cluster are assumed to be moving at the same speed, measuring redshifts for different stars within the same cluster is a good way to check the accuracy of their results.

Hubble found the speed of recession to be directly proportional to distance by a factor that came to be called the "Hubble constant," which he estimated to be 170 kilometers per second for each million light-years of distance. The modern value is 15 kilometers per second per million light-years. His original value for the constant indicated an age for the universe of only 2 billion years, much less than the 3 or 4 billion years that geologists had derived for the age of the Earth. His figure created an anomaly that persisted until Baade's discovery of two stellar populations, which reduced the size of the constant and increased the estimated age of the universe. (Today, through measurements taken by the Wilkinson Microwave Anisotropy Probe the age of the universe has been measured at 13.7 billion years.)

Impact

The establishment of the expansion of the universe is one of the most significant achievements of twentieth century astronomy. Establishing the scale of distance was a key to understanding the nature of the universe, which has led to Hubble's being considered the founder of extragalactic astronomy.

Hubble was not the first to presume that there were objects of interest beyond the Milky Way galaxy. Many astronomers had suspected that Sir William Herschel was correct in his opinion that "nebulae," those faint patches of light scattered throughout space, were "island universes" of stars, located outside the bounds of the Milky Way. In the mid-1920's, Lemaître theorized that the universe originated from an original superdense "cosmic egg" that had expanded into the present universe; two decades later, his idea would expand into the big bang theory.

See also Big Bang; Black Holes; Cepheid Variables; Cosmic Microwave Background Radiation; Galaxies; Inflationary Model of the Universe; Quarks; Spectroscopy; String Theory; Wilkinson Microwave Anisotropy Probe.

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—*Ivan L. Zabilka*

EXTRASOLAR PLANETS

THE SCIENCE: Careful analysis of light from Upsilon Andromedae revealed the first known multiple-planet system orbiting a normal star.

THE SCIENTISTS:

R. Paul Butler, astronomer, Anglo-Australian Observatory, Epping, Australia

Geoffrey W. Marcy (b. 1964), astronomer, San Francisco State University and the University of California, Berkeley

Peter Nisenson, astronomer and member of team at the Whipple Observatory, Mount Hopkins, Arizona

DETECTING NEW PLANETARY SYSTEMS

Planets are detected about stars other than the Sun by carefully monitoring the spectra of those stars to look for evidence of periodic motion. Starlight is collected with a large telescope and focused onto a slit. Light passing through the slit falls on a diffraction grating that spreads the light out into a rainbow, or spectrum—a series of colored images of the slit. Patterns of dark lines in the spectrum reveal which elements are present in the star. If the star is moving toward or away from Earth, these patterns are shifted slightly toward the blue or red ends of the electromagnetic spectrum. This shifting toward the blue or red because of the star's motion is an example of the Doppler shift. To see the small shifts caused by planets, extreme care must be taken to keep the parts of the instruments at a constant temperature, properly aligned, and calibrated.

Planetary Orbits

A planet does not really orbit the center of a star; instead, both the planet and the star orbit the center of mass of the system. The greatest motion of the star occurs if it has a massive planet very close to it. Therefore, the detection method used is most likely to discover "hot Jupiters," or massive planets orbiting close to their parent stars. Most of the planets discovered so far have been hot Jupiters.

Using an especially sensitive method, the first extrasolar planetary system may have been discovered in 1992, but unlike Upsilon Andromedae, it is a bizarre system of cinders orbiting a dead star. Periodic Doppler shifts in the radio pulses from the pulsar PSR 1257+12 indicate the presence of three small planets near the pulsar and a Saturn-sized planet much farther away. A pulsar is a rapidly rotating neutron star, a stellar remnant of a supernova explosion. It was previously believed that no planetary-sized bodies could survive such an explosion. Perhaps these planets are the remnants of giant planets, or perhaps they were formed from the supernova debris. Hence, until 1999, no extrasolar planets had been discovered orbiting "normal" stars such as that in our solar system.

The Upsilon Andromedae System

On April 15, 1999, two teams of astronomers—represented by R. Paul Butler, Geoffrey W. Marcy, and Peter Nisenson—independently obtained evidence that three planets orbit the star Upsilon Andromedae A, a "normal" star not too different from the Sun. Marcy and Butler had earlier announced their discovery of the planet Upsilon Andromedae B in January, 1997. This planet is at least 0.71 Jupiter masses and whirls around the star Upsilon Andromedae A in 4.6 days at a distance of only 0.06 astronomical units (an astronomical unit is the distance between Earth and the Sun). Upsilon Andromedae A is only slightly hotter than our Sun, but it is 30 percent more massive and three times as luminous as the Sun. Compared with sunlight on the Earth, Upsilon Andromedae's scorching rays are 470 times as intense on B.

Surprisingly, the fit between theory and data grew worse as the astronomers made additional measurements at the Lick Observatory. This suggested that another planet might be oribiting Upsilon Andromedae A, so a second team including Nisenson began their own measurements at the Whipple Observatory. On April 15, 1999, the two teams made a joint announcement of two new planets. Upsilon Andromedae C and D have minimum masses of 2.11 and 4.61 Jupiter masses. The elliptical orbit of C takes it from 0.7 to 1.0 astronomical units from its star so that it gets from 3.7 to 1.8 times the intensity of radiation that Earth receives from the Sun. The orbit of D also is elliptical, taking it from 1.5 to 3.5 astronomical units from Upsilon Andromedae A, making its radiation extremes 0.8 to 0.1 times the intensity that Earth receives.

Because all three planets are gas giants, they do not have solid surfaces and cannot have Earth-type life. They may have habitable satellites, but those of B and C are likely to be too hot. A satellite of D might be habitable if it has a thick atmosphere, but D's elliptical orbit would produce extremely harsh seasons. To have Earth-like conditions, an Earth-type planet would require a nearly circular orbit 1.7 astronomical units from Upsilon Andromedae A, but the large masses and elliptical orbits of C and D would probably make such an orbit unstable.

In 2005, Eric Ford, Verene Lystad, and Frederic A. Rasio announced in an article published in *Nature* the possibility of a fourth planet oribiting Upsilon Andromedae. Their hypothesis was based on analysis of computer data gathered for more than a decade since the discovery of the system. The highly elliptical orbits of the two outer planets had led scientists to wonder what caused this eccentricity; a fourth planet might just be the explanation. Ford, a postdoctoral fellow at the University of California, Berkeley, explained that "the outer planet's original orbit was circular, but it got this sudden kick that permanently changed its orbit to being highly eccentric. To provide that kick, we've hypothesized that there was an additional planet that we don't see now. We believe we now understand how this system works." Ford's colleague Rasio explained this phenomenon as "planet-planet scattering—a sort of slingshot effect due to the sudden gravitational pull between two planets when they come very near each other."

Impact

The Upsilon Andromedae was the first multiple-planet system discovered orbiting a normal star. Because the detection method yielded only an estimate for the minium mass of the planet, some astronomers wondered if those previously discovered planets were actually small stars instead of planets. It was therefore important that the bodies orbiting Upsilon Andromedae were unlikely to be anything other than planets.

The discovery encouraged astronomers to search for more multiple planetary systems, and by 2005 more than 150 extrasolar planets had been found, including six double planet systems. For the first time, astrophysicists were able to collect data that might reveal how planetary systems and orbital patterns are formed.

See also Cassini-Huygens Mission; Galileo Mission; Gravitation: Einstein; Halley's Comet; Heliocentric Universe; Herschel's Telescope; Hubble Space Telescope; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mars Exploration Rovers; Moon Landing; Nebular Hypothesis; Oort Cloud; Pluto; Saturn's Rings; Solar Wind; Stellar Evolution; Van Allen Radiation Belts; Voyager Missions.

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—*Charles W. Rogers, updated by Christina J. Moose*

FAHRENHEIT TEMPERATURE SCALE

THE SCIENCE: Gabriel Fahrenheit developed sealed mercury thermometers with reliable scales which agreed with each other. His thermometers used three fixed points: 0°, 32° (freezing point of water), and 96° (human body temperature). Later scientists recalibrated his scale, fixing 212° as the temperature of boiling water.

The Scientists:

Daniel Gabriel Fahrenheit (1686-1736), German physicist
Ole Rømer (1644-1710), Danish astronomer
Anders Celsius (1701-1744), Swedish astronomer
Galileo (1564-1642), Italian mathematician, scientist, and inventor
Ferdinand II de' Medici (1610-1670), scholar, scientist, and grand duke of Tuscany
Joseph Nicholas Delisle (1688-1768), French astronomer
René-Antoine Ferchault de Réaumur (1683-1757), French scientist
Carolus Linnaeus (1707-1778), Swedish physician and botanist
Jean Pierre Christin (1683-1755), French scientist
William Thomson, Lord Kelvin (1824-1907), British physicist

Early Temperature Scales

Temperature scales of a subjective nature were widely used by physicians in the Renaissance. Such scales could be useful for performing rough diagnoses, but they were inappropriate as instruments of scientific research and measurement. The first thermometer was constructed early in the seventeenth century by Galileo for use in his public lectures in Padua. It was a relatively crude, gas-filled, open glass vessel that enabled Galileo to demonstrate observable differences in temperature between different substances or within the same substance as it was heated or cooled. Knowledge of his device spread rapidly, and in the next century, thermometers of increasing usefulness were constructed by many different people. Ferdinand II de' Medici is credited with developing the first sealed thermometer, which prevented temperature measurements from being affected by changes in atmospheric pressure.

Rømer's Thermometer

In 1701, a Danish astronomer named Ole Rømer made a wine-filled (alcohol) thermometer. Rømer used a scale in which the temperature of a mixture of ice and salt water was 0° and that of boiling water was 60°. In the same year, after the death of his parents, Daniel Gabriel Fahrenheit moved to Holland, where he began making scientific instruments. In 1708, Fahrenheit visited Rømer in Denmark and observed Rømer's methods for calibrating thermometers. Fahrenheit subsequently decided that Rømer's temperature scale was too cumbersome for common use but adopted the use of ice baths for instrument calibration.

Fahrenheit made his first alcohol thermometer in 1709. He visited Berlin in 1713 to investigate the expansion of mercury in Potsdam glass thermometers, and in 1714 he made his first reliable mercury thermometer. Fahrenheit sought to ensure that all his thermometers would produce the same measurements, and he picked three specific points on a temperature scale at which to standardize his thermometers. Like Rømer, he established 0° with a mixture of ice and salt water (or ice, water, and sal ammoniac); 32° was set by a mixture of ice and pure water, and 96° was set as the temperature reached when a healthy man placed a thermometer under his armpit or in his mouth.

Fahrenheit's Thermometer

Fahrenheit produced and calibrated thermometers using the scale he had developed, and his instruments were known to be of high quality, yielding standardized results. His thermometers were widely adopted, and his scale therefore came into wide use. Herman Boerhaave, a noted chemist, bought his thermometers from Fahrenheit and once brought to Fahrenheit's attention that his alcohol and mercury thermometers read slightly differently. Fahrenheit incorrectly attributed the differences to different glass being used, rather than to the difference between the rates of expansion of alcohol and mercury.

In 1724, Fahrenheit became a member of the English Royal Society and published the results of his investigations in their journal, *Philosophical Transactions*. His thermometers were the preferred instruments in Holland and England. After his death in 1736, scientists recalibrated Fahrenheit's thermometers, setting 212° as the temperature of boiling water. Recalibration then established the normal human body temperature as 98.6°, rather than the 96° used by Fahrenheit.

Fahrenheit's basic design for the sealed mercury thermometer was not changed significantly after his death. The subsequent history of the instrument revolves around the development and refinement of different scales at which to calibrate it. Thermometers made for use in the late eighteenth century and throughout the nineteenth century often had two or more scales marked upon them, allowing them to be marketed to different areas where different scales were in use. The Fahrenheit thermometer scale never became popular in France, for example.

Celsius's Thermometer

Anders Celsius, a Swedish astronomer, used René-Antoine Ferchault de Réaumur's thermometer scale, which assigned ice water as a zero point and 80° as the temperature of boiling water. Celsius also used a thermometer made by Joseph Nicholas Delisle, which used an inverted scale in which 0° was the boiling point of water. Although not an instrument maker like Fahrenheit, Celsius did perform experiments using thermometers. Celsius suggested a new temperature scale that would place 0° at water's boiling point and 100° at its freezing point. Celsius worked in very cold climates in Sweden, Russia, and the North Atlantic, and using an inverted scale enabled him to avoid dealing with negative temperatures.

Celsius's inverted temperature scale was rapidly changed to a direct scale, as the boiling point of water was set at 100° and its freezing point was set at 0°. This change may have been suggested by Jean Pierre Christin in 1743 or 1744, although Pehr Wargentin, secretary of the Royal Swedish Academy of Sciences in 1749, mentioned an astronomer named Stroemer and an instrument maker named Daniel Ekström in connection with the development of the direct temperature scale. Ekström was the manufacturer of the thermometers used by both Celsius and Carolus Linnaeus, and Linnaeus may also have been the one to invert Celsius's scale. It is certain that Linnaeus rapidly adopted the Celsius scale in his work, as did other Swedes. The Celsius scale became popular in France, although Réaumur's scale remained in use for about another century there. When metric units were introduced, the Celsius scale was referred to as the centigrade scale.

IMPACT

In 1848, William Thomson, Baron Kelvin, devised a temperature scale that placed its 0 point at the temperature below which matter cannot be cooled. This point is equal to –273.15° Celsius and –459.67° Fahrenheit. The Kelvin scale is used by scientists and is the international standard temperature unit. The unit of 1 degree Celsius is equal to 1 Kelvin. Therefore, the so-called triple point of water, at which temperature water vapor, ice, and liquid water can exist in equilibrium, is 273.16 Kelvin. (Kelvin temperatures omit the "degree" unit required when stating Fahrenheit and Celsius temperatures.)

Throughout the English-speaking world, the Fahrenheit scale continued to be preferred until the late twentieth century, when most countries switched to the Celsius, or centigrade, scale as part of their move to the metric system. In the early twenty-first century, the Fahrenheit scale continued to be used by most people in the United States. It is still very rare to hear Celsius temperatures used in U.S. news reports or published in U.S. newspapers. In Canada, Celsius temperatures are always used in weather reports and newspapers.

Mercury and alcohol thermometers are limited in use by the boiling point and freezing point of their respective mediums. By the late twentieth century, highly accurate temperature measurements were being made over wide temperature ranges through the use of radiometers, which detect and measure thermal radiation. The most common such devices are infrared radiometers, used to detect surface temperatures of buildings, animals, and terrain features. Some radiometers are designed to display color-coded images of the observed temperatures of objects, although measurements by sensitive scientific radiometers usually are fed into a computer or data recording device for analysis. With growing awareness of the health risks posed by mercury, the United States and other countries began banning the manufacture and sale of all devices containing liquid mercury, including thermometers, in the late twentieth century.

See also Celsius Temperature Scale; Kelvin Temperature Scale.

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—*Anita Baker-Blocker*

FALLING BODIES

THE SCIENCE: Galileo's scientific experiments, the uses he made of them, and the concepts he developed led directly to reexaminations of the traditional Aristotelian view of nature and laid the foundation for Newtonian mechanics.

THE SCIENTISTS:

Galileo Galilei (1564-1642), Italian mathematician and astronomer

Guidobaldo Marchese del Monte (1545-1607), scientist, engineer, wealthy aristocrat, and Galileo's patron

Santorio Santorio (1561-1636), innovative medical doctor and a member of Galileo's learned circle

Vincenzio Viviani (1622-1703), Galileo's pupil and first biographer
Paolo Sarpi (1552-1623), highly educated and influential monk and a member of Galileo's learned circle

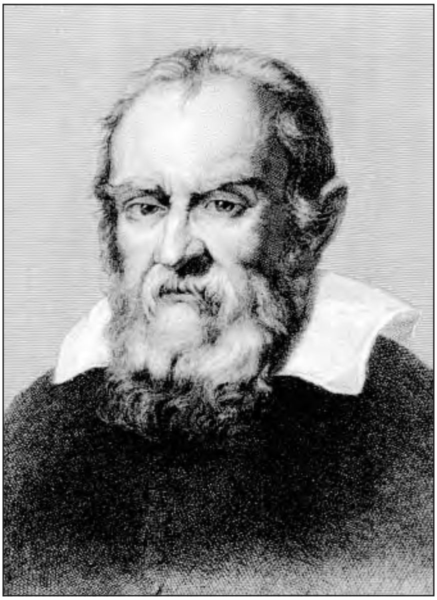
ARISTOTLE'S ERRORS

One of Aristotle's predictions, which was passed down to the seventeenth century, concerned the behavior of falling bodies. Aristotle, adhering to his philosophy that all effects require a cause held that all motion (effect) required a force (cause), and hence that falling (a motion) required a force (the weight, or what we now know as mass, of the object falling).

The Italian astronomer and mathematician Galileo Galilei was one of a number of scientists who questioned the Aristotelian view of the workings of nature and turned to experimentation to find answers. In 1589, at the recommendation of his friend and patron Guidobaldo Marchese del Monte, Galileo was appointed chair of mathematics at the University of Pisa. Some of Galileo's lecture notes from 1589 to 1592 were gathered into a collection referred to as *De motu* (c. 1590; *On Motion*, 1960). In it, Galileo still used the Aristotelian concepts of natural and forced motions, but he proved Aristotle wrong on several points.

Galileo introduced the new concepts of infinitesimal forces and "neutral motion," a precursor to the modern concept of inertia. He reported on his experiments with bodies falling in various media, and by casting the problem in terms of relative densities, he was able to avoid some of Aristotle's errors.

Around 1590, according to Vincenzio Viviani, Galileo climbed to the top of the Leaning Tower of Pisa and simultaneously dropped a large cannon ball and a smaller musket. The two hit the ground at nearly the same time, contrary to Aristotle's prediction that the two bodies would reach the ground at different times. While others before Galileo had done the same experiment and reached the same conclusion—and although it is still uncertain if Galileo performed such



Galileo. (Library of Congress)

an experiment personally—Galileo's supposed public demonstration assured not only that his experiment would be remembered but also that it corrected false tradition. Perhaps even more important, it underscored the importance of empirical evidence to corroborate a hypothesis. Aristotle had reasoned from logic; Galileo reasoned from experience.

The Law of Falling Bodies

The experience launched other experiments—for example, taking into account that some bodies would have differences in their rates of acceleration based on mass, as a result of air resistance—and Galileo refined his observations until, about two decades later, he had formed the law of falling bodies:

> A falling body accelerates uniformly: it picks up equal amounts of speed in equal time intervals, so that, if it falls from rest, it is moving twice as fast after two seconds as it was moving after one second, and moving three times as fast after three seconds as it was after one second.

Galileo would go on to describing bodies that fall on an incline, noting, for example, that for a ball rolled down an incline at a fixed angle to the horizontal, the ratio of the distance covered to the square of the corresponding time is always the same. He would also describe the motion of bodies in free fall after they have been shot or catapulted forward—that is, the trajectory of a projectile.

The Parabolic Trajectory

The flight of a cannon ball is far too swift for the eye to determine its trajectory, but evidence found in Galileo's notes, and in those of his intellectual colleagues Guidobaldo and Paolo Sarpi, shows that around 1592, Galileo and Guidobaldo proved that the trajectory was a parabola. Their marvelously simple method was to cover a small brass ball with ink, fasten a sheet of paper to a board, and hold the board nearly upright. Then the ball was launched upward against the paper and allowed to trace out its path. They quickly recognized the inked curve as a parabola. The ascending and descending arcs of the trajectory were the same, contrary to Aristotle's claim.

When Galileo recognized that the trajectory of a projectile was a parabola, he would have known by the parabola's mathematical properties that the distance the projectile fell increased as the square of the time elapsed.

FALLING FOR GALILEO

In Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican *(1632), Galileo used three voices—those of the traditional Aristotelian Simplicio, the scientist Salviati, and the supposedly objective Sagredo—to discuss the problem of falling bodies.*

SALVIATI: . . . I seriously doubt that Aristotle ever tested whether it is true that two stones, one ten times as heavy as the other, both released at the same instant to fall from a height, say, of one hundred braccia [cubits], differed so much in their speeds that upon the arrival of the larger stone upon the ground, the other would be found to have descended no more than ten braccia.

SIMPLICIO: But it is seen from his words that he appears to have tested this, for he says "We see the heavier . . ." Now this "We see" suggests that he had made the experiment.

SAGREDO: But I, Simplicio, who have made the test, assure you that a cannon ball weighing one or two hundred pounds (or two hundred, or even more) does not anticipate by even one span the arrival on the ground of a musket ball of no more than half [an ounce], both coming from a height of two hundred braccia.

SALVIATI: . . . [I]f we had two moveables whose natural speeds were unequal, it is evident that were we to connect the slower to the faster, the latter would be partly retarded by the slower, and this would be partly speeded up by the faster. Do you not agree with me in this opinion?

SIMPLICIO: It seems to me that this would undoubtedly follow.

SALVIATI: But if this is so, and if it is also true that a large stone is moved with eight degrees of speed, for example, and a smaller one with four, then joining both together, their composite will be moved with a speed less than eight degrees. But the two stones joined together make a larger stone than that first one . . . ; therefore this greater stone is moved less swiftly than the lesser one. But this is contrary to your assumption.

SIMPLICIO: I find myself in a tangle, because it still appears to me that the smaller stone added to the larger adds weight to it; and by adding weight, I don't see why it should not add speed to it, or at least not diminish this [speed] in it.

SALVIATI: Here you commit another error, Simplicio, because it is not true that the smaller stone adds weight to the larger.

SIMPLICIO: Well, that indeed is beyond my comprehension.

Source: Stillman Drake, trans., *Galileo: Two New Sciences* (Madison: University of Wisconsin Press, 1974), pp. 66-67.

Thus, he had all of the elements of "the law of the fall" but did not publish these results until many years later, when he could present them as part of a coherent system. These and other observations are compiled in Galileo's lectures, collected in *Le meccaniche* (c. 1600; *On Mechanics*, 1960), considered the best work on simple machines up to that time.

IMPACT

Ideally, science has a dual role: it approaches questions theoretically by soundly predicting the outcome of "events," and then it proves those predictions through sound experiment and observation. Galileo's experiments, backed by mathematical models and proofs, paved the way for Isaac Newton's formulation of the three laws of motion. They also reinforced the growing proclivity among scientists to undertake their own observations before accepting prevailing Aristotelian views—albeit often at the risk of persecution by the Church.

See also Ballistics; D'Alembert's Axioms of Motion; Gravitation: Newton; Medieval Physics.

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—*Charles W. Rogers*

FERMAT'S LAST THEOREM

THE SCIENCE: Andrew Wiles presented his proof of the "last theorem" of Pierre de Fermat, which had defied solution by mathematicians for more than three and a half centuries.

THE SCIENTISTS:

Pierre de Fermat (1601-1665), French mathematician

Andrew J. Wiles (b. 1953), English mathematician working at Princeton University

Richard L. Taylor (b. 1962), mathematician at Cambridge University and a former student of Wiles

Fred Diamond (b. 1964), Cambridge mathematician, also a Wiles student

AN OLD MYSTERY

Pierre de Fermat was a French jurist whose genius at mathematics led to his occasional nickname, "the father of number theory"—number theory being the study of the relations of whole numbers. In 1637, while rereading the *Arithmetica* of the third century Alexandrian mathematician Diophantos, Fermat was struck by a discussion of the Pythagorean theorem, which states that, for a right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides, or, in mathematical notation $x^2 + y^2 = z^2$, where z is the hypotenuse and x and y are the other sides; x, y, and z are all integers. The most familiar whole-number example of the Pythagorean relationship is probably that in which $x = 3$, $y = 4$, and $z = 5$.

Generalizing the Pythagorean equation to $x^n + y^n = z^n$, Fermat noted in the book's margin that this equation had no whole-number solutions for any n larger than 2, and that he had a "truly marvelous" proof of this assertion—which was, unfortunately, too long to write in the margin. This deceptively simple equation, and the implied proof of Fermat's statement, came to be called Fermat's last theorem (FLT), because it was the last of a number of his mathematical assertions left unproven at his death, and the only one to resist solution by later mathematicians.

Fermat himself provided a proof of FLT for $n = 4$, and the Swiss mathematician Leonhard Euler did so for $n = 3$. By mid-nineteenth century, FLT was proved for all cases up to n = one hundred, and in the 1980's computer calculations extended this to four million. Yet demonstrations of specific cases, however extensive, are not the mathematician's definition of "proof." Proof must be established for the absolutely general case, from which an infinite number of specific cases can be deduced.

The Solution

This was where the matter stood when Andrew Wiles began work on FLT in 1986. His approach was to establish x, y, and z as points on "elliptic curves" (curves with the general equation $y^2 = x^3 + ax^2 + bx^{-1} + c$), then to make use of the Taniyama-Shimura conjecture, which maps these points onto a non-Euclidian surface called the "hyperbolic plane." (An alternative explanation relates the elliptic curves to a group of "modular curves" that are related to complex number planes. Both explanations are oversimplifications of very difficult mathematical ideas.) If elliptic curve solutions existed that violated FLT, they could not be mapped onto the hyperbolic plane, and the Taniyama-Shimura conjecture would be violated. Thus, solutions that violate FLT are impossible, and FLT is proved by this contradiction.

The difficulty Wiles faced was that no one had proved the Taniyama-Shimura conjecture, even for the limited set of cases he needed. This was the problem that occupied him for seven years. He solved it by devising mathematical counting systems for a group of elliptic curves called "semistable" and their modular counterparts. He could then show a one-to-one correspondence between the two groups that proved the Taniyama-Shimura conjecture in the limited case that was sufficient for his FLT argument. This was the greater part of the material of the three lectures at Cambridge University from June 21 to June 23, 1993, in which Wiles presented his findings. In the third of these lectures, he announced his proof of FLT almost as an afterthought, as a corollary of the work discussed in the first two lectures. The audience of normally reserved mathematicians burst into spontaneous applause.

The lecture presentations were gathered and expanded into a two-hundred-page paper submitted to the journal *Inventiones Mathematicae*, and flaws were found by the six referees to whom the manuscript was sent. Most of the flaws were quickly repaired, but one serious flaw involving the unproven upper limit of a mathematical construct, the Selmer group, took nearly two years to straighten out. Wiles finally appealed to one of his former students at Cambridge, Richard L. Taylor, and together they found a way around the missing proof. Wiles's overall proof of FLT was published in revised form in the *Annals of Mathematics* in 1995; in the same issue, Wiles and Taylor published the Selmer group work as a separate article.

Impact

Proof of FLT was the headline story of Wiles's achievement, because of the longtime intractability of the problem and the near-hero status accorded its conqueror. To the world of mathematicians, however, the real story was the limited proof of the Taniyama-Shimura conjecture, which is already on the way to a more general proof in the hands of a student of Wiles, Fred Diamond of Cambridge University. The Taniyama-Shimura conjecture provides a bridge between two major areas of mathematics, algebra and analysis, and is expected to further the Langlands program, a hoped-for grand unification of all mathematics. In the meantime, Wiles's work has drawn on so many areas of mathematics that it has opened the way to a host of other advances in the field, and research papers building on his ideas have begun to appear in many journals.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Robert M. Hawthorne, Jr.*

FOSSILS

The Science: Through scientific observation, Girolamo Fracastoro, Nicolaus Steno, and others developed early theories that fossils are the remains of once-living organisms, the remnants and traces of the history of life on Earth.

THE SCIENTISTS:

Girolamo Fracastoro (c. 1478-1553), Italian physician, geologist, and poet
Nicolaus Steno (1638-1686), anatomist and founder of stratigraphy
Leonardo da Vinci (1452-1519), Italian artist and inventor

CARVED STONES

Prior to the speculations of Girolamo Fracastoro, fossils were viewed as inorganic products of the mineral kingdom formed in situ. During the Middle Ages, definitions of fossils were based on assumptions made by Aristotle, who believed fossils resulted from the petrified and then sedimented remains of an abundance of organisms that came to life through spontaneous generation. Fossils, believed to be formed by many different forces, were classified as oddities of nature, carved stones, or mineral concretions that were by-products of the motions of the stars, seminal vapors, or unidentified petrifying or plastic forces. To further compound the confusion, religious dogma of the time designated all fossils to be relics of Noah's ark and the great flood.

By the early sixteenth century, three questions had begun to dominate discussions about fossil origins: Are fossils inorganic? Are they relics of Noah's ark? Are fossils the product of a long history of past life on Earth? Fracastoro and his contemporary, Leonardo da Vinci, favored the theory that fossils represented a record of a long history of life on Earth.

EVIDENCE OF PAST LIFE

Leonardo's notebooks contain many acute and accurate observations of living mollusks and their ecology and notes on the process of sedimentation. He recognized that similarities between living marine life and fossils were so exacting that a causal explanation was necessary to account for a fossil's existence. Leonardo noted that fossils were preserved in various stages of growth and exhibited markings of a life history on their surfaces such as bore holes and parasites. He further speculated that fossils were embedded in stratified rock and were consolidated from "drying out." However, because Leonardo recorded his theories regarding the marine origin of fossils into his famous coded private notebooks, his ideas had little to no influence on later researchers of fossils.

In 1517, Fracastoro observed fossil mollusks and crabs that had been discovered in the foundations of buildings in Verona. He believed they were the remains of once-living shellfish buried after the landscape changed over time, and he argued against suggestions that they were embedded because of a biblical flood or because of a molding force from within the Earth. Fracastoro's interpretation of fossils as organic remains embedded during the continual process of geological and geographical change, was clearly secular. He suggested that the existence of fossils could be explained completely in terms of natural law. It is important to note, though, that Fracastoro was an Aristotelian thinker and that it was acceptable to define fossils also as spontaneously generated. Fracastoro attributed the process of spontaneous generation to explain some of the more difficult fossil samples he observed.

Early Stratigraphy

Fracastoro's ideas, made public, would inspire Conrad Gesner's *De rerum fossilium, lapidum, et gemmarum maximè, figuris et similitudinibus liber* (1565; on the shapes and resemblances of fossils, stones, and gems); Andrea Chiocco's *Musaeum Francisci Calceolari Veronensis* (1622), which quotes Fracastoro; and Nicolaus Steno's pivotal work *De solido intra solidum naturaliter contento dissertationis prodromus* (1669; *The Prodromus to a Dissertation Concerning Solids Naturally Contained Within Solids*, 1671). Although Steno does not quote Fracastoro in his publication, most scholars believe he was familiar with and influenced by Fracastoro's ideas.

Steno's work, considered the founding text of modern geological science, examines the general question of how one solid (fossil) could be contained within another solid (rock strata). It also contests the explanation of fossils as relics of the biblical Flood. Steno believed that strata were formed by the deposition of sediments in water; what looked like organic remains found within stratified rock must represent once-living organisms that existed in water at the time the sediments were deposited. Through direct observation, Steno also theorized that the process of sedimentation takes place at a slow rate over long periods of time.

Impact

During the seventeenth century, standard Ptolemaic and Aristotelian doctrines of cosmology and the origins of life were being questioned and investigated. The growing interest in fossils and what caused them was tied to the belief in "spontaneous generation," long accepted from Aristotle's doctrine that "non-copulative" organisms, such as mollusks, reproduced wherever conditions were appropriate not through sexual or inherent asexual reproduction but in response to an external life force. Fossils were simply the petrified evidence of such spontaneous populations.

This doctrine was questioned even before Steno's time, although it would not be fully abandoned until the explication of cell theory in the nineteenth century. Steno's proposal was revolutionary not only for the formation of fossils but also for the understanding of rock strata and how they relate to geologic time. He is therefore known as the father of modern stratigraphy.

STENO ON STRATIGRAPHY

Born Niels Stensen in Copenhagen in 1638, Nicolaus Steno studied medicine at the University of Leiden and became a physician at a hospital in Tuscany under the patronage of Ferdinand II. Renowned for his studies of anatomy, in 1666 he was sent the head of a huge shark caught by two fishermen near Livorno and noticed that the teeth resembled glossopetrae, the "tongue stones" found in some rocks. Dissatisfied with conventional explanations for how these formations occurred, Steno theorized that these stones could once have been living matter transformed over time by the exchange of "corpuscles" (atoms) that altered their composition.

Steno's interest did not stop there. He was curious about all sorts of formations found in rocks, and he developed an integrated theory consisting of the following principles:

> PRINCIPLE OF HORIZONTALITY: Sedimentary rocks form in rough layers and later folding or tilting of the originally horizontal orientation postdates the sedimentary deposition.
>
> PRINCIPLE OF SUPERPOSITION: If a solid body is enclosed on all sides by another solid body, of the two bodies that one first became hard which, in the mutual contact, expresses on its own surface the properties of the other surface.
>
> PRINCIPLE OF LATERAL CONTINUITY: Strata extend in all directions until they terminate at the edge of a region of deposition or grade horizontally into another kind of rock.
>
> PRINCIPLE OF CROSS-CUTTING RELATIONSHIPS (developed further by Charles Lyell): Any intrusive body or crack [such as a dike, sill, or fault] must be younger than the rock it intrudes.

Steno correctly realized that disturbances in the layers of earth were caused by some hard object—whether stone, bone, wood, or other material—falling into soft sediments long ago. Such bodies forced the surrounding sediment to conform to their shapes. On the other hand, mineral deposits that are found in rock *after* it has become solid, Steno contended, must conform to the surrounding rock—a clear distinction between fossil and mineral formations. Also, it is possible to determine the ages of objects in one layer relative to those in others, since the lower layers are older. Steno had articulated the basic principles of stratigraphy.

See also Amino Acids; *Australopithecus*; Cro-Magnon Man; Evolution; Geologic Change; Gran Dolina Boy; Human Evolution; Lamarckian Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Microfossils; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Randall L. Milstein, updated by Christina J. Moose*

FRACTALS

THE SCIENCE: Benoît Mandelbrot's introduction of fractals—figures with fractional dimensions—revolutionized mathematics and many other fields of science.

THE SCIENTIST:

Benoît Mandelbrot (b. 1924), Polish American mathematician

ORDER IN CHAOS

Fractals are mathematical figures that have fractional dimensions rather than the integral (nonfractional) dimensions of familiar geometric figures such as one-dimensional lines and two-dimensional planes. Fractals offer an extremely concise way of describing objects and formations that are irregular in nature. Many structures, such as the bronchi in the human lung, are made up of similar, smaller repetitive patterns. If an examination is conducted on a small scale, a single fundamental element can be identified in the repeated pattern. This element describes the fractional dimension of the structure.

The term "fractal" comes from the Latin word *fractus*, which refers to something that has been broken into irregular fragments. Fractal dimensions were introduced to the English-speaking community in 1977 by Benoît Mandelbrot in his book *Fractals: Form, Chance, and Dimension*. In that book, Mandelbrot discussed the problem of the length of the coastline of Great Britain, responding to a question posed in 1926 by Louis Fry Richardson: How long is the coastline of Britain? This question has no answer unless one describes how one will evaluate the length.

The key idea introduced into applied mathematics by Mandelbrot is that rugged (irregular), indeterminate systems can be described by extending classical Euclidean dimensional analysis to include a fractional number that describes the ruggedness of the system. Many familiar shapes—such as those of clouds, mountains, and raindrop patterns, for example—are best described as having fractal dimensions. The study of fractals has led to a field known as "chaos theory." Chaos theory is defined as a cutting-edge mathematical discipline that attempts to make sense of the inexpressible, to find order in the seemingly random.

THE GEOMETRY OF CHAOS

The earliest problem posed by Mandelbrot that laid the groundwork for fractal geometry was the paradox of the length of the coastline of Great Britain. One way to determine the length of the coastline is for a person to walk around and calculate that its length is a certain number of steps. If that person is reduced to the size of an ant, however, the number of steps will be much larger. Mandelbrot concluded that the coastline can be considered infinitely long if smaller and smaller steps are used to estimate its length.

Image Not Available

SIERPINSKI TRIANGLES

Fractals are really a geometric language. They are not, however, expressed in terms of primary shapes, as is the case in Euclidean geometry. Instead, fractals are expressed as algorithms, or sets of mathematical procedures. In fact, large-scale computers are often used to generate complex fractal patterns.

One of the simplest examples of a class of geometric shapes is the Sierpinski gasket, also called the Sierpinski triangle, which is known as a "deterministic fractal." A deterministic fractal scales exactly; in other words, if its parts are magnified, they match the whole fractal precisely. Fractals such as the Sierpinski gasket are found exclusively in the world of mathematics, but fractality itself is an attribute of nature. In fact, those who are proponents of the idea of fractality would even say that fractality dominates nature. Clouds, mountains, human bronchi, and neural networks, which are all fractal structures, are phenomena that are called "nonlinear."

Fractality is a factor in various areas of chemistry. One involves fractal chemical surfaces upon which chemical reactions can occur. Another has to do with fractal growth processes that result in fractal structures. In addition, heterogeneous chemical reactions, which involve reactions of chemicals that are not in the same phase (for example, a heterogeneous chemical reaction might involve a liquid and a gas, or a solid and a liquid), have been shown to exhibit fractal behavior. Protein dynamics is still another area in which chaos theory and fractal behavior operate.

All fractal shapes are irregular and fragmented, but merely being so does not make an object fractal. A true fractal object must also be self-similar. A self-similar, or scale-invariant, object is one that looks the same—either exactly or to some extent—when it is contracted or expanded uniformly in all directions.

IMPACT

Fractals have brought about a scientific and mathematical revolution, making it possible to describe things that previously were indescribable. Chemists, powder metallurgists, physicists, biologists, businesspersons, and physicians have found fractal geometry and chaos theory applications in their fields.

For example, Ary Goldberger, associate professor of medicine at Boston's Beth Israel Hospital, believes that a little chaos may underlie good health. By bringing chaos theory into the clinic, he and his colleagues made some fascinating discoveries about the biology of aging, heart disease, cocaine overdoses, and space sickness. Their findings suggested that some erratic behavior in a biological system is a good thing; in fact, the waning of chaos may be a sign of disease.

In another area, Wall Street financiers believe that fractal theory may help to predict trends in the stock market. Eventually, chaos theorists may persuade money managers to put their money where their theories are.

See also Chaotic Systems; Weather Fronts.

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—*Jane A. Slezak*

GALACTIC SUPERCLUSTERS

THE SCIENCE: Discovery of the local supercluster of galaxies in the 1920's, along with subsequent observations by astronomers such as Gérard

Henri de Vaucouleurs, sparked the study of the large-scale structure of the universe.

THE SCIENTISTS:

Gérard Henri de Vaucouleurs (1918-1995), French-born American astronomer
George Ogden Abell (1927-1983), American astronomer
Charles Donald Shane (1895-1983), American astronomer and director of the Lick Observatory
Carl Alvar Wirtanen (1910-1990), American astronomer
Jerzy Neyman (1894-1981), American statistician and educator
Elizabeth Leonard Scott (b. 1917), American astronomer and statistician

CLUSTERS OF GALAXIES

In the early 1920's, the debate over the nature of "spiral nebulae" was resolved. One school of thought was that spiral nebulae were pieces of the Milky Way—relatively nearby, small objects. Another theory held that they were distant, very large, independent star systems. In 1924, the American astronomer Edwin Powell Hubble was able to settle the debate by determining the distance to the Andromeda nebula. The distance was found to be a large one, which indicated that the Andromeda nebula is, in fact, a huge system, independent of the Milky Way. The American astronomer Harlow Shapley, in the 1920's, discovered the dimensions and rough structure of the Milky Way galaxy, and the work of Hubble and Shapley brought about the beginning of the present picture of the universe: The Milky Way is a spiral galaxy in a universe that contains other galaxies of various shapes and sizes.

Sky surveys, in which large portions of the sky are photographed and galaxies are counted and positioned, revealed interesting information about the way that galaxies appear to be distributed in space. Even before the nature of the spiral nebulae was known, astronomers had noted that spiral nebulae appear in clusters. In 1922, a band of nebulae stretching nearly 40° across the northern sky was observed by the English astronomer J. H. Reynolds. In addition to identifying the "local group" (a group of nearby galaxies, of which the Milky Way is a part), astronomers identified other groupings of galaxies. The Coma cluster and the Virgo cluster of galaxies were defined and named for the constellations in which they appear. Hubble photographed faint galaxies, so faint that he thought he was seeing as far into the universe as he could and that he was witnessing a limit to the phenomenon of clustering. An earlier scheme had suggested that there was a hierarchy of structure to the universe, with clusters of galaxies making up larger clusters of clusters, which in turn made up still larger structures. Hubble's observations seemed to indicate that this hierarchy was not likely to exist.

By 1950, the largest cluster known was the Coma cluster, which contained more than one thousand individual galaxies. The galaxies in clusters were mostly elliptical galaxies (rounded or oval in shape, with no distinguishing structural features) and spirals without much spiral arm structure. Astronomers had also identified so-called field objects: isolated galaxies, mostly spirals, that did not appear to belong to any cluster. It had been suggested that perhaps the group of galaxies in the Virgo area of the sky might contain more than one cluster, but Hubble's work still seemed to rule out this possibility.

Clusters of Clusters

It was on the basis of a sky survey, completed at Lick Observatory between 1947 and 1954 by Charles Donald Shane and Carl Alvar Wirtanen, that Elizabeth Leonard Scott and Jerzy Neyman applied the techniques of statistics to the question of the large-scale structure of the universe. Between 1952 and 1954, they published several papers regarding the laws that describe clustering, proposed that all galaxies belong to clusters, and mentioned the existence of "clouds" of galaxies. (That was their term for "superclusters"; a supercluster is simply a group of neighboring clusters of galaxies.) George Ogden Abell, at the University of California, Los Angeles, used plates taken at Mount Palomar Observatory to make a catalog of 2,712 clusters of galaxies, and his work indicated that many of the clusters seemed to be members of superclusters.

In the early 1950's, Gérard Henri de Vaucouleurs first defined and described what is called the "local supercluster." De Vaucouleurs had begun working at the Mount Stromlo Observatory in Australia to update the Shapley-Ames catalog of bright galaxies, a standard tool for astronomers. While doing this work, he observed that the local group was located at the edge of a much larger grouping of clusters of galaxies. He referred to this larger grouping as a "supergalaxy," and he further estimated that other supergalaxies might exist as well.

De Vaucouleurs estimated the local supercluster to be approximately fifty million light-years across and to be roughly disk shaped. The supercluster is centered on the Virgo cluster of galaxies, about fifty million light-years away. De Vaucouleurs also identified what appeared to be another supercluster, which he called the "southern supergalaxy"; he posited that the local supercluster is neither unique nor unusual. De Vaucouleurs would go on to conduct many studies of the superclustering phenomenon.

IMPACT

Astronomers now estimate the local supercluster to be about one hundred million light-years across and to have a total mass of about one thousand trillion times that of the Sun. Astronomers also have discovered fine detail in the local supercluster and other superclusters. In addition to the local supercluster, others have been identified: the Hercules, Coma, and Perseus-Pisces superclusters. Common features of these superclusters have been identified. The hypothesis of de Vaucouleurs—that superclusters exist as organized structures—has been confirmed. Fine structure has been discovered, such as filaments and streamers, or strings of galaxies that link the various parts of the superclusters. In addition, astronomers have discovered voids, or spaces, in which no bright galaxies appear.

The structure of superclusters may have much to teach astronomers about how the universe cooled and formed after the big bang theory. This field is at the forefront of cosmological research and may reveal even more startling information about the large-scale structure of the universe and how it came to be.

See also Cepheid Variables; Expanding Universe; Extrasolar Planets; Galaxies; Gamma-Ray Bursts; Hubble Space Telescope; Inflationary Model of the Universe; Neutron Stars; Oort Cloud; Planetary Formation; Pluto; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe; X-Ray Astronomy.

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—*Mary Hrovat*

GALAXIES

THE SCIENCE: Vesto Melvin Slipher obtained the spectra of the Andromeda nebula and showed that it had a large radial velocity, suggesting that it, and other spiral nebulae, were not part of our own Milky Way galaxy but were galaxies in their own right. His observation that most galaxies are receding at high velocity helped demonstrate that the universe is composed of many galaxies expanding away from one another.

THE SCIENTISTS:

Vesto Melvin Slipher (1875-1969), American astronomer who became the director of the Lowell Observatory (1916-1952), perfected spectroscopic techniques, and used them to study planetary atmospheres and rotations

Percival Lowell (1855-1916), American astronomer who founded Lowell Observatory and suggested spectroscopic problems to Slipher

Heber Doust Curtis (1872-1942), American astronomer who was an early and ardent supporter of the "island universe" idea and who engaged in a debate with his leading opponent, Harlow Shapley

Harlow Shapley (1885-1972), American astronomer who worked on Cepheid variables, globular clusters, and galaxies and opposed the "island universe" idea

Adriaan van Maanen (1884-1946), Dutch American astronomer whose systematic error in measurement caused a delay in the acceptance of the "island universe" idea

Edwin Powell Hubble (1889-1953), American astronomer who was the founder of modern extragalactic astronomy, his work confirmed the "island universe" idea and provided observational evidence for the expansion of the universe

Milton L. Humason (1891-1972), the astronomer who extended Slipher's observational work on galactic spectra, leading to Hubble's discovery of the expansion of the universe

SPIRAL NEBULAE

The general view held by astronomers in the first two decades of the twentieth century was that the universe consisted of a single aggregation of stars, the Milky Way galaxy, which was a system of stars estimated to be about 10,000 light-years in diameter. All objects that were visible in the heavens through the largest telescopes were thought to be part of our galaxy; beyond, a trackless, undifferentiated void extended infinitely far.

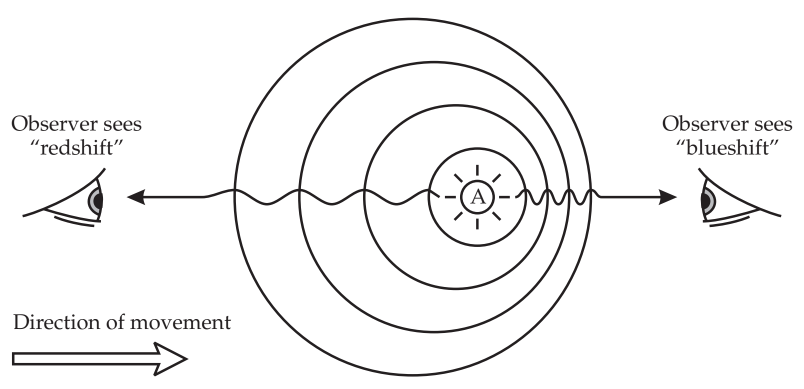
By the early part of the twentieth century, astronomers had compiled extensive catalogs listing the visible constituents of the galaxy, which included numerous stars and various nebulae, misty patches of light in the sky whose complete nature was not understood then but were presumed to consist primarily of gases. Photographs of nebulae showed that some had irregular shapes but that many had a distinctly spiral structure.

Percival Lowell was keenly interested in the study of the spiral nebulae. A member of a prominent Boston family, Lowell was able to finance the construction of his own observatory in Flagstaff, Arizona, dedicated to the study of planets. Lowell's interest in the spiral nebulae lay in the notion, held by nearly all astronomers at the beginning of the twentieth century, that they were planetary systems in the process of formation. The study of spiral nebulae, Lowell hoped, would disclose valuable clues to the origin of the solar system.

BEYOND THE MILKY WAY

In 1901, Lowell hired Vesto Melvin Slipher as an observer at Lowell Observatory and assigned him to a project on spiral nebulae. Slipher was to take spectra of the brighter ones and look for Doppler shifts in their light, which would reveal motions taking place within them. Lowell expected the results to support the theory that the spiral nebulae were rotating, contracting clouds of gas which would eventually form a planetary system or

THE DOPPLER SHIFT

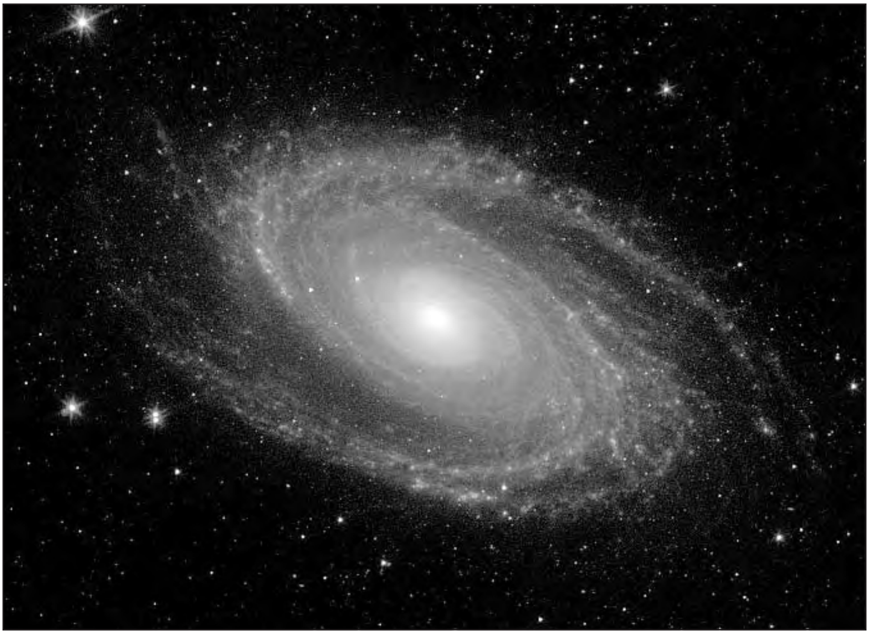


In the phenomenon known as the Doppler shift, light waves appear bluer (because they are shorter) when the source is moving toward the observer and redder (because they are longer) when the source is moving away from the observer. Above, "A" is a source of light, such as the Andromeda nebula.

a cluster of stars. Slipher thought this was unlikely; he believed the spirals were probably systems of stars outside our own galaxy.

By late 1912, and using the 61-centimeter refractor at the Lowell Observatory, Slipher had photographed four separate times the spectrum of the Andromeda nebula, one of the largest and brightest of the spirals. Because of the slowness of the photographic emulsions of the time, Slipher found it necessary to expose each photograph for twenty to forty hours, spread over several nights. When examined, the spectra were found to be similar to those of stars like the Sun, a band of colors from blue to red crossed by dark lines which are characteristic of the elements found in the stars. Slipher had provided the first hint that a spiral nebula was a system of stars rather than a collection of gases. Without knowing the distance to the Andromeda nebula, however, Slipher was not able to demonstrate conclusively that the nebula was external to the Milky Way. Slipher interpreted, as did many other astronomers who learned of his work, the failure to detect individual stars in the spirals as an indication of their large distances.

In the spectra of the Andromeda nebula, Slipher noticed that there was a systematic shift of all the dark lines toward the blue end of the spectrum. Such a Doppler shift of all the lines toward either the red or blue was attributed to a systematic motion of the emitting nebula as a whole. If the object is moving toward the observer, the shift is toward the blue end of the opti-



Galaxy Messier 81. (NASA/JPL)

cal spectrum and is called a blueshift. If the object is moving away, there is a corresponding redshift. The size of the shift in the position of the dark lines provides a direct measure of the speed with which the object is moving toward or away from the observer. In the case of the Andromeda nebula's blueshift, Slipher's data indicated that it was approaching at the speed of 300 kilometers per second, a speed greater than that of any astronomical object measured at the time.

Slipher extended the work on spiral nebulae and by 1914 had analyzed the spectra of twelve additional spirals, making a total of thirteen spirals whose Doppler shifts had been measured. Two of the spectra displayed a blueshift (one was that of the Andromeda nebula), but the other eleven were all redshifts, indicating that these nebulae were receding. If the spirals were part of the Milky Way galaxy, astronomers expected that roughly half would be approaching and half would be receding. Moreover, the speeds of recession measured by Slipher ranged up to an astounding 1,100 kilometers per second. A pattern was beginning to emerge, and astronomers began to suggest openly that the spirals must be stellar systems outside our galaxy. The speeds of the spiral nebulae seemed to be too great for them to be gravitationally bound to our galaxy. Slipher's results helped direct attention to the spiral nebulae and to the theory that space is populated by visible galaxies.

REDSHIFTING GALAXIES

Slipher was fastidious, methodical, and careful. Although his results until 1914 suggested that most spirals were in recession, he believed it necessary to continue this line of inquiry and extend the survey further; a sample of thirteen Doppler shifts was not convincing. By 1923, Slipher had measured Doppler shifts in forty-one different nebulae; thirty-six had redshifts, and the remaining five had blueshifts. Meanwhile, other astronomers had added four more to the list; these were all redshifts. When it was discovered in 1925 that the Milky Way galaxy as a whole was rotating and that the Sun, because of the rotation, was moving with a speed of 250 kilometers per second in a direction generally toward the Andromeda nebula, the Doppler speeds of the nebulae, as measured by Slipher, were corrected for the rotation of the galaxy. Thus, the 300-kilometer-per-second approach of the Andromeda nebula is composed of a 250-kilometer-per-second motion of the Sun toward the spiral and an intrinsic 50-kilometer-per-second approach of the spiral. When so corrected, of the total of forty-five nebular Doppler shifts measured, forty-three were redshifts.

Slipher had demonstrated clearly that the general trend was for the spiral nebulae to exhibit redshifts in their spectra, indicating that they were receding from the Milky Way galaxy and from one another. The two exceptions were the largest spirals, and therefore probably the nearest. Nevertheless, Slipher's work forcefully showed that spirals were probably galaxies in their own right, external to the Milky Way, and that the overwhelming preponderance of redshifts indicated that galaxies were all rushing away from one another.

A New Picture of the Universe

Slipher's pioneering work on the redshifts of the spiral nebulae provided the foundation for a coherent picture of the evolution of the universe. In the late 1920's, Slipher's evidence was juxtaposed, along with the cosmological arguments that were being discussed by astronomers. It provided the impetus for a major new project to determine the distances to the galaxies.

Following the construction of the giant 254-centimeter telescope on Mount Wilson, California, Milton L. Humason and Edwin Powell Hubble were able to study the spiral nebulae in much greater detail than had been possible for Slipher. In fact, with the new telescope, individual stars could be discerned in some of the larger spirals, the Andromeda nebula in particular. Now, all doubt was removed regarding the spiral nebulae: They were galaxies, vast systems of stars similar to the Milky Way of which the Sun is a part.

With individual stars available for study, they could be compared with stars in the Milky Way, and the distance to the galaxy could be estimated. The Andromeda galaxy lay at a distance of 750,000 light-years, far outside the Milky Way. Other spirals had even greater distances. Using the redshift data inherited from Slipher, Hubble combined those results, together with the distance measurements based on his and Humason's observations to arrive at a relationship between distance and recessional velocity: The greater the recessional velocity of a galaxy, the greater is its distance.

Impact

To astronomers of the time, the cause of the recession was now clear. To explain the rush of galaxies away from one another, the universe must be expanding. Such an idea had its roots in the theory of general relativity published by Albert Einstein in 1916. Thereafter, Einstein and other astronomers and physicists examined the consequences of the theory and found that the universe should generally be in a state of either expansion or contraction. Slipher's redshift measurements and Hubble's correlation with distance demonstrated that the universe is expanding, an observation of central importance to cosmology. Since as time progresses, the universe expands, it must have been the case that in earlier epochs the galaxies were very close together and, at one time, entirely coalesced. Astronomers reached the startling conclusion that the universe was born in a titanic explosion (now called the big bang) that hurled the material from which the galaxies eventually formed. The high-speed rush of galaxies away from one another is direct evidence of that genesis.

Humason extended the redshift work, and by 1935 had added 150 measurements to Slipher's list. Recessional speeds now were up to 40,000 kilometers per second. When distances were determined for the galaxies, Hubble's redshift-distance relation still held. By the mid-1930's, astronomers pictured a universe full of galaxies that were rushing apart from one another as a result of a fiery birth in the distant past. This model of the universe has remained fundamentally unchanged to the present.

See also Cepheid Variables; Expanding Universe; Extrasolar Planets; Galactic Superclusters; Gamma-Ray Bursts; Hubble Space Telescope; Inflationary Model of the Universe; Neutron Stars; Oort Cloud; Planetary Formation; Pluto; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe; X-Ray Astronomy.

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—*Anthony J. Nicastro*

Galen's Medicine

The Science: Galen synthesized ancient medical knowledge, combining preexisting medical knowledge with his own ideas in writings that dominated European medical thinking for some fifteen hundred years after his death.

THE SCIENTISTS:

Galen (129-c. 199 C.E.), Roman physician and medical author

Hippocrates (c. 460-c. 370 B.C.E.), Greek physician, considered the Greek father of medicine

PHYSICIAN TO THE ANCIENTS

Galen, a Greek subject of the Roman Empire, was born in 129 C.E. in Pergamon (or Pergamum), a city in Asia Minor considered to be second only to Alexandria as a great center of learning in the Roman Empire. After studying philosophy in Pergamon and serving as a surgeon to gladiators, he moved to Alexandria to study anatomy. In 169, Galen took a position as the personal physician of the Roman emperor Marcus Aurelius, and his eminence as a medical teacher was widely recognized. At Rome, he had access to the imperial library's vast collection of medical writings from the farthest reaches of the empire. Combining his own observations and research with this great store of medical knowledge, Galen's writings, more than any other source, influenced Western medical thinking for approximately fifteen hundred years after his death.

HIPPOCRATES' LEGACY

Galen wrote down for posterity the accomplishments of the great early figures of medicine. Hippocrates, the father of medicine, is largely known to the modern world through the writings of Galen. The Hippocratics, followers of Hippocrates, built on the scientific foundation laid by Hippocrates. Their collections of observations and research were kept alive by Galen for subsequent generations. If not for Galen, most of the Hippocratic literature would have perished, and the modern world would know nothing about the work of the great Alexandrian anatomists of the fourth and third centuries B.C.E. such as Herophilus and Erasistratus who pioneered work on the nervous and circulatory systems. Galen's seventeen-volume medical treatise *De usu partium corporis humani* (written between 165 and 175 C.E.; *On the Usefulness of the Parts of the Body*, 1968) summarized the medical knowledge of his day and preserved the medical knowledge of his predecessors.

FOUR HUMORS

In his book *De naturalibus facultatibus* (c. late second century C.E.; *On the Natural Faculties*, 1916), Galen expanded on Hippocrates' theory of the four humors, or bodily wet substances: black bile, yellow bile, blood, and phlegm.

According to Galen, in addition to the physiological abnormalities caused by imbalances of these humors, psychological differences would also result. Furthermore, overabundances of different humors were linked with distinct temperaments (personality predispositions). Thus, excess black bile could result in sadness (melancholic temperament); too much yellow bile in excitability and being easily angered (choleric temperament); excess phlegm in sluggishness and introversion (phlegmatic temperament); and too much blood in cheerfulness and extroversion (sanguine temperament).

The influence of Galen's theory of humors is still seen in the contemporary use of words such as "sanguine" and "phlegmatic" and in expressions such as, "Are you in a good humor today?" Even the red-striped barber's pole was originally the sign of an individual who would drain blood to improve the health of others.

Body, Mind, and Spirit

Although he was not a Christian, Galen was strongly opposed to atheistic, materialistic explanations of nature and the human body. He believed that nature reflects a divine design and so does the body. God breathes life into nature, and according to Galen, the divine life-giving principle in humans is called *pneuma* (from the Greek "breeze"). Three adaptations of *pneuma* give the following attributes of living creatures: the natural spirit produces growth; the vital spirit causes locomotion; and the animal (from the Latin term *anima*, meaning soul) spirit is what makes intellectual functioning possible. Galen's studies of anatomy and physiology were often conducted to determine the flow of these spirits throughout the human body. *Pneuma* theory dominated Western medical thinking until well into the eighteenth century.

Galen not only wrote on the impact of physiological factors on mental activities but also concluded that thinking could affect physiology. This is illustrated in an incident in which Galen was treating a female patient. Galen noticed that when the name of Pylades, a male dancer, was mentioned, the patient's heart rate became irregular. When the names of other male dancers were mentioned, there were no effects on her pulse. Galen concluded from this that the patient was "in love" with the dancer and that thinking can lead to physiological consequences. Thus, the first clear description of a psychosomatic (mind-body) relationship can be said to originate with Galen.

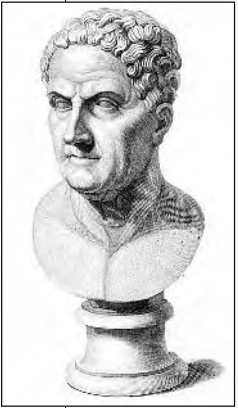
THE APE DOCTOR

The son of Nicon, a prosperous Roman architect, Galen spent his youth at Pergamon, which featured both a great library and a temple of Asclepius, the god of healing. According to tradition, when he was sixteen Galen's father had a dream in which Asclepius appeared and announced that Galen would become a physician. Galen accordingly traveled to Egypt and Asia Minor to study and returned to Pergamon as physician to the gladiators. Because gladiators often received severe wounds, a physician was obliged to attend to their diet, exercise, and convalescence.

Galen did not perform much surgery on the gladiators, and his knowledge of anatomy was derived exclusively from dissections on animals. Slaves or students would prepare the cadavers of pigs, sheep, oxen, cats, dogs, fish, and other animals by shaving and flaying them. Galen particularly favored the Barbary ape, for which he was nicknamed the Ape Doctor.

In 162 C.E., when a war between the Pergamonites and the Galatians began, Galen left for Rome. He rented a large house, practiced as a physician, attended medical meetings in the Temple of Peace, and continued his interest in philosophy. When Galen's outspoken and contemptuous criticism of those he considered charlatans put his life in danger, he decided to return to Pergamon.

His recuperation from Rome-weariness was short. He received a letter from the co-emperors Marcus Aurelius and Lucius Verus, ordering him to join the Imperial camp in the western city of Aquileia, where legions were gathering against the barbarians. These military preparations were disrupted by plague, a form of typhus or smallpox probably transmitted by travelers from Syria and stubbornly resistant to treatment. The emperors decided to leave the army, but when Verus died in 169, Marcus ordered Galen back to Rome to take medical charge of Marcus's eight-year-old son, Commodus.



(Library of Congress)

As court physician under Marcus and then Commodus, Galen strengthened his position. He remained in Rome until 192, when a fire destroyed the Temple of Peace, as well as many libraries. Many of his writings were annihilated. Under Commodus, the climate for scholars and philosophers became intolerable. The emperor, a superior athlete who regarded himself as a reincarnation of Hercules, placed a premium on hunting and circus games rather than on intellectual pursuits. Galen again returned to Pergamon in 192, where he had yet another encounter with the plague but saved himself by letting his own blood. After that, he devoted most of his time to meditation and writing, and he died about 199.

Dealing with psychological problems was also a concern of Galen. He wrote of the importance of counsel and education in treating psychological problems. Therapy, according to Galen, should involve a mature, unbiased older person, confronting clients whose passions, such as anger and jealousy, were thought to be primarily responsible for their psychological problems. Such advice by Galen illustrates an ancient idea of psychotherapy. Other advice by Galen on psychological matters is contained in his books *De propriorum animi cujusque affectuum dignotione et curatione* and *De cujuslibet animi peccatorum dignotione atque medela* (c. late second century C.E.; translated together as *On the Passions and Errors of the Soul*, 1963).

IMPACT

Galen's ideas dominated Western medical thinking from his era until the Renaissance. His strongly theistic attitudes were embraced by the Christian thinkers, who began to prevail over the affairs of the later Roman Empire. Early Christian writers from the second to the fourth centuries C.E., such as Tertullian, Lactantius, Nemesius, and Gregory of Nyssa, integrated Galen's ideas into many of their works. Unfortunately, Galen's numerous medical treatises (more than four hundred) were often summarized and distorted by other, inferior, writers, and the Galenism that dominated Western medical thinking from the Dark Ages through medieval times was often far removed from Galen's original writings. Nevertheless, Galen's influence was so profound that even many Renaissance texts began with an acknowledgment to the great contributions of Galen, particularly his emphasis on observation and experimentation.

The profound impact of Galen on subsequent Western thinking is demonstrated most clearly in examining the influence of his theories of *pneuma* and humors. The three adaptations of *pneuma* can be seen to be influential in the writings of the great theologian Saint Thomas Aquinas (1224/1225-1274) in his description of the faculties (or powers) of the soul. The philosophy of René Descartes (1596-1650) is often considered to mark the beginning of the modern period of philosophy. He has also been called the father of physiology for his descriptions of the workings of the human body. These descriptions contained something new, the demonstration of the circulation of the blood by William Harvey (1578-1657), and something old, the animal spirits from Galen's writings.

The old theory of humors, expanded on by Galen, resurfaced in the twentieth century in the work of two noted psychologists. Ivan Petrovich Pavlov (1849-1936), whose work on classical conditioning is one of the greatest contributions to the history of psychology, accepted Galen's classification of temperaments and even extended the theory to dogs, the primary subjects of his research. The distinguished British psychologist Hans Eysenck presented a personality theory in 1964 that incorporated some of Galen's ideas. Indeed, modern research on introversion and extroversion can be seen to have its philosophical antecedents in Galen's theory of humors.

The work of Galen united philosophy with science and rationalism (major source of knowledge is reason) with empiricism (major source of knowledge is experience). His writings are a connection to ancient thinkers and yet his influence on twentieth century theories can be seen. Galen was a practical man dedicated toward discovering the facts of medicine, and his influence is likely to continue to be found in future medical practices.

See also Contagion; Germ Theory; Greek Medicine; Human Anatomy; Microscopic Life.

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—*Paul J. Chara, Jr.*

GALILEO PROBE

THE SCIENCE: After a six-year journey through interplanetary space, the unmanned spacecraft Galileo passed within 370 miles of Jupiter's moon

Europa, revealing an ice-enshrouded world whose surface characteristics suggest an underlying planetary ocean that may harbor extraterrestrial life.

THE SCIENTISTS:

William J. O'Neil, Galileo project manager at the Jet Propulsion Laboratory (JPL)
Torrence V. Johnson, JPL Galileo project scientist
Neal E. Ausman, Jr., Galileo mission director at JPL
Marcia Smith, probe manager
Richard E. Young, probe scientist
Wesley T. Huntress, Jr., associate administrator, NASA Headquarters Office of Space Science
Donald Ketterer, NASA Headquarters program manager for Galileo
Jay Bergstralh, NASA Headquarters project scientist for Galileo
Eugene M. Shoemaker (1928-1997), geologist with the U.S. Geological Survey
Carolyn Shoemaker (b. 1929), astronomer with the U.S. Geological Survey
Donald E. Williams (b. 1942), commander of STS-34

MISSION LAUNCH

The Galileo mission to Jupiter was formally approved by the United States Congress in 1977, several years before the space shuttle *Columbia* made its maiden flight into Earth orbit. The mission was a cooperative project involving scientists and engineers from the United States, Germany, Canada, Great Britain, France, Sweden, Spain, and Australia. Even though the Voyager 1 and Voyager 2 spacecraft had performed flybys of planet Jupiter and its sixteen moons in 1979, the Galileo mission was envisioned to initiate several novel observations of Jupiter, the most massive gas planet of the solar system, and its principal moons, and conduct exclusive, often in situ, experiments on their fascinating environments.

Galileo was carried aboard the space shuttle *Atlantis* (flight STS-34) and was launched from the shuttle on October 18, 1989. Galileo was the first spacecraft to image the surface of Venus without using radar (a radio-wave pulse detector). Using its near-infrared solid-state imaging camera, it photographed Jupiter's atmospheric banding and its satellites from a half-billion miles away on its way to Venus in December, 1989, and subsequently observed numerous mountain ranges and valleys on Venus's oven-hot surface through its thick atmosphere and clouds on February 10,

1990. The image resolution of Galileo's cameras (the smallest object size that can be detected by them) was around 12 meters, a millionfold improvement over Galileo's original observations.

JUPITER

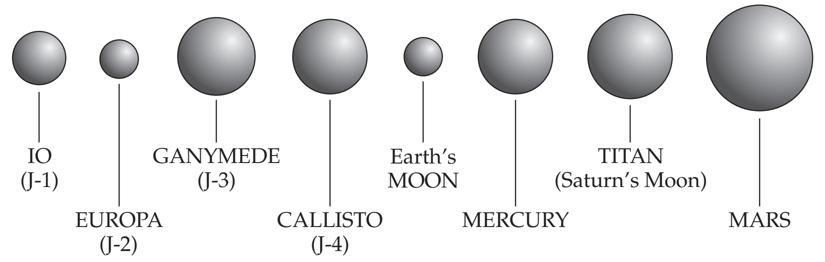
As a planet, Jupiter is by far the largest in the solar system. It has a volume about 1,400 times that of the Earth; in fact, its volume is 1.5 times the combined volume of all the other planets, moons, asteroids, and comets in the solar system. Jupiter is a "gas giant" planet composed of vast amounts of hydrogen gas. The gas runs thousands of kilometers deep. The gases on Jupiter swirl around in massive hurricanes whose sizes are of the order of the size of the Earth. The famous Great Red Spot on Jupiter is in fact a hurricane three times the diameter of Earth; it has been raging in the Jovian atmosphere for more than three hundred years. It is believed that, given its enormous size, Jupiter would have become a thermonuclear reactor (that is, a star like the Sun), if only it were thirty times heavier. Jupiter rotates about its axis much faster than the Earth; hence, a Jovian day is only 9 hours and 48 minutes long. This fast rotation causes Jupiter to be somewhat squashed, or oblate: its equatorial radius is 71,392 kilometers (compared with the Earth's 6,400 kilometers), while its polar radius is about 4,000 kilometers smaller. This causes an object to weigh about 25 percent heavier at Jupiter's poles than at its equator.

ARRIVAL AND DATA GATHERING

In 1994, while the Galileo spacecraft was approaching Jupiter, it became a direct witness to an astounding astrophysical event. The Comet Shoemaker-Levy 9 (SL-9) had broken up into several small fragments and was expected to plunge directly into Jupiter's atmosphere.

Galileo spent much of the year 1995 preparing for the dual-craft arrival at Jupiter on December 7. In July, 1995, the Galileo probe and the orbiter spacecraft separated to fly their independent missions to Jupiter. After the probe had separated for atmospheric entry, the orbiter's main engine was fired to aim it to go into orbit around Jupiter. The probe entered with an initial velocity of 170,000 kilometers per hour, decelerating for two minutes, then plunging into the wind-torn clouds beneath its Dacron parachute, sending measurements for almost an hour. The orbiter, meanwhile, measured the Jovian environment, received a gravity assist from Io, received and recorded the probe data, then fired its main engine to become the first artificial satellite of Jupiter. The successful arrival was enthusiastically cel-

Sizes of the Jovian Moons Relative to Other Bodies



ebrated at NASA Headquarters on December 7, 1995. On December 9, Galileo began relaying the probe data to Earth.

Galileo continued to gather data from the Jovian system for nearly five years after its arrival. The first Ganymede and Io encounters began June 27, 1996, and a second Ganymede encounter on September 6, 1996. The first encounter with Callisto occurred on November 2, 1996, and with Europa on December 19, 1996. Each encounter involved a one-week, high-rate observation of Jupiter and at least one satellite. Each flyby brought Galileo to within a few hundred kilometers of the satellites and gave it a gravity assist into the next orbit. In January, 1997, Galileo and Jupiter entered another superior conjunction, after which the orbiter continued its close flybys for another year. On February 20, 1997, the Galileo orbiter encountered Europa for a second time. It encountered Ganymede on April 5, 1997, at a distance of only 3,095 kilometers, nineteen times closer than Voyager 2, and, again, on May 7, 1997. This time it got within 1,600 kilometers of the satellite—thirty-seven times closer than Voyager 2. On June 25, 1997, the probe glided to within 415 kilometers of Callisto. It reencountered it on September 17, 1997. Between November 6, 1997, and February 1, 1999, Galileo played tag with Europa nine times, swooping down on its icy surface. On May 5, 1999, Galileo began another four-visit tour of Callisto, ending on September 16, 1999.

In late 1999 and early 2000, the Galileo spacecraft dipped closer to Jupiter than it had been since it first went into orbit around the giant planet in 1995. These maneuvers allowed Galileo to make three flybys of the volcanically active moon Io and also made possible new high-quality images of Thebe, Amalthea, and Metis, which lie very close to Jupiter, inside the orbit of Io. Volcanic calderas, lava flows, and cliffs could be seen in a false-color image of a region near the south pole of Jupiter's volcanic moon, Io. Combining a black-and-white image taken by the Galileo spacecraft on February 22, 2000, with lower-resolution color images taken by Galileo on July 3, 1999, JPL scientists created the image. Included in the image are three small volcanic calderas about 10 to 20 kilometers in diameter.

The fourteen-year odyssey of Galileo concluded on September 21, 2003, with a controlled plunge into the outer atmosphere of Jupiter while the spacecraft was on its thirty-fifth orbit. The spacecraft passed into Jupiter's shadow and the Deep Space Network received its final signal from Galileo at 12:43:14 Pacific daylight time, or 19:43:14 Coordinated Universal Time (UTC). Galileo hit the outer atmosphere just south of the gas giant's equator at a speed of 48.3 kilometers per second. Due to the time delay in receipt of light signals, this message arrived 46 minutes after Galileo was crushed, vaporized, and dispersed into Jupiter's dense atmosphere.

Impact

Galileo mission data provided answers to many questions regarding Jupiter and its large assembly of satellites, which are sometimes compared to a miniature solar system. The data have cast light on the Jovian moons' atmospheres, Jupiter's large magnetosphere, its unique ring system, the geologic history of the Jovian system, the volcanic characteristics of Io, the possibility of any liquid water under Europa's ice crust, and, perhaps most important, clues to the early history of the solar system, which help our understanding of our own planet and its relationship to the universe. The Galileo mission required several new technologies to be developed, which are already paying off handsomely in terms of the knowledge gained (and to be gained further) via Galileo's operations.

See also Jupiter's Great Red Spot; Voyager Missions.

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—Monish R. Chatterjee, updated by David G. Fisher

GAME THEORY

THE SCIENCE: Hungarian mathematician John von Neumann established the science of game theory and proved the fundamental stability theorem.

THE SCIENTISTS:

John von Neumann (1903-1957), Hungarian mathematician who made important contributions to physics, mathematics, game theory, and computer science

Émile Borel (1871-1956), French mathematician who contributed to measure theory, analysis, and game theory

Oskar Morgenstern (1902-1977), mathematical economist and associate of von Neumann

John F. Nash (b. 1928), mathematician who expanded on von Neumann's work in economics and game theory

THE STUDY OF CONFLICT

Since the dawn of civilization, conflicts over limited resources and systems of competition and cooperation have characterized human interactions. Many hieroglyphs and cuneiform tablets attest historical exploits, tactics, and bargaining decisions in economic, military, and political institutions. Artificially created conflict for leisure likewise has a long history, as in chess, go, and poker. In 1913, set theorist Ernst Zermelo published the first theorem of game theory, on chess, but as an isolated entity.

While early historical accounts and texts on strategies are numerous, the formal study of the foundations of competition began in the 1920's. Prior works by such historical figures as Julius Caesar, Niccolò Machiavelli, and other leaders are primarily descriptive, prescriptive, or historical. Even the "minimax" principle and similar concepts were informally or briefly noted in eighteenth and nineteenth century literature, but more as observed concepts or oddities than as formal ideas.

Before the study of conflict could become a deductive and mathematical theory, mathematical representations of conflict situations had to be developed. In a series of papers published from 1921 to 1927, Émile Borel provided some of the foundations of game theory. He applied the concept of utility (essentially, profit or value), a notion originating in the works of Daniel Bernoulli, an earlier probability specialist. Probability theory already had developed for centuries. The role of chance in simple probabilistic "games" was well known.

The Logic of Games

Working with such fundamental concepts, John von Neumann constructed a major theory. He used the branch of mathematics known as linear algebra as the framework for his theory. He used algebraic variables to represent the strategic decisions that a game player could make in the course of a game, and he used a form of table known as a matrix to record the result, or "payoff," of each decision. The earliest and simplest models von Neumann constructed analyzed competitions between two players (called "two-person games"). Another simplifying assumption von Neumann incorporated into his theory was the "zero-sum property," which meant that a loss to one player was always balanced by a gain to the other player, and vice versa.

Although his analysis of two-person games was interesting and theoretically important, its limitations restricted its practical value. In the mid-1920's, while a lecturer at the University of Berlin, von Neumann formulated an algebraic model for competitions between multiple players, or "n-person games." After formulating the necessary algebraic definitions and concepts, he analyzed the optimal decision-making approach for a player.

In one approach (called a "mixed strategy"), a player would select his decisions based on a judgment of the probability of their being correct. For example, in a simple two-person game, if the first player noticed that the second player often chose a particular strategy, then the first player would adapt by choosing a strategy designed to counter the second player's preferred strategy. Likewise, the second player might adapt, changing strategies in response to the first player's moves. Von Neumann formulated these various possibilities as mathematical "probability vectors" and "expected profit functions."


John von Neumann. (Library of Congress)

Von Neumann noted that in many games, a single ("pure") strategy can be optimal for each player, without any probabilistic jumping. The condition required for such a stable situation is called the "minimax" condition, or "saddle point." For example, in many simple two-player games, if a player conservatively picks a strategy with the least harmful potential, that player cuts his losses, producing a payoff value that von Neumann called "maximin." If the other player also applies that principle, it produces a value called "minimax." If the value of minimax equals that of maximin, the condition is met whereby both players could permanently choose a pure strategy without fear of being caught off guard. The game is stable, and adaptive scuffling and strategy-hopping ends. It should be noted, however, that not all games satisfy the minimax condition; even such a simple two-player game as "evens and odds" has no saddle point. Moreover, even in games that satisfy the minimax condition, extreme greed in both players can induce "maxmax" frenzies.

After formulating the minimax theorem, von Neumann went further and rigorously proved it. Von Neumann presented a preliminary version of his paper in 1926 at the Göttingen Mathematical Society. The final version was published in 1928 in the journal *Mathematische Annalen*.

IMPACT

At Princeton University, von Neumann, in collaboration with Oskar Morgenstern, produced a magnum opus, *Theory of Games and Economic Behavior*, which was published in 1944. Their work furthered the axiomatic and mathematical approach that revolutionized economics, becoming the classic text in the discipline; game theory subsequently became a major part of the study of economics.

One of von Neumann's students, John F. Nash, developed von Neumann's theories to explain the contrasting principles of cooperative and noncooperative games. His theory of strategic balance between players, known as the "Nash equilibrium," had an important influence on economics, leading to Nash's receipt of the 1994 Nobel Prize in Economics.

With the advent of linear programming, a powerful method for determining optimal solutions, game theory received a computational tool for determining optimal mixed strategies in standard n-person games. Again, von Neumann was heavily involved in the construction of computers and automata.

The notion of stability developed in game theory has consequences in many areas. Military inquiry and research into game theory proceeded immediately, producing such applications as war games and simulations. The analysis of the Cold War and nuclear stability became important fields of study. Ironically, von Neumann's brilliance contributed both to the stability of the nuclear "game" and to the creation and evolution of atomic weapons.

Important applications of game theory also exist in psychology, biology, and numerous other fields. In computer science, games are used to determine complexity-bound results. In artificial intelligence, minimax is a standard algorithmic model for game-playing search procedures.

More profoundly, games are used in logic to construct models of infinite mathematical structures. The difference between these games and games of leisure are the rules: Games can be arbitrarily complex, up to the hardest human endeavor and beyond.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*John Panos Najarian*

GAMMA-RAY BURSTS

THE SCIENCE: Gamma-ray bursts are high-energy explosions that occur daily throughout the universe. The Swift space telescope was the first telescope of its kind designed to detect and study these emissions in real time. Data from Swift promise to give astronomers their first chance to view a gamma-ray burst in the critical first few minutes.

THE SCIENTISTS:

Neil Gehrels, principal investigator, Goddard Space Flight Center (GSFC)
Joe Dezio, project manager, GSFC
Nicholas White, Science Working Group chair, GSFC
John Nousek, mission operations lead, Pennsylvania State University (PSU)
Padi Boyd, science support center lead, GSFC
Lorella Angelini, High-Energy Astrophysics Science Archive Research Center lead, GSFC
Scott Barthelmy, Burst Alert Telescope lead, GSFC
Dave Burrows, X-ray Telescope lead, PSU
Pete Roming, Ultraviolet/Optical Telescope lead, PSU

STAR DEATHS AND BLACK HOLES

The physics of the formation of black holes is one of the most intense areas of theoretical and observational study in science. When a star collapses to form a black hole, it releases gamma-ray bursts that have been detected on Earth since the 1960's. These gamma-ray bursts contain information on the evolution of the universe as well as the high-energy processes in black holes. The Swift Gamma Ray Burst Mission, launched November 20, 2004, was aimed at studying these gamma-ray bursts as soon as they were detected.

Theories about gamma-ray energy existing in the universe were well developed by the 1960's, but there was no technology capable of measuring it. In the early 1960's, however, the U.S. military was deeply concerned about Soviet nuclear weapons testing. Such weapons would release small amounts of gamma-ray energy into the atmosphere, so the United States launched the Vela satellites, which were equipped to detect this energy. These satellites did detect gamma rays but found that, instead of coming from the Soviet Union, the rays were originating in outer space. By the 1970's, this information had been released to the civilian scientific community, and there was much debate as to the source and strength of the gamma-ray bursts.

Gamma rays have the shortest wavelengths in the electromagnetic spectrum and energies of up to 10^{46} joules. They are produced by nuclear explosions or nuclear reactions. The radiation produced by these processes is deadly to humans but can be used in small quantities to fight diseases, especially cancer. Gamma-ray bursts from space are hard to detect on Earth because most of them are absorbed by the Earth's atmosphere, protecting the biosphere from this radiation.

Mysterious Origins

The two leading hypotheses on the origins of gamma rays are that they result from neutron star mergers, or hypernovae. As two neutron stars orbit each other, they gain gravitational energy, losing rotational energy. Eventually their orbits decay and they collide to form a black hole. The energy released in this process is one possible method of generating gamma rays. The other leading theory is that at the end of a massive star's lifetime it explodes as a supernova to become either a neutron star or a black hole. Stars with masses greater than about forty solar masses may release about one hundred times more energy when they explode. These hypernovae may also be a source of gamma-ray bursts.

Gamma-ray bursts were first detected by satellites in the early 1960's, but image resolution was poor. The exact location of the bursts could not be determined, and there was no way of looking at the burst immediately after it was detected. It took time to move the satellites into position, so all that was visible was the afterglow of the burst. The result was only limited information as to where the gamma-ray bursts originated. The scientific community was divided into two schools of thought. One group believed that gamma-ray bursts were sufficiently powerful to have been generated outside our Milky Way galaxy; the other believed that they must come from within the Milky Way.

The Compton, Beppo-Sax, and Hubble Telescopes

To resolve this question, the National Aeronautics and Space Administration (NASA) launched the Compton Gamma Ray Observatory (GRO) in the early 1990's. One of the instruments on board GRO was the Burst and Transient Source Experiment (BATSE). BATSE monitored the sky for gamma-ray bursts and recorded the numbers of bursts detected. After several years of monitoring, BATSE data showed scientists that not all gamma-ray bursts were on the plane of the Milky Way, but that did not necessarily mean that they could not be coming from elsewhere in our galaxy.

In 1997 an Italian telescope, Beppo-Sax, detected an afterglow at a recent gamma-ray site. The discovery of the afterglow made redshift measurements possible, giving the distance to the gamma-ray bursts. This information made it clear that not all gamma-ray bursts came from within the Milky Way galaxy.

The Hubble Space Telescope gave scientists a more detailed view of deep-space objects than ever before. With Hubble, sites where gamma-ray bursts had been detected could be observed to see their effects on the environment. While Hubble had no instruments to measure gamma rays directly, the views of past gamma-ray sites helped scientists better understand the origins and the effects of gamma-ray bursts.

The pictures from Hubble led to a much greater understanding of gamma-ray bursts but, because the Hubble had no gamma-ray equipment and because of the amount of time it took to turn Hubble, there were still no pictures from the first few critical minutes of a gamma-ray burst site. NASA therefore launched the Swift Gamma Ray Observatory to fill this gap.

THE SWIFT OBSERVATORY

The Swift observatory is named after a small, nimble bird. The observatory is built to be able to spot a gamma-ray burst and quickly move to observe the area of its origin. It does this much the same way the bird would spot its prey and quickly move to attack.

There are three main telescopes aboard the observatory: the Burst Alert Telescope (BAT), the X-ray Telescope (XRT), and the Ultra-Violet/Optical Telescope (UVOT). These three telescopes work together to gain as much information as possible about each gamma-ray burst. The BAT first detects the gamma-ray burst and slews the observatory to the area of the sky from which it came. Next, the XRT narrows in on the exact area of the bursts and finishes the alignment of the telescope. The UVOT finalizes the positioning of the telescope by producing the most accurate coordinate set.

The BAT is Swift's first line of detection. It scans the sky for any gamma-ray counts that are significantly above the background gamma-ray radiation. When the radiation reaches the detector, it passes through a filter, which produces a shadow. From the image of the shadow, BAT can calculate the position of the gamma-ray bursts to within five arc minutes in about ten seconds. This position is then immediately sent to the ground-based operations while Swift automatically starts slewing to it. BAT also has a hard X-ray detector designed to produce an all-sky survey twenty times more sensitive than the last one, done in the 1970's by High-Energy Astronomical Observatories 1 A4 (HEAO-1 A4). BAT also watches for transient hard X-ray sources and transmits their data to the ground.

Once BAT has allowed Swift to slew so that the gamma-ray source is within the XRT's line of sight, the XRT takes over. X rays, unlike gamma rays, can be focused so that a more exact location of the gamma-ray burst site can be determined to within a five arc second accuracy. The XRT measures the fluxes, spectra, and light glows of both the gamma-ray bursts and their afterglows. It also calculates redshifts from these afterglows, which is useful because no distances to short gamma-ray bursts have yet been calculated. Finally, the XRT looks at absorption and emission spectra to determine the material surrounding the gamma-ray burst sources.

Once the XRT has narrowed the field of vision down to 5 arc seconds, the UVOT detects the source and starts observing. It can narrow the location down to a 0.3 arc second accuracy. The UVOT studies the gamma-ray burst and afterglow with a series of filters, tracking the changes over time in different colored filters. Also, for redshifts greater than one, the UVOT can provide redshift and distance information.

Impact

The Swift observatory was activated on January 19, 2005. In the first twelve days, nine gamma-ray bursts were detected, which was more than was expected, but that was followed by two weeks of nothing being detected. On December 19, 2004, a long gamma-ray burst was detected as well as an infrared flash and its radio counterpart. On December 23, an optical afterglow was also detected. The only problem with activation was that the thermo-electric cooler did not work as expected. This means that the temperature of the observatory cannot be regulated as desired, so the spectral resolution will be shifted a few percentage points per year. Also, more on-orbit calibration time will be required and the flight parameters will have to be modified.

The primary objectives of the Swift mission had been met as of mid-2005, and most of the secondary objectives have remained unaffected by the small problems that Swift has encountered. Swift is now observing and coming fully online to develop a more complete understanding of gamma-ray bursts, their origins, and their affects on the environment in which they occur.

Classes of gamma-ray bursts will be established based on their characteristics, and bursts will be grouped into them. Swift will allow the study of what fraction and kinds of gamma-ray bursts have underlying supernovae. The universe will be looked at back to a redshift value of about 15, which will allow the study of the first stars.

See also Mössbauer Effect; Spectroscopy.

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—Rebecca B. Jervey

GENE-CHROMOSOME THEORY

THE SCIENCE: Thomas Hunt Morgan's experiments led to the discovery of the principles of the gene-chromosome theory of hereditary transmission.

THE SCIENTISTS:

Thomas Hunt Morgan (1866-1945), professor of experimental zoology who won the 1933 Nobel Prize in Physiology or Medicine

Calvin Blackman Bridges (1889-1938), geneticist and one of Morgan's assistants

Alfred Henry Sturtevant (1891-1970), geneticist and another of Morgan's assistants

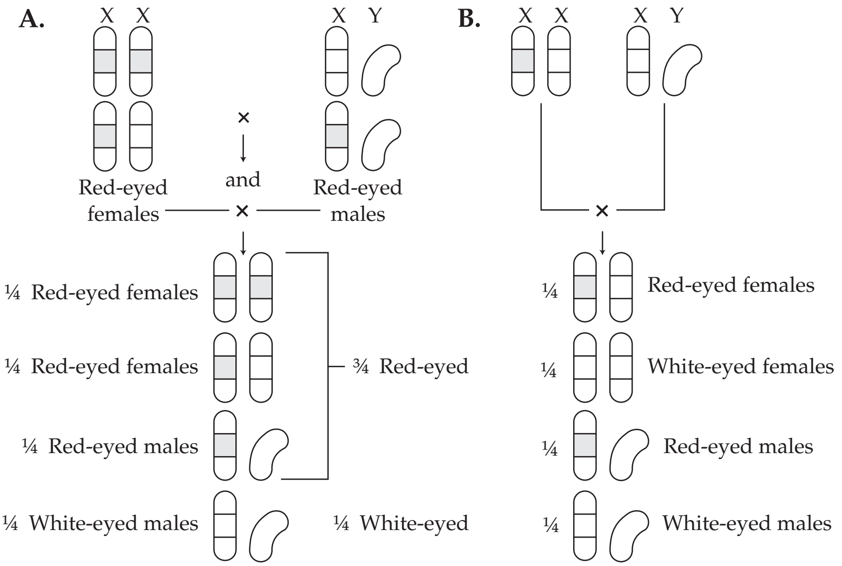
Hermann Joseph Muller (1890-1967), geneticist and Morgan's student, who won the 1946 Nobel Prize in Physiology or Medicine

THE FORTUITOUS FRUIT FLY

In 1904, Thomas Hunt Morgan, a young professor of biology, began work at Columbia University as professor of experimental zoology. That same year, through a friend, Morgan met Hugo de Vries, the Dutch biologist who had been one of the trio of scientists who in 1900 had rediscovered the work of the Austrian botanist Gregor Johann Mendel. (Mendel's work had been published first in 1866, but it was promptly ignored and forgotten.) De Vries had a theory that new species originated through mutation. (A mutation is defined as a change occurring within a gene or chromosome that produces a new and inheritable feature or characteristic.)

The rediscovery of Mendel and the contact with de Vries influenced Morgan to initiate experiments to try to discover mutations and to test the Mendelian laws. He began to experiment with *Drosophila melanogaster*, the fruit fly. It bred rapidly and ate little, and Morgan and his students found that thousands of these tiny insects could be contained in a small collection

THOMAS HUNT MORGAN'S EXPERIMENTAL WORK WITH FRUIT FLIES



Morgan's experiments revealed such results as the following: A. A red-eyed female is crossed with a white-eyed male. The red-eyed progeny interbreed to produce offspring in a ratio of ¾ to ¼. All the white-eyed flies are male. B. A white-eyed male is crossed with its red-eyed daughter, giving red-eyed and white-eyed males and females in equal proportions. (Electronic Illustrators Group) of milk bottles that they "borrowed" from the Columbia cafeteria.

In 1908, Morgan had one of his graduate students perform an experiment to breed generations of *Drosophila* in the dark, in an attempt to produce flies whose eyes would waste away and become useless. After sixty-nine generations, however, the experiment was abandoned; the sixty-ninth generation could see as well as the first.

Morgan's experiments did not reveal mutations. In fact, they turned up enough exceptions to Mendel's laws that Morgan began to doubt the validity of the laws. One day in 1910, however, he found a single male fly with white eyes rather than the standard red. Morgan bred the white-eyed male with a red-eyed female and the first-generation offspring were all red-eyed, suggesting that white-eyed was a Mendelian recessive factor. He then bred the first-generation flies among themselves, and the second generation were red-eyed and white-eyed in a 3:1 ratio, appearing to confirm that white eyes were Mendelian recessive.

Morgan noted that all the white-eyed flies were males. He had discovered "sex-limited" heredity (in which inheritable characteristics may be expressed in one sex but not in the other). The Mendelian factor, or gene, that determined white eyes was located on the same chromosome as the gene that determined male sex—on the male chromosome, that is.

Linkage and Crossing-Over

Chromosomes—which appear as stringlike structures within cells—had been discovered by cell researchers in the 1850's. It had been theorized, without much hard evidence, that they were involved in heredity. Morgan had considered such theories and rejected them. Meanwhile, researchers had discovered an odd-shaped chromosome (all other chromosomes occurred in similarly shaped pairs) that seemed to be related to male sex (now called the *Y* chromosome). The discovery of sex-limited heredity revealed the association of Mendelian genes with chromosomes and the function of chromosomes in heredity.

Following this discovery, Morgan saw that a concerted effort was required to expound fully the Mendelian-chromosome theory and therefore enlisted a group of exceptional students to share the work in his so-called fly room. The nucleus of the group consisted of Calvin Blackman Bridges, Alfred Henry Sturtevant, and Hermann Joseph Muller.

Between 1910 and 1915, Morgan and his team developed and perfected the concepts of linkage, in which various genes are located on the same chromosome and are transmitted together, and crossing-over, in which these paired (linked) chromosomes break apart and recombine during meiosis. This creates new gene combinations. Crossing-over and linkage therefore produce two opposite results. Based on an understanding of linkage and crossing-over, the team was also able to create chromosome maps, plotting the relative locations and distances of the genes on the chromosomes.


Hermann Joseph Muller. (The Nobel Foundation)

The culmination of the work of Morgan's team was the publication in 1915 of *The Mechanism of Mendelian Heredity*, coauthored by Morgan, Sturtevant, Muller, and Bridges. For the next twelve years, strictly genetics studies were performed mainly by Sturtevant and Bridges and other team members. Morgan returned to his previous areas of interest of embryology and evolution, pursuing connections between those areas and the new discoveries in genetics. He also was occupied in publicizing the new views of heredity and their ramifications through publications and lectures.

IMPACT

The discovery and demonstration that genes reside on chromosomes provided the key to all further work in the area of genetics. Mendel was extremely fortunate in the design of his experiments in that each of the characteristics he investigated in his pea plants happened to reside on a separate chromosome. This facilitated discovery of the Mendelian hereditary principles but made for experimental results that were rather predictable. When a larger number of characteristics is investigated, because of linkage of genes located on the same chromosomes and crossing-over of chromosomes, the results will be more complicated and will not reveal so clearly the Mendelian pattern. This is what happened in Morgan's early experiments. It was only by carefully examining—using tweezers and a magnifying glass—generations upon generations of the tiny *Drosophila* that the mechanism of inheritance began to emerge.

Although Morgan did not pursue medical studies, his studies laid the groundwork for all genetically based medical research. As was stated when the Nobel Prize was presented to Morgan, without Morgan's work "modern human genetics and also human eugenics would be impractical." It is generally accepted that Mendel's and Morgan's discoveries were responsible for the investigation and understanding of hereditary diseases.

The darker side of the genetics research and discoveries was that they also laid the groundwork for Adolf Hitler's iniquitous eugenics experiments and associated racial purity fantasies. Morgan, however, was always extremely distrustful of any such experiments on the human species. In his Nobel acceptance speech, Morgan pointed out that geneticists were now able to produce populations of species of animals and plants that were free from hereditary defects by suitable breeding. He noted, however, that it was not advantageous to perform genetic experiments on humans, except to attempt to correct a hereditary defect. Morgan believed it was improper to "purify" the human race. One must look to hereditary research for new developments to ensure a healthy human race.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*John M. Foran*

GENETIC CODE

THE SCIENCE: After years of work by many molecular biologists, Marshall W. Nirenberg succeeded in unraveling the mystery of the genetic code.

THE SCIENTISTS:

Marshall W. Nirenberg (b. 1927), American biochemist and cowinner of the 1968 Nobel Prize in Physiology or Medicine
J. H. Matthaei, a German postdoctoral fellow
Francis Crick (1916-2004), English biologist and cowinner of the 1962 Nobel Prize in Physiology or Medicine
George Gamow (1904-1968), Russian theoretical physicist and cosmologist

THE STRUCTURE OF PROTEINS

It had been confirmed by 1944 and accepted by 1952 that nucleic acids somehow carried the blueprint of proteins, but it took James D. Watson and Francis Crick's discovery of the molecular structure of deoxyribonucleic acid (DNA) to suggest how the necessary process of information storage, replication, and transmission might occur. Their model served to fix the course of subsequent research that would eventually lead to a deciphering of the genetic code and an understanding of the relationship between protein and the genetic material.

Proteins make up most cellular structures and also serve as "catalysts" (substances that cause chemical change to occur without changing their own composition). Proteins play a role in almost all chemical reactions in living organisms.

Proteins are also "polymers" (molecular chains composed of similar chemical units called monomers) that are made of amino acids, of which there are twenty main types. The linear sequence of amino acids is the primary structure of the protein molecule, and their order causes the molecule to fold into a three-dimensional form. That form is the most important factor in determining the function of the molecule.

DNA is composed of four different types of links, which are called "nucleotides" or "bases." These links are attached to a backbone made up of alternating phosphate and sugar groups. Two chains usually intertwine in a characteristic double-helical (double-spiral) form so that the bases pair up in a regular fashion. The four major types of bases are adenine (A), guanine (G), thymine (T), and cytosine (C); these bases join by means of hydrogen bonds so that A's always pair with T's and G's always pair with C's. Ribonucleic acid (RNA) has a similar structure, except that uracil (U) replaces thymine (T).

GAMOW'S DIAMOND CODE

In 1953, George Gamow, a theoretical physicist who had been inspired by the Watson-Crick DNA model, came up with an idea that would define the discussion of the genetic coding problem. Noting the four-base linear structure of DNA and the linear primary structure of proteins, he theorized that the order of the DNA determined the protein structure. He reasoned that the problem was to determine how the four-letter "alphabet" of nucleic acid bases could be formed into "words" that would translate into the twenty-letter alphabet of amino acids. If the words were one letter long, then four nucleotides could code for only four amino acids. Two-letter sequences could combine to code for only sixteen. That meant that a three-letter sequence, which would make possible sixty-four combinations (called "codons"), was therefore the minimum required to code for twenty amino acids. Gamow proposed an ingenious three-letter solution, the "diamond" code, which was based on what he took to be twenty types of diamond-shaped pockets (into which he thought the amino acids could fit) formed by the bases in the double helix. This proposal spurred interest in the coding problem, and a flurry of theoretical work followed.

MISSING PUNCTUATION

Gamow's diamond code immediately ran into mechanical and chemical difficulties. For example, the model required that protein production take place in the cell nucleus, but evidence suggested that it took place in the cytoplasm. Also, in order to fit the spacing of the diamonds to typical amino-acid spacing, the code had to be fully overlapping; that is, each code letter in a chain would be used in three codons in a row. This overlapping structure, however, ruled out certain sequences that were known to exist. A variety of other overlapping codes were suggested, but it was eventually shown to be impossible for a fully overlapping structure to work. If the code was overlapping and was to be read as a series of triplets, then the problem of punctuation arose. Unless there was something that functioned like a comma, there was no way for the cell to know where a triplet began.

To avoid this problem, creative attempts were made to devise codes that included "nonsense" triplets that did not correspond to any amino acid, and there was some excitement when mathematical permutations of this approach were discovered that produced codes with exactly twenty "sense" combinations. This approach, however, implied that DNA molecules in all species should have more or less the same composition, but it was discovered that they actually could vary tremendously.

Breaking the Code

In the summer of 1961, at the Fifth International Congress of Biochemistry in Moscow, Marshall W. Nirenberg, a young researcher from the National Institutes of Health in Bethesda, Maryland, reported that he and his associate J. H. Matthaei had shown experimentally that the triplet UUU was a codon for the amino acid phenylalanine. The first word of the genetic code had been translated.

Nirenberg and Matthaei had discovered how to add an RNA message to a test-tube system that synthesized proteins to determine which amino

The Genetic Code

second position → first position ↓	T	C	A	G	third position ↓
T	Phenylalanine	Serine	Tyrosine	Cysteine	T
	Phenylalanine	Serine	Tyrosine	Cysteine	C
	Leucine	Serine	END CHAIN	END CHAIN	A
	Leucine	Serine	END CHAIN	Tryptophan	G
C	Leucine	Proline	Histidine	Arginine	T
	Leucine	Proline	Histidine	Arginine	C
	Leucine	Proline	Glutamine	Arginine	A
	Leucine	Proline	Glutamine	Arginine	G
A	Isoleucine	Threonine	Asparagine	Serine	T
	Isoleucine	Threonine	Asparagine	Serine	C
	Isoleucine	Threonine	Lysine	Arginine	A
	Methionine	Threonine	Lysine	Arginine	G
G	Valine	Alanine	Aspartic Acid	Glycine	T
	Valine	Alanine	Aspartic Acid	Glycine	C
	Valine	Alanine	Glutamic Acid	Glycine	A
	Valine	Alanine	Glutamic Acid	Glycine	G

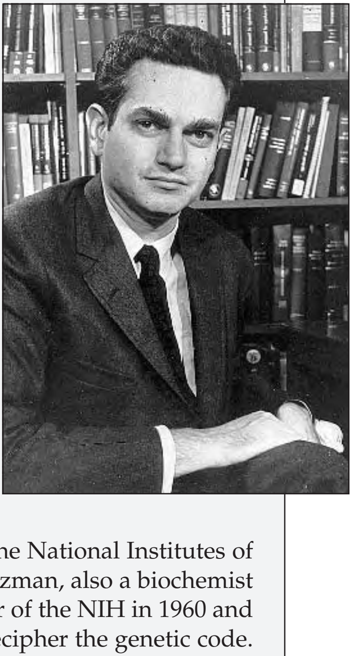
The amino acid specified by any codon can be found by looking for the wide row designated by the first base letter of the codon shown on the left, then the column designated by the second base letter along the top, and finally the narrow row marked on the right, in the appropriate wide row, by the third letter of the codon. Many amino acids are represented by more than one codon. The codons TAA, TAG, and TGA do not specify an amino acid but instead signal where a protein chain ends.

acid was synthesized by it. The technique involved extracting the protein-synthesis machinery (ribosomes, messenger RNA, and enzymes) from *Escherichia coli*, the common bacteria that inhabits the human intestine. Such extracts, when given an energy source, are called "cell-free systems"; these systems are able to incorporate amino acids into protein.

Cell-free systems had been developed by other researchers several

MARSHALL NIRENBERG, CODE BREAKER

Marshall Warren Nirenberg was born on April 10, 1927, in New York City. In 1948 he received his degree in zoology from the University of Florida and in 1949 began graduate work in the department of biology. From 1950 to 1951, he was a research associate in the nutrition laboratory, working in biochemistry with radioisotopes. In 1952, he earned his master's degree in zoology with a thesis titled "The Caddis Flies of Alachua County, with Notes on Those of Florida."



(The Nobel Foundation)

This thesis was a systematic and ecological account of those insects following years of zoological study. However, Nirenberg's experience at the nutrition laboratory awakened other interests that would overcome his zoological pursuits. Biochemistry and molecular biology were such new fields of science that they were not yet a part of the curriculum at the university. At the nutrition laboratory, Nirenberg first met biochemists and became interested in biochemical research. He moved to Ann Arbor, Michigan, in 1952 and entered the University of Michigan, where he held a teaching fellowship in the department of biological chemistry (1952-1957). He received his Ph.D. in biochemistry with a dissertation titled "Hexose Uptake in Ascites Tumor Cells."

Nirenberg next moved to Bethesda, Maryland, and began his scientific career at the National Institutes of Health (NIH). In 1961, he married Perola Zaltzman, also a biochemist at NIH. He became a permanent staff member of the NIH in 1960 and began the research that was to lead him to decipher the genetic code. He became chief of the Laboratory of Biochemical Genetics of the NIH in 1966. For his groundbreaking work on the genetic code he received many awards, including the National Medal of Science, the Franklin Medal, the Priestley Medal, the Louisa Gross Horwitz Prize, and in 1968 the Nobel Prize in Physiology or Medicine.

years earlier, but they were unreliable because the enzymes and the messenger RNA disintegrated rapidly. Nirenberg and Matthaei had increased the systems' stability by adding a chemical that allowed them to freeze the systems for storage without causing loss of activity. The twenty amino acids, radioactively labeled with carbon 14, were added to the systems. When these ingredients were mixed, only very little incorporation of amino acid into protein occurred. Next, the artificial RNA message (UUU) was added. This produced an eight-hundredfold increase in the activity level; an amino acid had been incorporated into the protein. Subsequent tests showed that the amino acid was phenylalanine.

After Nirenberg's 1961 discovery, work proceeded rapidly. By the following year, Crick's laboratory had confirmed that the code was indeed a triplet code. Nirenberg and other researchers had correctly decoded thirty-five of the triplets by 1963. A new test developed in Nirenberg's laboratory increased the number of triplets by fifty, and by 1966, all but three of the sixty-four possible triplets had been assigned to a corresponding amino acid. The final three triplets (UAA, UAG, and UGA) were revealed to be "chain terminators"—punctuation that specified the end of an amino acid "sentence"—and this brought the coding problem, as it was originally conceived, to a final solution.

IMPACT

From a theoretical standpoint, the near universality of the code supports the hypothesis that all forms of life on Earth are related to one another by common evolution; at some point very early in the evolution of life, a single successful chemistry emerged, and all subsequent variation has been built upon that structure. From the standpoint of applied science, the universality of the code simplifies the technology of bioengineering, since it allows bits of DNA from one organism to be spliced into that of another organism. The impact of this technology, which was made possible by building upon the sorts of techniques developed to elucidate the genetic code, is only beginning to be felt. It has given rise to many new legal and ethical problems that have not yet been resolved.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Robert T. Pennock*

GEOLOGIC CHANGE

THE SCIENCE: Charles Lyell's *Principles of Geology* posited that the Earth had been formed by familiar forces at a more or less steady rate of change over eons. Although later scientists would disprove this "uniformitarian" view of geologic change, Lyell's disciplined argument against biblical views of Creation and change made Darwinian evolution conceptually possible.

THE SCIENTISTS:

Sir Charles Lyell (1797-1875), English naturalist and founder of uniformitarianism

Charles Robert Darwin (1809-1882), English naturalist who developed the theory of evolution through natural selection

James Hutton (1726-1797), Scottish physician and naturalist

Georges-Louis Leclerc, comte de Buffon (1707-1788), French naturalist

SEPARATING RELIGION FROM SCIENCE

Charles Lyell's uniformitarianism was a determined effort to separate geology from the biblical view of Creation and place it on the same footing as the general sciences. As such, it was part of a tradition dating back to the French mathematician René Descartes (1596-1650), who tried to detach astronomy from religion by arguing that existence was composed of "thinking substance" (spirit) and "extended substance" (matter) and that theology was concerned only with the spirit and should be separate from investigations of nature. Uniformitarianism also reflected the Cartesian view that physical change was the result of law-bound matter in motion.

The claim that matter was law-bound and outside the proper area of theologians worked its way from cosmology into geology in the works of a noted French naturalist, Georges-Louis Leclerc, comte de Buffon. A great admirer of Sir Isaac Newton (1642-1727), who had demonstrated that matter was indeed law-bound, Buffon sharply criticized the mixing of science with religion. Theologians, he insisted, should confine themselves to scripture while naturalists should rely on accurate observations of natural occurrences.

Catastrophists vs. Uniformitarians

Buffon's arguments, advanced in the first volume of his four-volume *Histoire naturelle, générale et particulière* (1749-1789; *Natural History, General and Particular*, 1781-1812), were largely rejected by his contemporaries and immediate successors, and for the next half century geological speculation was dominated by catastrophists such as Jean-Étienne Guettard (1715-1786), Nicolas Desmarest (1725-1815), Abraham Gottlob Werner (1750-1817), and Georges Cuvier (1769-1832). All these naturalists accepted intellectual limits imposed on them by the Bible, although they might disagree about the importance of the various upheavals that shaped the Earth's features. Guettard and Desmarest were vulcanists, convinced that underground fires and the volcanoes they produced played an important and previously underappreciated role in Earth history. Werner and Cuvier, on the other hand, were neptunists, convinced that a primeval Earth-spanning ocean (followed, after the rise of continents, by catastrophic floods) largely determined the shape of the physical environment.

Buffon's challenge to a biblical view of Creation was renewed in a more effective way by the Scottish physician and naturalist James Hutton, whose *Theory of the Earth* (1795) contained key uniformitarian principles. Hutton was not a consistent uniformitarian and did not try to separate science from religion, for he viewed continental uplift as a cataclysmic event and saw geological processes as proof of the workings of divine providence. The Earth's ecosystem, he claimed, floated on an enormous sea of magma and was meant to be self-maintaining through constant renewal; it was part of God's plan for humankind. This view was consonant with the prevailing Deism of the Enlightenment, which viewed God as having established Creation with all its natural forces but then as taking a passive role as those natural forces worked.

Yet if Hutton incorporated Deist elements into his theory, he also rejected biblical creationism. He insisted that the present was the key to an understanding of the past, that geological change could, and should, be explained in terms of the ordinary actions of natural forces acting normally. That view, which emphasized the slow action of temperature, wind, and water on landforms, automatically required an extension of the Earth's age that contradicted the account in Genesis.

Constant Forces

A full-blown uniformitarianism finally appeared in 1830, when the English geologist Charles Lyell produced the first volume of his *Principles of Geology*. With impressive consistency, Lyell insisted on explaining geological change strictly in terms of known physical agents operating at current levels of force. The Earth was sculpted by the interplay of water and heat—as he expressed it, by aqueous and igneous phenomena. Through the erosion cycle, the action of water tended to level the Earth. The raising or depressing of the Earth's surface was caused by volcanoes and earthquakes, which were themselves products of the Earth's enormous internal heat. Furthermore, the cycles of raising and lowering, of construction and destruction, tended to proceed at the same approximate rate. Even volcanoes, the most violent natural force considered by Lyell, produced about the same amount of lava from eruption to eruption. This meant that the surface of the Earth—or, more exactly, the successive surfaces of the Earth—remained in roughly the same general condition throughout its enormously lengthy history.

Lyell's work was more impressive than that of Hutton for several reasons. Unlike Hutton's work, it was thoroughly documented and tightly argued. Second, its unrelieved insistence on uniformity and regularity within the bounds of familiar phenomena was solidly within the Newtonian tradition and therefore fit the current model of good science. Finally, Lyell went beyond Hutton by incorporating organic as well as inorganic change into his theory. He flatly rejected progressiveness in the fossil record. He did, however, believe that organic remains were vital evidence of fluctuating geologic and climatic conditions, for ecological change would be marked by shifting species distributions, mass extinctions, and a certain amount of species mutability.

Impact

The *Principles of Geology* immediately touched off a dispute over the rate of geological change known as the uniformitarian-catastrophist debate.

ABOUT CHARLES LYELL

Sir Charles Lyell was born on November 14, 1797, into a substantial London mercantile and naval family on a Scottish estate, Kinnordy. Sickly as a boy, he received a private grammar school education and matriculated at Exeter College, Oxford, in 1816. His interest in geology was aroused by William Buckland's mineralogy and geology lectures, supplemented by bits of geologizing with family friends.

In the 1820's, an amateur making original contributions to geology was not unusual. Geology was still in its infancy, and most work was done by collecting and observing. There was plenty of room for the gifted amateur. While no theoretical framework for geology was accepted or recognized, most believed that the Earth's geological past could be unraveled and ordered. Geologists believed that the sequence of rock strata appeared in the order in which they were deposited as sediments, with the youngest layers at the top and the oldest at the bottom. This stratigraphic concept was combined with the ideas of William Smith and his map of 1816, which showed that each stratum's characteristic fossils indicated relative age. The Geological Society of London—founded in 1807 on the basis of this empirical, rather than theoretical, consensus—consciously shunned theorizing and stressed observation.

Lyell served as secretary of the Geological Society (1823-1826) and was elected a fellow of the Royal Society in 1826. He made geological expeditions to the Paris Basin and published his observations in professional publications. George Scrope's *Memoir on the Geology of Central France* (1827) focused Lyell's attention on a complex series of lava flows in central France, which seemed to offer a key to geological forces and successions. In 1828, Lyell visited the Auvergne with Roderick Murchison, a retired army officer and amateur geologist. Viewing the continually reexcavated riverbeds and successive lava flows suggested to Lyell analogies between past and present geological actions.

From France—"the best and longest geological tour which I ever made . . . which made me what I am in theoretical geology"—he traveled to Italy with Murchison and then alone to southern Italy and Sicily. Struck by the number of fossil shells of living Mediterranean species, Lyell realized that one could order the most recent rocks according to the relationship of living to extinct species and noted that past changes in land levels near volcanic Mount Etna could be explained by analogy to present forces. The Italian trip led to his major work, *Principles of Geology* (1830), in which his uniformitarian theory was fully explicated.

That dispute soon flowed into the question of whether change was progressive or whether the Earth remained in structural equilibrium, in a sort of Lyellian steady state. In both cases, the controversy promoted further research, especially in potentially revealing areas such as mountain building.

Lyell's views were partly invalidated by later research, which found that intermittent cataclysmic episodes did interrupt the normal flow of uniform forces and that the fossil record was, indeed, progressive. Yet if he represented a philosophic extreme, he still occupied a prominent place in the development of modern geology. In undermining the legitimacy of a linkage between earth history and scriptural belief, in extensive documentation of his generalizations, and in searching for regularity in geological processes, he pushed that emerging discipline toward maturation.

Lyell's work was also crucial to the development of Charles Darwin's theory of evolution. Darwin was deeply impressed by Lyell's *Principles of Geology*, which he read carefully during his famous voyage around the world on HMS *Beagle*. As he later noted, Lyell's insights allowed him to see the natural world through different lenses.

There are several ways in which uniformitarianism prepared the ground for Darwin's later activities. First of all, any notion of evolution in small increments required freedom from rapid, catastrophic change and a vast time span within which to operate. Lyell's theory provided Darwin with both of these conditions. Also, Darwin found that his observations of the fossil record supported Lyell's conclusions about the correlation between species distribution, climate, and geography. That increased awareness of paleoecology deepened his understanding of the ways living plants and animals were distributed and allowed him to make connections between the

Charles Lyell. (Library of Congress)

living conditions of past and present life-forms. Finally, Lyell's geologic uniformitarianism provided a model for Darwin's vision of the gradual modification of species. Darwin was unaware of the breakthrough in genetics achieved by the Austrian monk and botanist Gregor Johann Mendel (1822-1884) and could not accurately describe the way characteristics were transmitted from parents to offspring. Still, he conceived of biological change in a Lyellian, uniformitarian manner. It was gradual, steady, and cumulative, reacting to known forces operating in known ways.

In sum, Lyell's work is significant because of the way it furthered Cartesian values in two emerging disciplines. In geology, his uniformitarianism further distanced science from theology and promoted Descartes's fundamental notion that the natural world was formed by law-bound matter in motion. In biology, it advanced the Cartesian definition of life as highly organized law-bound matter in motion by freeing geological time from scriptural bonds. In both cases, Lyell's uniformitarianism accelerated the rise of modern scientific disciplines.

See also Continental Drift; Earth's Core; Earth's Structure; Evolution; Fossils; Geomagnetic Reversals; Hydrothermal Vents; Mass Extinctions; Microfossils; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating; Seafloor Spreading; Uniformitarianism.

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—*Michael J. Fontenot*

GEOMAGNETIC REVERSALS

THE SCIENCE: Richard Rayman Doell and Brent Dalrymple discovered that Earth's magnetic field has reversed many times during geologic history.

THE SCIENTISTS:

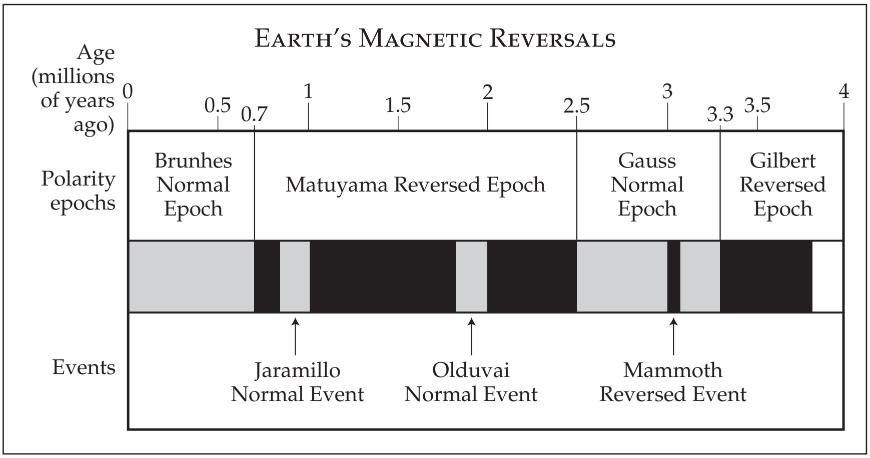
Richard Rayman Doell (b. 1923), American geophysicist and paleomagnetist
Brent Dalrymple (b. 1937), American radiometrist and paleomagnetist
Allan V. Cox (b. 1926), pioneering American paleomagnetist

PALEOMAGNETISM

Paleomagnetism is the study of the direction and intensity of Earth's magnetic field through geologic time. It has been an important tool in unraveling the past movements of Earth's tectonic plates. By studying the magnetic field left in ancient rocks, earth scientists are able to learn how the continental and oceanic plates have shifted through time.

It was not until the early twentieth century that observers began suggesting that the polarity of the Earth's magnetic field had experienced changes in the past. This was based on studies by geophysicists of remanent magnetization (that is, magnetization that remains in some materials after the magnetizing force has been removed) of volcanic rocks and baked earth. In 1906, Bernard Brunhes, a French physicist, found volcanic rocks magnetized in the opposite direction with reference to Earth's present magnetic field. He concluded that the magnetic field had reversed. His conclusion was accepted, but scientists were not interested in this type of research at that time.

Laboratory studies showed that volcanic rocks and baked earth, when heated to their Curie temperature (the temperature above which a substance is no longer magnetic) and allowed to cool, acquired a weak and stable remanent magnetization that was parallel to the Earth's present magnetic field. Scientists also found bricks and baked earth in archaeological sites that



had their magnetism reversed because of fires made by humans. Lava flows also change the magnetisms of rocks (baked earth) that they have covered.

In 1925, R. Chevallier studied lava flows from Mount Etna, which contained remanent magnetizations that correlated with the magnetic field of the Earth at the time of their eruption. In 1926, Paul L. Mercanton suggested that if magnetized rocks showed a reversed magnetic field for the Earth, then those reversals should have been recorded worldwide in other rocks. The first paleomagnetist to determine the times when the magnetic field had reversed itself was Motonori Matuyama, in 1929. He accomplished this by determining the ages of rocks. He found that the youngest rocks with reversed polarity were of the early Quaternary period (within the last 2.5 million years).

SEARCHING FOR CONSISTENT EVIDENCE

Many geologists and geophysicists have conducted research on paleomagnetism, but the work of Richard Rayman Doell and Brent Dalrymple provided a complete picture of the paleomagnetic reversals of the past five million years. Allan V. Cox, Doell, and Dalrymple spent five years (1959-1964) working on continental volcanic rocks from Alaska, Hawaii, Idaho, California, and New Mexico. They wanted to determine if evidence for the last magnetic reversal from reversed polarity (named the "Matuyama reversed epoch") to the present normal polarity (named the "Brunhes normal epoch"), which occurred approximately one million years ago, was consistent throughout the world.

In 1965, while Cox was doing research abroad, Doell and Dalrymple continued their study of volcanic rocks from the Valles Caldera in New

Mexico, which is part of the Jemez Mountains located 56 kilometers northwest of Santa Fe. On November 4, 1965, at a meeting of the Geological Society of America in Kansas City, Missouri, Dalrymple presented a paper titled "Recent Developments in the Geomagnetic Polarity Epoch Time-Scale." It contained evidence that another magnetic reversal of the Earth's poles could have occurred "at about 0.9 million years." Because such events are of "short duration," Dalrymple noted, "the chances of finding another one are rather small."

On May 20, 1966, *Science* published a two-page article by Doell and Dalrymple titled "Geomagnetic Polarity Epochs: A New Polarity Event and the Age of the Brunhes-Matuyama Boundary." Doell and Dalrymple determined the age of nineteen Pleistocene volcanic rock units collected during the summer of 1964 in the Valles Caldera. These samples indicated that several reversed polarity events had occurred within the last million years or so, and that these events tended to be relatively brief.

The Vine-Matthews Hypothesis

In 1963, Fred J. Vine, Drummond H. Matthews, and Lawrence W. Morley independently proposed the hypothesis that the rock of the ocean floor showed evidence of magnetic field reversals. These magnetic stripes mirrored each other on opposite sides of midoceanic ridges and were of the same thickness. In February, 1966, the new geomagnetic polarity-reversal time scale developed by Doell and Dalrymple was correlated with the magnetic anomaly profiles across midoceanic ridges. The Vine-Matthews-Morley hypothesis (better known as the "Vine-Matthews hypothesis") was confirmed, and the theory of seafloor spreading and continental drift became widely accepted.

About the same time, polarity reversals were demonstrated in deep-sea sediment cores. In February, 1966, while Vine was visiting Neil Opdyke at the Lamont-Doherty Geological Observatory, Opdyke mentioned to Vine that he and his colleagues had discovered a new magnetic anomaly occurring at about 0.9 million years ago in deep-sea sediment cores from the South Pacific's East Pacific Rise. These scientists had found the same magnetic reversal that Doell and Dalrymple had found on land. Other oceanic cores from various parts of the world also showed the reversal. These discoveries lent additional support to the theory of worldwide continental drift.

Impact

Paleomagnetism provided the missing piece in the puzzle of continental drift. It also added credence to what came to be known as the plate tectonics theory. Other scientific data that had been collected and studied also helped confirm the idea of seafloor spreading promoted by Harry Hammond Hess. A revolution in the earth sciences was triggered by the work of Doell and Dalrymple.

See also Continental Drift; Earth's Core; Earth's Structure; Evolution; Fossils; Geologic Change; Hydrothermal Vents; Mass Extinctions; Microfossils; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating; Seafloor Spreading; Uniformitarianism.

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—*Roberto Garza*

GERM THEORY

THE SCIENCE: Prior to the 1850's, fermentation was viewed as purely a chemical process, somehow catalyzed by the presence of yeast. Louis Pasteur demonstrated that specific living organisms are required for fermentation and the process itself is biological. Similarly, Pasteur identified microorganisms as the etiological agents of animal diseases in what became known as the germ theory of disease.

THE SCIENTISTS:

Louis Pasteur (1822-1895), French chemist whose early work in the area of fermentation and diseases of silkworms led to the germ theory

Friedrich Henle (1809-1885), German pathologist

Marcellin Berthelot (1827-1907), rival of Pasteur who argued in favor of a chemical basis for fermentation

Robert Koch (1843-1910), German physician and another originator of germ theory
Justus von Liebig (1803-1873), German chemist

FERMENTATION

In the mid-nineteenth century, several investigators were interested in the process of fermentation. These scientists included Louis Pasteur at the École Normale in Paris, France. In his initial report on the subject in 1860, Pasteur acknowledged the contribution by Cagniard de Latour, who in 1835 observed the decomposition of sugar and production of carbon dioxide following the introduction of yeast. The prevailing theory of the time, however, was that the yeast was consumed in the process—that fermentation was a purely chemical (inorganic) process. Perhaps the leading proponent of this idea was the German chemist Justus von Liebig.

Liebig believed that the fermentation process was a by-product of the decomposition of yeast and a subsequent release of enzymes. It was well known that inorganic (nonliving) material was capable of catalyzing certain fermentative reactions. Reflecting his background as a chemist, Pasteur had primarily made quantitative measurement of reaction products, providing an explanation for how they were being consumed. For example, nitrogen in the mixture, rather than being released as ammonia, was being converted into components within the yeast itself. Furthermore, Pasteur demonstrated that the sugar in the mixture is converted into cellulose (or at least a complex polysaccharide) within the yeast "globule."

Perhaps Pasteur's most important observation from his fermentation experiments was the effect on the quantity of the yeast itself. Pasteur measured the yeast, demonstrating an increase in quantity as well as in the components which form the microbe. Pasteur concluded that yeast was a living organism and that the process of fermentation was a biological process. He also found that the yeast was anaerobic (capable of growing and fermenting in the absence of oxygen). Finally, he demonstrated that specific types of yeast were associated with different products of fermentations.

PASTEURIZATION

Pasteur continued this area of research with investigations into the souring of beer, as well as wine. Observing several types of yeast in soured alcohol, Pasteur concluded that the problem originated with contamination from the environment. He found that mild heating would kill undesired contaminants, a process that came to be known as pasteurization.

Louis Pasteur: National Hero

By 1868, Louis Pasteur was a household word in France, having improved the French sugarbeet, wine, vinegar, silk, and beer industries through his method of pasteurization. He was assisting French silkworm farmers to combat the devastating pébrine disease when, in October, he suffered a cerebral hemorrhage at the young age of forty-five. Many thought he would die; his left side was completely paralyzed. However, he regained partial use of his left side and walked again, though with a severe limp. Thereafter he depended on his assistants for physical help, but his mind remained keen, and by 1870 he had rescued the French silk industry.

Perhaps providence allowed Pasteur to maintain his faculties, for his greatest contributions lay ahead of him. He confirmed the work of physician Robert Koch, who had discovered the complete life cycle of the anthrax bacillus, the cause of the disease anthrax. Hoping to outdo the German, Pasteur experimented with animals to produce a vaccine composed of weakened bacilli. If injected into an animal, it would confer immunity against anthrax. It was something Koch had never done.

Skeptical French veterinarians challenged Pasteur to a dramatic public test. His assistants cautioned against taking such a risk, but Pasteur was adamant. They caught the train for Pouilly-le-Fort, southeast of Paris. Pasteur's assistant, physician Émile Roux, immunized twenty-four sheep, one goat, and six cows with two injections of serum twelve days apart. Two weeks later, those animals and a control group of equal size were injected with a powerful culture of anthrax bacilli. All the immunized animals survived; all the others died. France went wild with the news.


(Library of Congress)

Pasteur next turned to conquer hydrophobia (rabies), probably motivated by childhood memories of an attack on his town by a rabid wolf. Collecting foam from the mouths of caged mad dogs, Pasteur and his men never found a responsible microbe (rabies is caused by a virus), but they made a vaccine and used it successfully on animals. Then a mother brought in her son, bitten by a rabid dog and sure to die. Pasteur ordered the child inoculated, and the child lived. Others came from as far as Russia and the United States; unless too much time had elapsed, they were cured.

It was a fitting climax to a brilliant career. On his seventieth birthday, a great celebration was held to honor Pasteur. His son had to deliver his father's speech, in which Pasteur said that it gave him immense happiness "to have contributed in some way to the progress and good of humanity."

In 1862, Pasteur and Claude Bernard demonstrated that a similar heating process could also be used to preserve other drinks such as milk.

Pasteur's biological theory of fermentation continued to have its critics. Marcellin Berthelot, like Pasteur a French chemist, continued to argue in favor of a "modified chemical basis of fermentation." Even Pasteur's colleague, Bernard, had some doubts. Pasteur's experiments nevertheless remained convincing, and gradually his ideas reached universal acceptance.

Sick Silkworms

In 1865, Pasteur was requested by the French government to study a form of silkworm blight known as pébrine. In the decade since the disease had been introduced into France, the silkworm industry was nearly ruined by the unknown cause. Pasteur discovered the agent was also a microorganism, a bacterium which infected the silkworm egg in the nursery. He demonstrated that by isolating healthy eggs and providing bacterium-free leaves as a food source, the disease could be prevented.

Pasteur's earlier work on spontaneous generation had proved that the atmosphere could be a source of microorganisms. The demonstration that pébrine was a bacterial disease lent credence to the idea that diseases of humans and other animals might also be associated with similar organisms. Fermentation and putrefaction were clearly the products of microbial action, and Pasteur gradually developed the idea that fermentation and disease had a similar microbial basis. His primary focus until the mid-1870's, however, was in the study of fermentation of beer.

Koch, Anthrax, and Germ Theory

The idea was not new with Pasteur. The German anatomist and pathologist Friedrich Henle had suggested this several decades earlier. Henle's later ideas for associating specific organisms with disease would become the basis for German physician Robert Koch's postulates in the 1880's. Pasteur's introduction to the role of bacteria and animal disease involved the study of the anthrax bacillus. Arguably his most famous rival in this field was Koch. The competition was not always friendly, given the contemporary political background and history of France and Germany.

Nevertheless, their respective work was complementary and formed the basis for what became known as the "germ theory of disease." Pasteur's contribution came in the confirmation that a specific bacillus is the cause of anthrax, and that when inactivated could become the basis for an anthrax vaccine. Koch meanwhile, developed a method to grow the organism, and others, in pure culture in the laboratory.

Earlier (c. 1880), Pasteur had observed that the microbe that caused chicken cholera could be inactivated by heating. When the inactive microbes were inoculated into healthy chickens, the animals developed immunity to the disease. In 1881, Pasteur applied this to his anthrax vaccine (and later in a vaccine against rabies). Using a chemically inactivated strain of the anthrax bacillus, Pasteur demonstrated that a similar immunity could also be developed in animals against this disease.

Impact

While Pasteur was not the originator of the germ theory of disease, his work established the presence of microorganisms in the fermentation process and, by extension, spoilage of food. Application of this work soon led to an understanding of the role played by microbes as etiological agents of disease, initially in silkworms and then later in humans and other animals.

Pasteur's early experiments with swan-necked flasks also demonstrated the error of the current theories of spontaneous generation, the notion that life could arise from nonliving matter. He established that contamination of drinks and most food could be traced to a clearly nonspontaneous cause, organisms in the environment. Hence, the living contamination was a product of other living organisms. With this understanding, Pasteur went on to develop a method to preserve these foods by killing the offending organisms: pasteurization.

His work must be viewed in the context of the time, not least of which was the rivalry with Koch. Koch was a physician, and his research and focus were primarily in health care. Pasteur's training was in chemistry, and his work must be viewed from that context. Pasteur had an ability to apply the knowledge from one area of investigation—fermentation as the result of microorganisms—to the analogous situation in which organisms were the source of food contamination, then extend this understanding to infections in animals. This process of generalization allowed Pasteur to anticipate the applications of his findings. Pasteur argued that if such infections were prevented, disease could be prevented. Thus, his insights presaged aseptic techniques applied in surgery and elsewhere. Perhaps fortuitously, Pasteur also observed that if "germs" were inactivated prior to inoculation of animals, the animal would develop an immunity to that disease. As Pasteur put it, "Chance favors the prepared mind."

See also AIDS; Antisepsis; Contagion; Diphtheria Vaccine; Galen's Medicine; Greek Medicine; Human Immunodeficiency Virus; Hybridomas; Immunology; Oncogenes; Penicillin; Polio Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Streptomycin; Viruses; Yellow Fever Vaccine.

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—*Richard Adler*

GLOBAL WARMING

THE SCIENCE: Syukuro Manabe and Richard Wetherald found that increased carbon dioxide in the atmosphere creates a greenhouse effect and hence global warming.

THE SCIENTISTS:
Syukuro Manabe (b. 1931),
Richard Wetherald (b. 1936), and
Stephen Henry Schneider (b. 1945), American climatologists
Svante August Arrhenius (1859-1927), Swedish physical chemist

TOO MUCH OF A GOOD THING

The Earth's climate is a complex and intricate mechanism, and many factors contribute to its behavior. Climatologists look to past climatic patterns to try to understand how the mechanism works and how it can be expected to work in the future. In addition, climatologists use computer simulations, or models, to mimic the atmosphere to see how the mechanism will react to different circumstances. Climatologists Syukuro Manabe and Richard Wetherald were among the first to use model atmospheres to attempt to predict the effect of increased carbon dioxide on climate.

Svante Arrhenius. (The Nobel Foundation)

It was around the beginning of the twentieth century that scientists first suggested that the carbon dioxide (then known as carbonic acid) released in the burning of fossil fuels might build up in the atmosphere and cause warming of the planet. Svante August Arrhenius in 1896 and T. C. Chamberlin in 1899 had warned of the possible impact of the burning of fossil fuels on the Earth's temperature. For many years, however, it was assumed that the climate is such a large and stable system that human activity cannot have any great effect on it. Climatologists have since learned that humans can, indeed, affect the climate in ways that are not yet fully understood but that might have important consequences.

Arrhenius and Chamberlin suggested the phenomenon that came to be called the "greenhouse effect." In 1861, Irish physicist John Tyndall first recognized that carbon dioxide and water vapor are transparent to light in the visible wavelengths, but not to infrared radiation (that is, heat). Thus, the Earth's atmosphere will allow certain wavelengths of radiation from the Sun, the wavelengths of visible light, to reach the ground. This visible light is absorbed and reemitted by the Earth at slightly longer wavelengths as infrared radiation that cannot be seen but can be felt as heat. The infrared radiation cannot pass back out through the atmosphere as easily as it came in because of the presence of carbon dioxide, water vapor, and other "greenhouse" gases such as fluorocarbons, oxides of nitrogen, sulfur dioxide, and methane. These gases absorb the infrared radiation and reemit it

SVANTE ARRHENIUS ON GLOBAL WARMING

In 1896, Swedish chemist Svante Arrhenius analyzed why previous ice ages had risen in geologically short periods of time and how they were related to variations of "carbonic acid" (carbon dioxide) in the atmosphere. His conclusions anticipated our current understanding of global warming.

In the Physical Society of Stockholm there have been occasionally very lively discussions on the probable causes of the Ice Age. . . . Conversations with my friend and colleague Professor Högbom, together with the discussions above referred to, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the belief that one might in this way probably find an explanation for temperature variations of 5 -10 C. I worked out the calculation more in detail, and lay it now before the public and the critics.

From geological researches the fact is well established that in Tertiary times there existed a vegetation and an animal life in the temperate and arctic zones that must have been conditioned by a much higher temperature than the present in the same regions. The temperature in the arctic zones appears to have exceeded the present temperature by about 8 or 9 degrees. To this genial time the ice age succeeded, and this was one or more times interrupted by interglacial periods with a climate of about the same character as the present, sometimes even milder. When the ice age had its greatest extent, the countries that now enjoy the highest civilization were covered with ice.

One may now ask, How much must the carbonic acid vary according to our figures, in order that the temperature should attain the same values as in the Tertiary and Ice ages respectively? A simple calculation shows that the temperature in the arctic regions would rise about 8 to 9 C., if the carbonic acid increased to 2.5 or 3 times its present value. In order to get the temperature of the ice age between the 40th and 50th parallels, the carbonic acid in the air should sink to 0.62-0.55 of its present value (lowering of temperature 4 -5 C.). . . .

Is it probable that such great variations in the quantity of carbonic acid as our theory requires have occurred in relatively short geological times? The answer to this question is given by Prof. Högbom . . . :

> . . . An increase or decrease of the supply continued during geological periods must, although it may not be important, conduce to remarkable alterations of the quantity of carbonic acid in the air, and there is no conceivable hindrance to imagining that this might in a certain geological period have been several times greater, or on the other hand considerably less, than now.

Source: Svante Arrhenius, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground." *Philosophical Magazine* 41 (1896): 237-276.

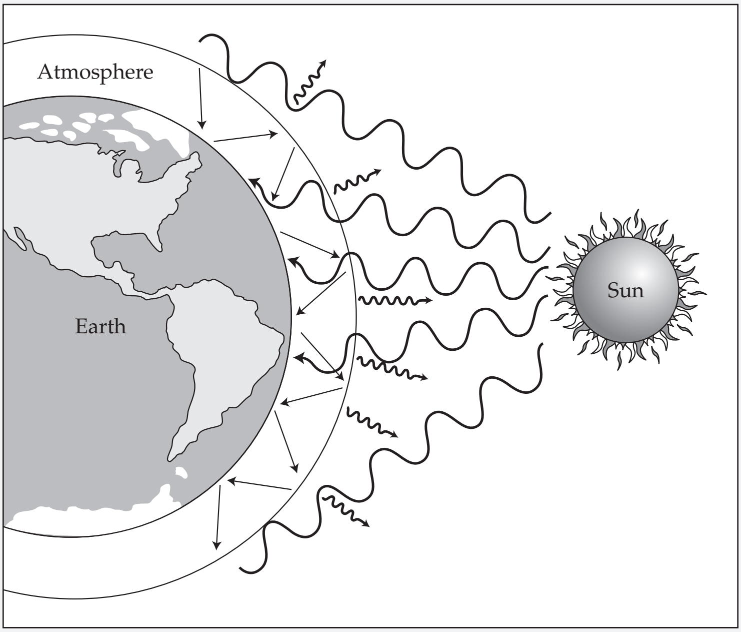
back toward Earth, where this heat becomes trapped near the surface of the Earth and cannot escape.

A certain amount of carbon dioxide is beneficial to life on Earth, but scientists began to wonder if perhaps too much carbon dioxide might not create an increase in temperature with which it would be difficult to cope.

THE GREENHOUSE EFFECT

Clouds and atmospheric gases such as water vapor, carbon dioxide, methane, and nitrous oxide absorb part of the infrared radiation emitted by the earth's surface and reradiate part of it back to the earth. This process effectively reduces the amount of energy escaping to space and is popularly called the "greenhouse effect" because of its role in warming the lower atmosphere. The greenhouse effect has drawn worldwide attention because increasing concentrations of carbon dioxide from the burning of fossil fuels may result in a global warming of the atmosphere.

Scientists know that the greenhouse analogy is incorrect. A greenhouse traps warm air within a glass building where it cannot mix with cooler air outside. In a real greenhouse, the trapping of air is more important in maintaining the temperature than is the trapping of infrared energy. In the atmosphere, air is free to mix and move about.



Modeling the Atmosphere

Scientists in the 1960's began creating models of how the atmosphere works; they inserted into these models an increased concentration of carbon dioxide to see how the model reacted. A model of the atmosphere is essentially a set of equations that describe the behavior of the atmosphere. Initial conditions, such as temperature and atmospheric composition, are established. Then the equations are solved to determine the resulting equilibrium state of the atmosphere—that is, the point at which all the factors are balanced and stable. This process is often repeated and the resulting climate condition is used as the "initial condition" to extrapolate further about how the climate will continue to behave.

When this is done, so-called feedback mechanisms—that is, ways in which something resulting from the initial change works to induce more change—can be explored. For example, if an increase in carbon dioxide were to increase the cloud cover, the increased cloud cover would then "feed back" into the calculations to produce other changes in the climate. The many calculations required to use these models are usually done on a computer.

In 1964, Manabe and Robert Strickler began working with a model atmosphere in order to study the effect of atmospheric water vapor on climate. In 1967, Manabe and Wetherald, working at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, published a continuation of this study.

Manabe and Strickler had studied an atmospheric model that considered distributions of absolute humidity. (Absolute humidity is a measure of how much water vapor is in the air.) They concluded from their work that, were the carbon dioxide in the atmosphere to double, something that many scientists believe could happen between the years 2020 and 2080, the average global temperature would increase by about 2.3° Celsius. The increase in different areas would vary from this average, with the greatest increase at the poles and the smallest increase at the equator. The differential warming would affect air circulation patterns and climate in general.

Impact

Other types of computer models followed. The makers of different models made different assumptions in setting up their equations, and thus the models arrived at different answers to the same question. This was obvious in the late 1960's and early 1970's, when predictions of the results of carbon dioxide doubling ranged from a global average of 0.7° Celsius to 9.6° Celsius.

In 1975, climatologist Stephen Henry Schneider looked at these studies with their varying predictions and attempted to take into account the assumptions made for each model and the way in which those assumptions related to the real world. He was able to find explanations for most of the variations in the predictions and found that the best estimate of temperature increase in the event of atmospheric carbon dioxide doubling was about 1.5° to 2.4° Celsius.

The experts still do not agree about the magnitude of temperature change that could be caused by increased atmospheric carbon dioxide or about the precise effects in climate this temperature change could have. Most scientists, however, agree that evidence supports the theory of global warming. Even those who have had a vested interest in denying global warming—such as automobile manufacturers—have at least acknowledged the need to mitigate emissions that can contribute to climate change as they slowly develop products for a growing market interested in low-emission vehicles. Yet because of the many vital implications of this work for governmental policy, the subject still arouses controversy in political and economic circles. The problem of potential global warming warrants serious thought and action.

See also Carbon Dioxide; Chlorofluorocarbons; Ozone Hole; Pesticide Toxicity.

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—*Mary Hrovat*

GRAN DOLINA BOY

THE SCIENCE: Anthropologists discovered the fossil skull of a boy who lived in Spain roughly 780,000 years ago. His skull combined features of both modern humans and earlier human species.

THE SCIENTISTS:
José Maria Bermúdez de Castro (b. 1952),
Juan Luis Arsuaga Ferreras and
Antonio Rosas, Spanish paleoanthropologists

THE PIT OF BONES

In 1976, paleontologists working in the Atapuercan hills, near Burgos in northern Spain, discovered the largest known collection of human bones from the Middle Pleistocene period, dating from between 350,000 and 500,000 years ago. In a large pit known as Sima de los Huesos (the cave or pit of bones), they found the bones of at least thirty-two people. The remains, difficult to date precisely, are still being analyzed. The bones at this site seemed similar to those of the Neanderthal species, which flourished from about 200,000 to 30,000 years ago. Also, the lack of evidence that this group of individuals lived in the cave, coupled with the large number of bones found there, suggested to some scientists that these early humans used the pit as a mass burial ground. The Neanderthals, too, were known to have buried their dead—although they were doing so around 100,000 (not around 400,000) years ago. Finally, by 1998 a single stone ax had been located at this site—the first tool associated with these bones. Although similar tools were found at nearby sites, this was the only ax found at Sima.

GRAN DOLINA

In the meantime, between 1994 and 1996, new fossils were discovered at another site not far from Sima de los Huesos: Gran Dolina. During the 1890's, the Sierra Company Railroad had carved into the landscape of Atapuerca, leaving a trench that exposed a cliff whose layers could be read like a history—or prehistory. Each layer was given a number preceded by "TD" (for *trinchera Dolina*, or Dolina trench). The layers of earth that contained bones, TD 6 and later, were dated (using periodic shifts in Earth's magnetic field as a guide) at about 780,000 years old—right in the middle of the Pleistocene age (which dates from 1.8 million to 10,000 years ago), when Earth was going through cycles of ice ages and temperate periods.

The period of TD 6 was temperate in the portion of Europe occupied by the Iberian Peninsula (Spain and Portugal today).

On May 30, 1997, a team of Spanish paleontologists, including paleoanthropologists José Bermúdez de Castro and Juan Luis Arsuaga Ferreras, in Madrid, Spain, announced in the journal *Science* that they had concluded an examination of stone tools and braincase fragments from six individuals found at the Gran Dolina site. The bones were found in an area that was once a cave, now filled in. One of the fossils found at Gran Dolina was the skull of a young boy about ten or eleven years old. The fossil was unique because it was nearly complete and displayed features that had not been seen in any human fossils found anywhere before.

A Mixture of Traits

The boy's skull showed an unusual mixture of ancient and modern human features. This mixture of traits led the Spanish team that found the fossil to speculate that it represented a new species in the line of human history, which eventually gave rise to both modern humans (who emerged as a species about 40,000 years ago) and the Neanderthals (a species of humans who lived from about 200,000 to 30,000 years ago). Neanderthals had disappeared because they were unable to compete with or perhaps interbreed with modern humans.

The Spanish scientists named the new species *Homo antecessor*, or "the human who came first." Antonio Rosas, a paleoanthropologist at the National Museum of Natural Sciences in Madrid, said that the boy's face had some features typical of more ancient human species. His brow ridge stuck out, and he had primitive teeth with multiple roots and a heavy jaw. Other aspects of the boy's face were like those of modern humans or Neanderthals—his cheekbones were sunken and had a horizontal rather than a vertical ridge where the upper teeth attach.

In addition, the boy's face was flatter than that of a typical Neanderthal, but it was not as flat as a modern human face is. The projecting nose and jutting mid-face gave the skull a shape that combined the features of both Neanderthals and modern humans. Like modern humans, the boy had a bony protrusion on the back of his skull. As a result, the boy's skull was an unusual blend of primitive and modern features that was not typical of any known human species. The Spanish paleoanthropologists therefore believed that the fossil proved the existence of a new species—one that came before both modern humans and Neanderthals and was the common ancestor for both of these later species.

Other scientists did not agree that the Burgos fossil represented a new human species. They stated that it was impossible to determine on the basis of a single skull whether other people living at the same time shared the same features as this boy. More comparison with other adults and juveniles from the same time and place was needed to prove that the boy was a typical member of his species and that these people were indeed a unique human species. These scientists also cited the difficulty of making accurate

A NEW HUMAN ANCESTOR?

In an interview in 1997, soon after his announcement of the Gran Dolina discoveries, Juan Luis Arsuaga Ferreras of the Universidad Complutense, Madrid, summed up his assessment of the skull of "Gran Dolina Boy" and other bones found at the site: "We realized right away that the face was modern-looking. We tried to put the fossils in *Homo heidelbergensis* [which is commonly accepted as a predecessor to modern humans], but they were so different that we could not." Arsuaga's colleague Antonio Rosas of the National Museum of Natural Sciences in Madrid has pointed to Gran Dolina's hollowed cheekbones and subnasal morphology as typical of modern humans and not found in *Homo heidelbergensis*. This may argue for *Homo antecessor* as an ancestor of *Homo sapiens*. Arsuaga welcomed the debate:

> There are two main groups of paleoanthropologists today. Those who consider that human evolution is like a ladder with only one species at a time—*Homo habilis*, *Homo erectus*, *Homo sapiens*—will never accept more species. The other group sees human evolution as a tree with many branches. Some authors think that *Homo erectus* represents a separate branch and that Neanderthals and modern humans are two separate branches with a common ancestor. This common ancestor used to be called "archaic" *Homo sapiens*, but now many people believe that Neanderthals are a different species (*Homo neanderthalensis*) from ourselves. So the common ancestor can no longer be called *Homo sapiens*. We agree in all of this, but the common ancestor is now called *Homo heidelbergensis*, after the Mauer mandible. Our opinion is that *Homo heidelbergensis* is a Middle Pleistocene European species, which is ancestral only to Neanderthals and not to modern humans. The last common ancestor to Neanderthals and modern humans is older, and it is the newly named species *Homo antecessor* [Gran Dolina boy] (of Lower Pleistocene age). We have only placed the common ancestor slightly back in time. What is important are the Dolina fossils and not the species we have named, and among the newly published fossils there is a wonderful partial face that has much to tell about human evolution.

Source: Interview with Juan Luis Arsuaga Ferreras conducted by Mark Rose for *Archaeology*, published online by the Archaeological Institute of America, July 27, 1997. Available at www.archaeology.org/online/news/gran.dolina.html. Accessed September, 2005.

projections about the appearance of adults at Atapuerca based on the appearance of a child. In response, Rosas stated that facial bones from the other five individuals found at Gran Dolina had the same modern features as the boy's face. However, the skulls from the other individuals were not complete, and extrapolating from partial fragments of bone is difficult.

IMPACT

The Atapuercan bones were the oldest human fossils ever found in Europe. Since the initial discoveries, nearly one hundred fossils have been found, along with some crude tools that can be associated with cut marks found on animal bones at the site. No fossils had ever been found in Europe, and very few in Africa, for the time period from about 1.8 million years ago (when the first humans left Africa) until about 500,000 years ago. The Gran Dolina fossils are therefore valuable for the information that they give scientists about what types of humans were living in Europe during this interim period, some 800,000 years ago.

Although paleoanthropologists are still studying these bones, they have learned that the people at Gran Dolina engaged in cannibalism without any evident need to do so, because animal life was abundant. Some human bones show the same cut marks as animal bones at the site. Is it possible that this practice had a ritual or symbolic significance long before the first humanoids previously known to engage in symbolic and artistic activity, the Neanderthals? The question remains unanswered: Certainly these remains, twice as old as those found at the Sima site, have shown no evidence that the inhabitants used fire to cook or engaged in art. They appear to have been a species distinct from those at Sima.

Still, the existence of the Gran Dolina fossils has also caused scientists to believe that humans began to move into Europe from Africa as early as about 2 million years ago; previous estimates of that arrival were between 1 million and 500,000 years ago.

Regardless of whether the Atapuerca fossils are those of a distinct species, they do show that a great deal of variation existed among different groups and species of early humans. In this way, humans are no different from other groups of animals, in which diversity of physical traits and behavioral patterns is the norm. Scientists had once thought that humans evolved in a steady line through time. The Gran Dolina fossils show that it is more likely that humans evolved in different ways at different times and in different places, with some groups surviving and others dying out or changing further to develop new variations on the species.

Where the Gran Dolina fossils fit in the overall picture of human history is not yet clear, but they do add another piece of evidence to what is known about ancient human ancestors. The future discovery of other early hominid sites in southern Europe will no doubt help to clarify the status of the Gran Dolina fossils as a separate species.

See also *Australopithecus*; Cro-Magnon Man; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Helen Salmon*

GRAND UNIFIED THEORY

THE SCIENCE: Howard Georgi and Sheldon L. Glashow developed the first of the unified field theories in subatomic physics, which, although tentative, could lead eventually to a single theory uniting all the laws of nature.

THE SCIENTISTS:
Howard Georgi (b. 1947), American physicist
Sheldon L. Glashow (b. 1932), American physicist
Abdus Salam (1926-1996), Pakistani physicist
Steven Weinberg (b. 1933), American physicist
Jogesh Pati (b. 1937), Indian physicist

WHERE EINSTEIN FAILED

Four known natural forces determine the behavior of every object in the universe, from the motion of planets and stars to the interaction and very form of matter itself. These are the gravitational force, the electromagnetic force, the weak force, and the strong force.

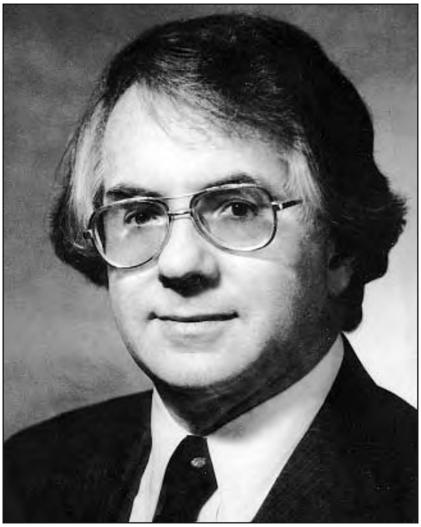
The gravitational force is generated by static mass (or mass in acceleration). It holds planets in their orbits and holds objects to the surface of planets. Although it is expressed over immense distances, it is the weakest of the four forces. The electromagnetic force exists between atoms and molecules. It is the force that drives machinery and electronic devices. The weak force exists at the atomic level and is responsible for the decay of radioisotopes; it is responsible for radioactivity. The strong force exists within the nucleus of the atom and holds together the elementary particles that make up protons and neutrons.

The goal of modern physics is the unification of all these forces into a single, elegant theory that has become known as the grand unified theory (GUT). The German American physicist Albert Einstein, famous for his formulation of the revolutionary theory of relativity, attempted to harmonize gravitational and electromagnetic forces only into a unified theory. Although he devoted much of his career to this aim, he failed utterly. Part of his failure may have been a result of his rejection of quantum physics, which he called "a stinking mess." Quantum physics is the only tool capable of delving into the forces within subatomic particles. Physicists who came after Einstein and utilized this powerful tool of quantum physics began to inch closer to the unification target.

ELECTROWEAK THEORY AND QCD

Between 1961 and 1968, a series of papers were written by the American physicists Sheldon L. Glashow and Steven Weinberg and the Pakistani physicist Abdus Salam. In 1971, physicist Gerard 't Hooft brought these ideas together in a paper that demonstrated that they had predicted all the elements that would unite the quantum (subatomic) theories of the electromagnetic and weak forces. It became the first of the quantum unification theories, called the "electroweak theory." Glashow, Weinberg, and Salam won the 1979 Nobel Prize in Physics for their work.

Grand unification (as a hypothesis uniting three of the elementary forces) came about as a tentative supposition in 1973. Glashow teamed up with Howard Georgi, a Harvard colleague and physicist, and seized on the newly emergent theory of quantum chromodynamics (QCD), which lent a



Sheldon Glashow. (The Nobel Foundation)

kind of order to the theory of atomic particles, particularly the relationship between electricity and radiation in regard to the electron. They reasoned that although the differences in forces were very great, QCD allowed for enough definition that each of the three elementary particles (proton, neutron, and electron) could be defined by a single coupling constant (a term that defines the force's absolute strength).

In 1973, Salam published a paper he had written with physicist Jogesh Pati. In that paper, the first mention of an altogether radical notion appeared: the possibility that the proton—the most stable entity in the known universe—could, in fact, ultimately decay. Glashow and Georgi's theory, SU(5), built on that notion. They rationalized through SU(5) that when a quark (the building block of a proton) decays during proton decay, it gives off a very heavy particle and the proton literally falls apart into leptons, which would finally translate into electrons and positrons. When they meet, forming photons, or light, the atom (matter) is gone forever.

IMPACT

Einstein spent decades on his failed attempt at grand unification. Glashow and Georgi spent twenty-four hours. Their article in *Physical Review* in 1974 unified the work of physics for the previous half century. On one hand, Einstein spent only two weeks hammering out relativity and laid out its formulations very briefly. On the other hand, Einstein synthesized the groundwork already laid out by the century of physicists before him. Therefore, Glashow and Georgi, already very well acquainted with the ideas of quantum mechanics, realized that the final pieces to the puzzle were contained in the ideas of quantum chromodynamics, which allowed the final demands of a grand unified theory to be met. Nevertheless, as promising as it is, the Glashow-Georgi theory is still tentative.

When the ultimate grand unified theory is written—one that accounts for gravity as well as the electromagnetic, strong, and weak forces of nature—then the main task of theoretical physics will have been completed.

PARTICLE ACCELERATORS

Quantum mechanics, as the study of the interior of the atom, depends on particle accelerators, which cause atoms to collide and split apart. Physicists collect the images of the atomic pieces (as traces on photographic plates) and examine them. As they delve deeper into the interior of the atom, however, larger and larger energies are required.

When physicists split the atom to verify elements of the electroweak theory, they used the most powerful particle accelerators known, which demanded as much power for a single experiment as a large city does to run itself. It is estimated that to verify the Glashow-Georgi theory, a particle accelerator many tens of millions times more powerful than any in existence would have to be built. Far beyond any known science, such an accelerator built to match scientific theories of the 1990's would have to be ten light-years in length. Thus, although the Glashow-Georgi theory seems well supported in concept, it may never be supported by experimental evidence. For this reason, the theory can only be considered tentative.

Again, the energies required to test and to verify these physical GUTs are so large, it is unknown whether any of them will ever be supported by experimental evidence. Without experimental confirmation, the world of the theoretical physicist becomes separated from the experimental. Such a separation will turn theoretical physics into what Georgi has called "recreational mathematical theology."

See also Electroweak Theory; Quantum Chromodynamics; Quantum Mechanics; Quarks.

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—*Dennis Chamberland*

GRAVITATION: EINSTEIN

THE SCIENCE: Measurements made during a total solar eclipse showed that the Sun's gravitational field bends the path of starlight.

THE SCIENTISTS:

Albert Einstein (1879-1955), German American physicist
Sir Arthur Stanley Eddington (1882-1944), English astronomer and physicist
Sir Frank Dyson (1868-1939), the English Astronomer Royal
Willem de Sitter (1872-1934), Dutch astronomer

BENDING LIGHT

Sir Isaac Newton's law of gravitation, published in 1687, states that every mass (every object composed of matter) attracts every other mass through gravitation. Gravitation is the tendency of every particle of matter in the universe to be attracted to every other particle. The more massive the bodies, the stronger the gravitational force between them, and the farther apart the bodies, the weaker the force between them.

Although this law was extremely successful, it seemed impossible that one body could exert a force on another body some distance away. To avoid this problem, scientists began to speak of a mass modifying the space around it by establishing a gravitational field. Another mass interacted with the field at its location but not directly with the first mass. How mass could establish a field was not explained.

Albert Einstein took gravitational theory a giant step forward. Taking a hint from the well-known result that all objects—no matter how massive—accelerate at the same rate when acted upon by gravity, Einstein deduced that gravitation and acceleration are equivalent in some fashion. He thought about how a beam of light might look to someone moving upward very quickly in an elevator. If the light beam were actually parallel with the floor as it entered the elevator, it would appear to bend downward slightly as the elevator accelerated. If acceleration and gravitation are equivalent, then gravity must also deflect light rays downward. Since light has no mass, as one normally thinks of it, this result was completely unexpected.

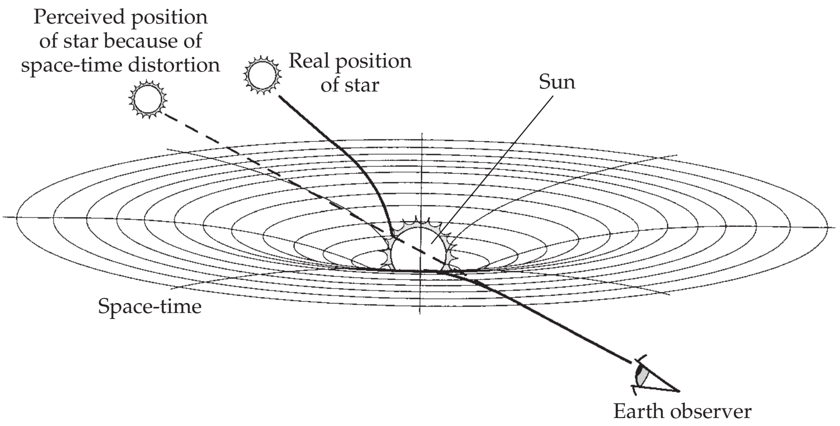
Einstein was perplexed about why a light beam took a curved path when traversing a gravitational field in an otherwise empty space. After all, the path taken by a light ray in an empty space is the definition of a straight line. Yet when is a straight line also a curved line? The answer is clear when the line is drawn on a curved surface such as a globe. For example, one may travel in a straight line along the Earth's equator and eventually return to the starting point without ever turning around.

CURVING SPACE-TIME

In 1915 and 1916, Einstein announced his general theory of relativity. This theory interpreted gravitation not as a force but as the result of curved space-time. Einstein's idea of space-time imagines the universe as being one unified "continuum" made up of four dimensions. These dimensions are length, width, and height—all of which are defined as "space"—and time. Within that space-time continuum, physical events occur and can be precisely located or mapped. A moving mass would produce a ripple in the curvature of space-time that would expand at the speed of light. By contrast, a weak gravitational field corresponds to almost no curvature of space-time, meaning that space-time is nearly flat.

Einstein suggested three effects that could be measured to see if his theory was accurate: the gravitational "redshift" of light, the advancement of the "perihelion" of the planet Mercury (the part of the planet's orbit that takes it closest to the Sun), and the deflection of starlight by the Sun. Einstein calculated that a ray of starlight just grazing the Sun should be deflected by only about 1.75 seconds of arc. Stars cannot normally be seen when the Sun is out, so Einstein suggested the measurement be made during a total solar eclipse.

THE CURVING OF SPACE-TIME



The Sun's gravity causes space-time to curve, which bends the star's light and makes it appear to be located where it is not.

Sir Frank Dyson, the British Astronomer Royal, sent out two expeditions to photograph the eclipse of May 29, 1919. Charles Rundle Davidson led one expedition to Sobral in northern Brazil, while Sir Arthur Stanley Eddington, an English astronomer and physicist, headed the other expedition to Príncipe Island in the Gulf of Guinea. Eddington's expedition took sixteen photographs of the eclipse. Comparing one of them with another photograph of the same star field taken six months earlier when the Sun was not present, Eddington was delighted to find the star images shifted by the same amount that Einstein had predicted.

On November 6, 1919, Dyson reported on the eclipse expeditions to a joint meeting of the Fellows of the Royal Society and the Fellows of the Royal Astronomical Society held at the Burlington House in London. Sir Joseph John Thomson, credited with the discovery of the electron and then president of the Royal Society, called Einstein's theory "one of the greatest achievements in the history of human thought."

IMPACT

After the confirmation of Einstein's general theory of relativity, the public was eager to learn more about him and his theory. Within one year, more than one hundred books on the subject had been published. Leopold Infeld, who cowrote a book with Einstein on relativity, suggested that the intensity of the public reaction was a result of the timing—World War I had just ended. "People were weary of hatred, of killing. . . . Here was something which captured the imagination . . . the mystery of the Sun's eclipse and of the penetrating power of the human mind." The general theory of relativity was a great achievement in which all humankind could take pride.

Einstein's theory of gravitation will continue to be tested under any circumstance that can be devised, for that is the nature of science. The general theory of relativity has passed the three tests Einstein suggested (gravitational redshift, perihelion advance of Mercury, and bending of starlight) as well as many more tests using radar, radio telescopes, pulsars, and quasars.

Einstein has shown that space is not simply an empty place. Space and time are not independent but must be considered together; furthermore, they are curved by mass. Perhaps most exciting is the picture of the universe that the theory predicts. Ironically, when Einstein's theory led to the conclusion that the universe was expanding, he rejected it at first, until 1929, when the American astronomer Edwin Powell Hubble offered experimental evidence to show that the universe is, in fact, expanding. Although the properties of the universe as a whole are not yet known, there is every reason to suppose that they will be consistent with the general theory of relativity.

See also Black Holes; Compton Effect; Electroweak Theory; Grand Unified Theory; Gravitation: Newton; Heisenberg's Uncertainty Principle; Mössbauer Effect; Photoelectric Effect; Quantum Mechanics; Relativity; Schrödinger's Wave Equation; Speed of Light; String Theory; Wave-Particle Duality of Light.

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—*Charles W. Rogers*

GRAVITATION: NEWTON

The Science: Newton's theory of universal gravitation provided the physical basis for the Copernican Revolution, establishing a mechanical universe governed by universal natural laws.

The Scientists:

Sir Isaac Newton (1642-1727), professor of mathematics at Cambridge University

Galileo Galilei (1564-1642), Italian mathematician who formulated laws of motion

Johannes Kepler (1571-1630), German astronomer who formulated new laws of the planets

Robert Hooke (1635-1703), English physicist and secretary of the Royal Society

Edmond Halley (1656-1742), English astronomer who applied Newton's laws to comets

John Locke (1632-1704), English philosopher who applied Newtonian ideas to social theory

From Copernicus to Newton

The publication of Sir Isaac Newton's theory of universal gravitation in his monumental treatise *Philosophiae naturalis principia mathematica* (1687; *The Mathematical Principles of Natural Philosophy*, 1729, better known as the *Principia*) marked the culmination of the scientific revolution. This revolution began with the 1543 publication by Nicolaus Copernicus of his heliocentric (Sun-centered) system of the planets (*De revolutionibus orbium coelestium*; *On the Revolutions of the Heavenly Spheres*, 1939; better known as *De revolutionibus*). Copernicus was unable to explain how the Earth could rotate on its axis and move around the Sun, however, and his system contradicted the philosophical and theological ideas of his time. Only a few astronomers began to develop his ideas, notably Galileo and Johannes Kepler.

In 1609, Galileo began to use the telescope for astronomy and discovered four moons that orbit Jupiter in much the same way that Copernicus described planetary motion around the Sun. He also introduced the concept of inertia, which proposed that motion is the natural state of an object, and described the constant acceleration of gravity. By 1619, Kepler had completed his laws of the planets, which described and correlated the speeds, sizes, and shapes of their elliptical orbits around the Sun. He made an unsuccessful attempt to explain how the Sun could cause the motion of the planets.

Sir Isaac Newton. (Library of Congress)

The mechanical concepts of Galileo and Kepler were further developed by French philosopher and mathematician René Descartes (1596-1650) and Dutch scientist Christiaan Huygens (1629-1695), but neither was able to account for planetary motion. In the latter half of the seventeenth century, Newton was able to correct and correlate these new mechanical ideas within a unified heliocentric system, but the emergence of this Newtonian synthesis involved many other scientists, and it is difficult if not impossible to assign credit properly.

Apples Fall, Moons Orbit

Newton was born on Christmas Day of 1642 at the farm of his mother's parents near Grantham in Lincolnshire, after his father had died. He was raised by his maternal grandparents and then enrolled in Trinity College, Cambridge, in 1661, to study mathematics under Isaac Barrow (1630-1677). After completing his degree in 1665, he returned home for nearly two years to escape an outbreak of the plague. During this isolation, he began to formulate his ideas about universal gravitation after making a connection between the fall of an apple and the motion of the Moon. His calculations revealed that the Moon in its orbit, which is sixty times farther from the center of the Earth than the apple, accelerates toward the Earth about 60^2 times more slowly than the falling apple. Thus, if gravity extends to the Moon, it diminishes according to an inverse square law.

After returning to Cambridge, Newton received his master's degree in 1668 and became Lucasian professor of mathematics a year later on the recommendation of Barrow. For nearly two decades, much of his work remained unknown beyond Cambridge.

Three Laws of Motion

In the meantime, Robert Hooke was trying to develop the idea that gravity was similar to magnetic attraction. In discussing the comet of 1664 with Christopher Wren, Hooke suggested that the gravitational attraction of the Sun caused the greater curvature of the comet's orbit near the Sun. After Huygens's formula for centrifugal force appeared in 1673, several scientists, including Hooke, Wren, and Edmond Halley, showed that circular orbits could be explained by a force that varied inversely as the square of the distance from the Sun. They were unable to show, however, that such an inverse square law could account for elliptical orbits.

In 1684, Halley visited Newton at Cambridge and posed the problem to him. Newton immediately replied that he had solved the problem, but he was unable to find his calculations. Three months later, he sent Halley a paper that successfully derived all three of Kepler's laws. Recognizing the importance of Newton's achievement, Halley returned to Cambridge and urged him to write a book on his new dynamics of the solar system. For nearly two years, Newton concentrated on writing his *Principia*, perhaps the single most important scientific treatise in the history of science.

When book 1 of three projected volumes reached the Royal Society in 1685, Hooke claimed that Newton had plagiarized his ideas. Newton was furious and proceeded to delete all references to Hooke. Although the society at first planned to publish the *Principia*, it was short of funds, so Halley agreed to pay the expenses himself. He received the completed manuscript in April, 1686, and it was published in the summer of 1687. In an introductory section entitled "Axioms or Laws of Motion," the three laws of Newton appear as the basis for his study of motion. The first two laws define inertia and force, based on the earlier work of Galileo and Descartes, while the third law introduces the idea that every force has an equal and opposite reaction.

UNIVERSAL GRAVITATION

In the first two books of the *Principia*, Newton derives a series of theorems from his three laws to describe motions for various kinds of forces. Using an inverse square force of attraction, he derives all three of Kepler's laws. In book 3, entitled *The System of the World*, he applies the hypothetical laws of the first two books to the universe as observed. The central concept is the law of universal gravitation, which generalizes the inverse square law to give the mutual attraction (F) between any two bodies as being proportional to the product of their masses (m and M) and inversely as the distance (R) between them. This is usually written as $F = G\,mM/R^2$ where G is the constant of universal gravitation.

Perhaps the single most important law in the history of science, the law of universal gravitation unifies terrestrial and celestial motions, assigning the same cause to the motion of projectiles and planets. Newton uses it to derive Galileo's law for falling bodies, calculates the bulge of the Earth's equator due to rotation and its effect on the acceleration of gravity, gives the first satisfactory explanation of the tides, and shows the requirements for an Earth satellite. He also accounts for the motions of comets, the slow wobbling of the axis of the Earth, and small deviations from Kepler's laws in the motions of the planets and the Moon.

A NEW FAITH

The collapse of the geocentric view of the universe had caused consternation and confusion, compounded by the idea of a moving Earth in infinite space. The Newtonian synthesis restored confidence in reason based on experience, giving birth to a new sense of optimism and progress in the eighteenth century that was later called the Enlightenment. It produced a new picture of the world as a great machine consisting of moving bodies subjected to universal laws in perfect order and harmony. Almost immediately it began to influence social theories.

Philosopher John Locke began the task of translating Newtonian science into political and philosophical theory. He argued that individuals are the atomic units of the state, which should be structured by self-evident natural rights such as life, liberty, and property, and the democratic ideals of equality and tolerance. He also suggested that the human mind is a *tabula rasa* (blank tablet) at birth, in which simple atomic ideas gained by sensation are correlated by the laws of association and reason to form complex ideas. Because reason must be based on experience, human knowledge is limited to the natural world, and humans can know God only through God's universal laws in nature, thus initiating Deism as a system of natural religion in which a clockmaker God is revealed only in nature.

Impact

In addition to its immeasurable impact on the future of physics and indeed all science, Newton's theory of universal gravitation marked the beginning of our modern view of the universe. Newton's ideas were brought to France by Voltaire, who, with his mistress the Marquise du Châtelet, wrote a popular account of Newtonian theory in 1738. In 1776, Locke's ideas were used as the basis of the American Revolution as expressed by Thomas Jefferson in the Declaration of Independence. In the same year, Scottish philosopher Adam Smith published the natural laws that govern economics. In Smith's theory of free enterprise, individuals are subject to market forces, requiring no interference because the market automatically adjusts to the forces of competition according to universal economic laws. Even the arts reflected the influence of Newton's theories, giving rise to formalized literary forms and musical styles.

See also D'Alembert's Axioms of Motion; Falling Bodies; Geologic Change; Gravitation: Einstein; Halley's Comet; Heliocentric Universe; Kepler's Laws of Planetary Motion; Medieval Physics; Pendulum; Quantum Mechanics; Relativity; Speed of Light; String Theory.

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—*Joseph L. Spradley*

GREEK ASTRONOMY

THE SCIENCE: Advances in Hellenistic astronomy were made when the ancient Greeks considered theories of an Earth-centered and a Sun-centered universe; the geocentric epicycle-on-deferent system proved to explain the most observations.

THE SCIENTISTS:

Heraclides of Pontus (c. 388-310 B.C.E.), Greek astronomer and head of Plato's Academy

Aristarchus of Samos (c. 310-c. 230 B.C.E.), Alexandrian astronomer and mathematician

Apollonius of Perga (c. 262-c. 190 B.C.E.), Alexandrian astronomer and mathematician

Eratosthenes of Cyrene (c. 285-c. 205 B.C.E.), Alexandrian astronomer, geographer, and mathematician

Hipparchus (190-after 127 B.C.E.), Greek astronomer and mathematician

Ptolemy (c. 100-c. 178 C.E.), Alexandrian mathematician and astronomer

THE GEOCENTRIC UNIVERSE

That Earth was spherical was known to learned Greeks of the fourth century B.C.E. by the shape of its shadow on the Moon during a lunar eclipse. The accepted view of the universe, however, was that Earth remained unmoving at its center, while around it in concentric spheres moved the seven planets of the ancient world: the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. About 340 B.C.E. at Athens, Heraclides of Pontus postulated that Earth rotated daily on its axis and that the Sun and the other planets revolved around the Earth. His work "On Things in the Heavens" is lost, so modern scholars do not know how he arrived at these conclusions.

This theory was the most advanced position taken by Greek astronomers by the time of Alexander the Great's conquest of Persia, which opened up a new world to scientists. At Babylon, Uruk, and Sippar, in Mesopotamia, fairly accurate observations of the movements of the heavenly bodies had been recorded and kept for centuries. Part of this mass of new knowledge became known to Greek scientists in the third century B.C.E. The Greeks also had their own means of acquiring data, for among the wonders of the new museum established in Alexandria as a sort of university was an observatory, a simple tower whose only instrument was a device without lenses for measuring the azimuth and angle of height of a star or planet.

EARLY SUN-CENTERED THEORIES

From these small beginnings, Greek astronomers reached astonishing conclusions. Aristarchus of Samos, invited to Alexandria, showed by the use of observations and of plane geometry that the Sun was some three hundred times larger than Earth. This estimate was a considerable improvement over the fifth century B.C.E. estimate that the Sun was about the size of the Peloponnesus. Aristarchus demonstrated his findings through geometrical proofs in his extant treatise *Peri megethon kai apostematon heliou kai selenes* (c. early third century B.C.E.; *On the Size and Distance of the Sun and the Moon*, 1913). Having established this fact to his own satisfaction, Aristarchus went on to deduce that the Sun, apparently because it was so much larger than Earth, must itself be the unmoving center of the cosmos, with Earth and the other planets revolving about it in circles, the Moon about Earth, and Earth rotating on its axis. The unmoving fixed stars were at an infinite distance. The book in which he explained his reasons for holding these bold hypotheses is lost and, because his system violated ancient authority and common sense and predicted a shift in the position of the stars that was actually too small to be observed at that time, his ideas were not widely accepted.

PLANETARY MOTION

Apollonius of Perga, on the other hand, made adjustments to the Earth-centered system that Greeks found to be more reasonable. He proposed the theory that the planets moved in epicycles around imaginary points on spheres called deferents. The points were also supposed to move in spherical orbits around Earth, but their centers were not Earth itself. The complex scheme accounted for variations observed in the speeds of the planets and their distances from Earth. It also explained why a planet sometimes seemed to be moving backward and why that "retrograde" motion coincided with the planet's brightest appearance.

EARTH'S CIRCUMFERENCE

Meanwhile, at Alexandria and Syene, Eratosthenes of Cyrene conducted an imaginative experiment during which he measured the circumference of Earth to within perhaps less than 2 percent. He noticed that at Syene on the Nile River (modern Aswān) at noon on the summer solstice, the Sun was exactly overhead. His proof began with the observation that then a vertical pole cast no shadow and the bottom of a deep well with vertical sides was completely illuminated. He arranged for an assistant at Alexandria to measure the angle cast by a vertical pole there at the same time on the same day. This angle measured one-fiftieth of a complete turn (7°, 12′), so he concluded that the distance between Syene and Alexandria was about one-fiftieth of the circumference of the Earth. Determining this land distance, Eratosthenes then calculated the circumference of the Earth as 250,000 stadia. This is an error of only about 250 miles (403 kilometers) according to some scholars' estimates of the length of a stade. He later changed his estimate to 252,000 stadia, although it is not known on what basis.

Eratosthenes actually made two mistakes: He wrongly assumed that Alexandria and Syene were on the same great circle, and his measurement of the distance between the two cities was inaccurate. Fortunately the two errors tended to cancel each other out, and his method was otherwise sound. Because he also knew that the distance from Gibraltar to India was only some sixty-nine thousand stadia, he made the remarkable prediction that another continental system would be found at the Antipodes by sailing west into the Atlantic Ocean or east into the Indian Ocean, an opinion held later by Christopher Columbus (1451-1506).

SOLAR STUDIES

Like most of these astronomers, Hipparchus of Nicaea said that he acted "to save the phenomena." Theoretically, he accepted the geocentric system, but he is most noted for numerous observational contributions. He measured the length of the solar year to within 6 minutes, 14.3 seconds, discovered the precession of the equinoxes, and cataloged more than 850 fixed stars together with their magnitudes into an accurate star map. He estimated the mass of the Sun as 1,800 times that of Earth and its distance as 1,245 Earth diameters, improvements on those figures of Aristarchus, whose system had otherwise faded away.

PTOLEMY'S SOLAR SYSTEM

The theories of the Hellenistic astronomers reached their culmination in Ptolemy. He added circular orbits and the concept of an equant point to the epicycle-on-deferent model of Apollonius, in part to resolve difficulties raised by the observations of Hipparchus. The equant point was as far from the true center of the universe as was the Earth. A planet in orbit swept out equal areas of its circle around the Earth in equal times with respect to the equant point. This system, which admittedly involved some complicated mathematics, remained influential into the Renaissance.

Ptolemy. (Library of Congress)

IMPACT

The researches of the Hellenistic astronomers laid the groundwork for modern astronomy, and also severed

PTOLEMY: A 1,500-YEAR LEGACY

Some historians maintain that the Alexandrian Greek mathematician Ptolemy merely plagiarized from Hipparchus; others have said that Ptolemy superseded Hipparchus and made the work of the earlier scientist superfluous. Whatever historical assessment is more correct, there is no doubt that Ptolemy's work in astronomy alone lasted until the great scientific achievements of Nicolaus Copernicus and Johannes Kepler in the sixteenth and seventeenth centuries.

Ptolemy used new instruments or improved on old ones to make his observations. In the *Mathēmatikē syntaxis* (c. 150 C.E.; *Almagest*, 1948), he employed the mathematical methods of trigonometry to prove that Earth was a sphere and went on to postulate that the heavens were also spheres and moved around an immobile Earth in the center of the solar system.

He dealt with the length of the months and the year and the motion of the Sun. He devised a theory of the Moon. He calculated the distance of the Sun and the order and distances of the planets, from Earth. Much of this was not new, not original; the *Almagest* was essentially a restatement of astronomical knowledge available three hundred years earlier. Ptolemy, however, was able to synthesize that scientific information into a system and to expound it in a clear and understandable manner. He was a teacher, and he taught well.

Ptolemy's contribution to mathematics was even more significant. Hipparchus had invented spherical and plane trigonometry for the use of astronomers. He then perfected this branch of mathematics so that, unlike his astronomical system, which was finally discredited, the theorems that he and Hipparchus devised form the permanent basis of trigonometry.

The *Almagest*, in which trigonometry was utilized to measure the positions of the Sun, Earth, Moon, and planets, was later translated into Arabic and then Latin. Along with his other works, it had an enormous impact on European thought through the Renaissance. It would be more than fourteen hundred years before his cosmology was challenged and proved wrong.

the association between astronomy and religion for the first time. Their investigations were intended to discover how the natural world worked for its own sake rather than to predict and interpret astronomic events as signs of a deity's intentions or wrath. While the hypothesis of a heliocentric universe was dismissed, the fact that such a hypothesis could be proposed, and that it was one of several competing hypotheses, indicates the radical change in worldview that had taken place within Greek science.

See also Brahe's Supernova; Copernican Revolution; Falling Bodies; Gravitation: Newton; Greek Medicine; Heliocentric Universe; Hydrostatics; Mayan Astronomy; Medieval Physics; Saturn's Rings; Scientific Method: Aristotle; Scientific Method: Bacon; Scientific Method: Early Empiricism; Speed of Light; Stellar Evolution.

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—*Samuel K. Eddy and Amy Ackerberg-Hastings*

GREEK MEDICINE

THE SCIENCE: Greek physicians developed the scientific practice of medicine, allowing reason to triumph over superstition in their search for knowledge about disease and its treatment.

THE SCIENTIST:

Hippocrates of Cos (c. 460-c. 370 B.C.E.), Greek physician associated with a medical school on Cos and a body of early medical writings

SENT BY THE GODS

One of the great accomplishments of the ancient Greek world was the development in the late fifth century B.C.E. of the scientific practice of medicine. Doctoring is as old as civilization itself, but only when the Greeks developed a purely rational way of looking at the world did medicine become a science.

Early Greek thought resembles that of other peoples: Illness, like all other facets of human life, was believed to be in the hands of the gods. Two of the brilliant masterpieces of Greek literature, Homer's *Iliad* (c. 750 B.C.E.; English translation, 1611) and Sophocles' *Oidipous Tyrannos* (c. 429 B.C.E., *Oedipus Tyrannus*, 1715), begin with plagues sent by an angered Apollo. The idea that supernatural forces are responsible for causing and for curing illness is also found in biblical writings, especially in the New Testament, where among the principal activities of Jesus are the casting out of demons and the healing of the sick. Curative powers were attributed to the pagan gods, and among the most common archaeological finds are votive offerings (many of which are models of the affected parts needing cure) and amulets. As attested by the *Oneirocritica* of Artemidorus (second century C.E.; *The Interpretation of Dreams*, 1644), Greeks also believed in the curative power of dreams. These nonscientific medical views were never abandoned by the ancient world but existed side by side with scientific medicine.

The Search for Natural Causes

The fifty years following the Persian Wars (which ended in 479 B.C.E.) saw spectacular intellectual development in the Greek world. Philosophy, which had begun with Thales of Miletus in the preceding century, came into its own. The natural philosophers of Ionia (now the western part of Turkey) sought an explanation of nature that did not rely on supernatural causation. They sought, instead, to show that all nature operated by the same set of physical laws. They offered different solutions to the questions of what the world was made from and how it functioned, and their theories were developed from arbitrary assumptions. Anaximenes of Miletus asserted air to be the basic element; Anaxagoras, a substance of indeterminate nature; Heraclitus of Ephesus, fire; and Empedocles, the four elements air, earth, fire, and water.

Because of the tremendous success of Greek mathematics, and of geometry in particular with its system of deductive reasoning based on very few axioms, there was a tendency among natural philosophers to seek systems of the physical universe that were deductive. Deductive reasoning produces the highest degree of certainty, and Aristotle is typical of the Greeks in affording the prize for scientific knowledge to sciences such as geometry and logic, sciences whose conclusions are reached through deductive reasoning from axioms and definitions. The results of the natural philosophers, however, were not satisfying: The material world does not yield to deductive reasoning. Medical writers of the fifth century B.C.E. and later very much wanted to separate themselves from the arbitrary axioms of the natural philosophers, and Celsus (fl. c. 178 C.E.) claims that Hippocrates was the first actually to do so.

Hippocrates and the Hippocratic School

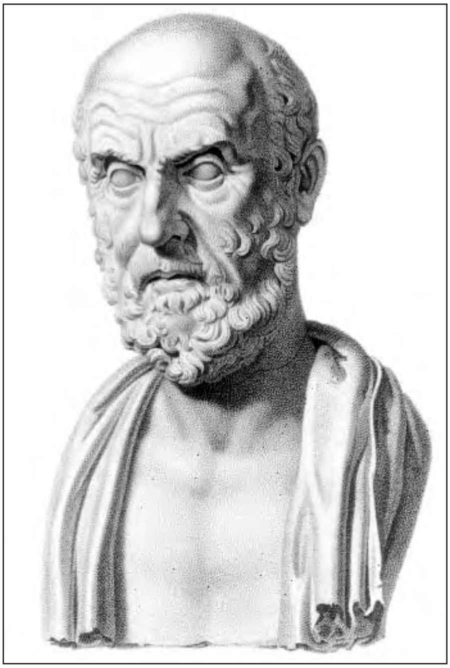
A key feature of Greek medical science was its rejection of gods and magic in the interpretation of disease. In popular Greek language, epilepsy was called the "sacred disease." The Hippocratic author who wrote the treatise *On the Sacred Disease* (English translation, 1923) claims that this disease is no more sacred than any other:

> I do not believe that the "Sacred Disease" is any more divine or sacred than any other disease, but, on the contrary, has specific characteristics and a definite cause. Nevertheless, because it is completely different from other diseases, it has been regarded as a divine visitation by those who, being only human, view it with ignorance and astonishment.

He continues by attacking as charlatans and quacks those who try to cure the disease by means of charms. He himself explains the disease as resulting from a discharge in the brain, and he supports this theory with the dissection of a goat that had suffered from the same disease. In addition to the physiological explanation, what is remarkable is that the author sees the same laws of nature operative in both humans and goats.

The man most identified with the development of Greek medicine is Hippocrates of Cos, who is said to have established a medical school on his native island. Virtually nothing is known of Hippocrates himself, though he is treated respectfully by writers of his era. Plato refers to him as a typical doctor, and Aristotle calls him the perfect example of a physician. Plato attributes to Hippocrates the revolutionary idea that in order to understand the body, it is necessary to understand it as an organic whole, that is, as a unity whose parts function together.

This organic view, however, is not explicitly stated in any of the extant Hippocratic books, which were most likely compiled in the fifth to fourth century B.C.E. The consensus of scholarly opinion is that there was no single author "Hippocrates." None of the fifty to seventy surviving books of the so-called Hippocratic corpus agrees with the views attributed in antiquity to Hippocrates. Moreover, the contents of these books are often at



Hippocrates. (Library of Congress)

odds with one another. Nevertheless, even if his actual works are not known, he appears to have been a real person and to have had (if Plato may be credited) a scientific outlook.

One of the important features of Greek medicine is the inquiry into the causes of disease. As in the case of natural philosophy, where a variety of views explained the universe, so in medicine there are various theoretical formulations, ranging from a single unitary cause for all disease to specific causes for each. The author of the Hippocratic work *Peri physon* (*On Breaths*, 1923), for example, thinks that because some breathing irregularity accompanies illness, breath is at the root of every disease. On the other hand, the author of *Peri archaiēs iētrikēs* (*Ancient Medicine*, 1849) criticizes physicians who do not distinguish between symptoms and causes. He also criticizes those who think that if a disease follows a certain action, the action was the cause of disease—a mistake known in philosophy as the *post hoc propter hoc* fallacy. An example would be eating a certain food and, if illness follows shortly after, assuming the food to be the cause of the illness.

Another feature of Hippocratic medicine, as detailed in the work *Prognostics* (translated into English in 1819), was the careful study of the progress of diseases. Once a physician had diagnosed a particular illness, he could tell the patient what to expect in the future as the disease ran its course. The ability to predict was certainly essential in establishing medicine’s status as a science.

Diagnosis and prognostication both incorporate the fundamental principle of Hippocratic medicine: that disease is a part of nature and acts in accordance with natural laws. Humans shared a common nature and diseases shared a nature that was regular and hence predictable; hence, a science of medicine was possible. For a disease to be treatable, what works for one patient had to work for another. Thus, medicine was obligated to analyze nature, catalog types of diseases, and define the appropriate treat-

The Hippocratic Oath

While not written by Hippocrates himself, the Hippocratic Oath is credited to his practices and has been followed by doctors and health professionals for more than two thousand years.

I swear by Apollo Physician and Asclepius and Hygieia and Panaceia and all the gods and goddesses, making them my witnesses, that I will fulfil according to my ability and judgment this oath and this covenant:

- To hold him who has taught me this art as equal to my parents and to live my life in partnership with him, and if he is in need of money to give him a share of mine, and to regard his offspring as equal to my brothers in male lineage and to teach them this art—if they desire to learn it—without fee and covenant; to give a share of precepts and oral instruction and all the other learning to my sons and to the sons of him who has instructed me and to pupils who have signed the covenant and have taken an oath according to the medical law, but no one else.
- I will apply dietetic measures for the benefit of the sick according to my ability and judgment; I will keep them from harm and injustice.
- I will neither give a deadly drug to anybody who asked for it, nor will I make a suggestion to this effect. Similarly I will not give to a woman an abortive remedy. In purity and holiness I will guard my life and my art.
- I will not use the knife, not even on sufferers from stone, but will withdraw in favor of such men as are engaged in this work.
- Whatever houses I may visit, I will come for the benefit of the sick, remaining free of all intentional injustice, of all mischief and in particular of sexual relations with both female and male persons, be they free or slaves.
- What I may see or hear in the course of the treatment or even outside of the treatment in regard to the life of men, which on no account one must spread abroad, I will keep to myself, holding such things shameful to be spoken about.
- If I fulfil this oath and do not violate it, may it be granted to me to enjoy life and art, being honored with fame among all men for all time to come; if I transgress it and swear falsely, may the opposite of all this be my lot.

Source: Translated from the Greek by Ludwig Edelstein in *The Hippocratic Oath: Text, Translation, and Interpretation* (Baltimore: Johns Hopkins University Press, 1943).

ment for each. Therefore, underlying assumption of ancient Greek medicine, as of modern medicine, was that the body functions best when its nature is maintained. Hence the physician's job is twofold: first, to do no harm—not to interfere with the body's nature but maintain it by means of preventive medicine, the principal forms of which are diet and exercise—and second, for those who are ill, to restore the body to its nature using therapeutic medicine.

Impact

From its birth in fifth century B.C.E. Greece, the scientific practice of medicine has been continually alive in the West. The centuries following Hippocrates saw advances in anatomy, as post mortem dissections became common. Specialized work in gynecology, orthopedics, and other branches of medicine continued and flourished. Later, in the Roman period, there followed major advances in public health, and the Romans bequeathed to posterity insights about hygiene, sanitation, water supplies, and public health.

See also Contagion; Galen's Medicine; Germ Theory; Human Anatomy; Microscopic Life.

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—*James A. Arieti*

HALLEY'S COMET

THE SCIENCE: Edmond Halley's successful prediction of the return of the comet named for him was a stunning confirmation of the correctness of Newton's law of gravity and his laws of motion. It also established that Comet Halley orbits the Sun, rather than coming from interstellar space and passing close to the Sun only once.

THE SCIENTISTS:

Edmond Halley (1656-1742), physicist and astronomer who discovered the orbit of the comet named for him

Sir Isaac Newton (1642-1727), member of the Royal Society, a great physicist and mathematician

Christopher Wren (1632-1723), successful architect, astronomer, and a founder of the Royal Society

Robert Hooke (1635-1703), experimental physicist and member of the Royal Society

Johann Georg Palitzsch (1723-1788), German astronomer who first sighted Comet Halley at its predicted return

A COFFEE BREAK

Following a meeting of the Royal Society of London in January, 1684, three of its members met in a coffeehouse for further discussion. They debated what a planetary orbit would be like if the attractive force of the Sun became weaker as the reciprocal of the square of the planet's distance from the Sun. Robert Hooke claimed that he had already determined that the orbit would be an ellipsis, but he offered no proof. He claimed that he would give his proof after others worked at it and found how difficult the problem was. Christopher Wren must have had his doubts, because he offered a reward of any book costing up to forty shillings to anyone who could offer a proof within two months. No one did.

The third member of the coffeehouse discussion was Edmond Halley, one of the great scientists of his day. In August, Halley visited Sir Isaac Newton at Cambridge to put the question about the planetary orbit to him. Newton immediately replied that the orbit would be an ellipsis (as Hooke had predicted), for he had worked the problem out years ago. Although he could not find his notes, he promised Halley that he would work out the proof again. When he received Newton's proof, Halley was so impressed that he urged Newton to expand his ideas into a book.

NEWTON'S *PRINCIPIA*

With Halley's frequent encouragement, Newton produced one of the greatest scientific books of all time, *Philosophiae naturalis principia mathematica* (1687; *The Mathematical Principles of Natural Philosophy*, 1729; best known as the *Principia*, 1848). Halley corrected and edited the *Principia* and then paid for its printing. Published in 1687, it contained Newton's law of gravitation and his three laws of motion. It was the key to understanding the motions of planets in the heavens and the falling of apples on the Earth, along with far more.

The book was published in sections, and in book 3, Newton collected his observations of the comet of 1680 and discussed the possibility that it was in parabolic orbit about the Sun. As book 3 neared publication, Hooke demanded that it include a preface acknowledging Hooke's priority in formulating the law of gravitation. Hooke was one of several who had suggested that gravity becomes weaker with the reciprocal of the square of distance from the Sun, but he never did anything with this idea. Newton was incensed and vowed to withhold publication of book 3, but Halley persuaded Newton to proceed with publication.

FLAMSTEED'S STAR MAP

Halley's diplomacy would be required again to stand between Newton and another scientist. John Flamsteed made it his life's work to produce a new map of the starry heavens. Appointed Astronomer Royal in 1675, he was expected to share his findings, but—always pleading that his measurements needed to be further refined—he had published almost nothing. Newton became president of the Royal Society in 1703. As such, he visited Flamsteed, who promised that his work would soon be ready. It was only after several more years, however, that Flamsteed gave a copy of his observations and a draft of his catalog to the Royal Society with the instruction that the catalog was not yet to be published.

More years passed with little progress, and Newton became quite abusive of Flamsteed. Finally, at Newton's request, Halley prepared Flamsteed's catalog for publication and had an incomplete version published in 1712 as *Historia coelestis Britannica* (complete version, in 3 volumes, published in 1725; partial English translation, 1982). The catalog extended the map of the northern skies from one thousand to three thousand stars. Astronomers were delighted, but although Halley had kept Flamsteed thoroughly informed and praised his work, Flamsteed was so enraged at Newton and Halley that he publicly burned all the copies he could get his hands

The Adventurous Edmond Halley

In 1684, Edmond Halley was a young scientist who had already made a name for himself as a precocious astronomer: He was the first to observe that the Sun rotated on an axis, during a trip to St. Helena in the South Seas. In 1680, during his Grand Tour of Italy and France, he had observed the comet that would bear his name. He had produced star catalogs and tidal tables, and he was trying to determine why Kepler's laws worked the way they did. Then, in April, his father's disfigured corpse was discovered near a riverbank; he had been missing for more than a month. Edmond's attention was redirected toward a bitter battle with his stepmother over the family estate.

(NASA)

Four months later, Halley was visiting Isaac Newton, who had solved the problems with Kepler's laws but had "misplaced" the solutions, supposedly worked out when Cambridge had been shut down during the plague of 1665. Halley began a campaign of diplomacy to get the eccentric and overly sensitive Newton to publish his results before someone else (Robert Hooke) derived the inverse square law and beat him to it. This was the genesis of Newton's *Principia* of 1687, published at Halley's expense.

In the meantime, Halley was supporting himself as a clerk at the Royal Society and working on a diverse array of projects, from determining the causes of the biblical Flood (which he unorthodoxly and dangerously placed earlier than the accepted date of 4004 B.C.E.) to making the connection between barometric pressure and altitude above sea level. He even calculated the height of the atmosphere, at a remarkably accurate 45 miles. Motivated by his persistent lack of money, Halley also designed various nautical instruments: a prototype diving bell, a device for measuring the path of a ship, and another device for measuring the rate of evaporation of seawater. He even prepared life-expectancy tables that became the basis for modern life insurance. Between 1696 and 1698, he became the deputy comptroller of the Royal Mint at Chester, a post offered him by Newton, who was then the warden of the Mint. Administration did not prove to be one of Halley's many talents, however, and Newton found himself having to defend his friend against the Lord's Commissioners.

In 1698, Halley set out on another expedition to the South Seas to study the magnetic variations of the Earth's compass. The journey was abandoned (with the ship's first lieutenant facing a court-martial on their return), but Halley tried again a year later with more success. He also went on a secret mission in 1701, about which little is known, traveling to France for the Admiralty on the pretext of yet another scientific expedition. In 1703, Halley became a member of the Council of the Royal Society in recognition of his work, and in the same year, he was appointed to the Savilian Chair of Geometry at Oxford, where he conducted his study of comets. It was around this time that he made the observation for which he became famous:

> Many considerations incline me to believe that the comet of 1531 observed by Apianus is the same as that observed by Kepler and Longomontanus in 1607 and which I observed in 1682. . . . I would venture confidently to predict its return, namely in the year 1758. If this occurs there will be no further reason to doubt that other comets ought to return also.

In 1719, on the death of John Flamsteed, Halley succeeded to the post of Astronomer Royal, a position he held until his death in 1742. The practicality and range of his interests made him a celebrity whose achievements far exceeded those for which he is remembered today. He did not live to see his comet, which was sighted on Christmas, 1758.

on. As a final twist in the affair, upon Flamsteed's death in 1719, Halley was appointed Astronomer Royal in his place.

HALLEY'S COMETS

About 1695 Halley began to collect detailed information on comets, both ancient and modern. While many reports were too vague to be of great use, others linked a comet's position in a constellation with a time. Using a method outlined in the *Principia* by which the five parameters defining an orbit could be deduced from three well-space observations, and after what he called "an immense labor," Halley published a list of orbital elements for twenty-four comets in 1705. It was first published in Latin by Oxford University, again in the Royal Society's *Philosophical Transactions*, and finally in English as *A Synopsis of the Astronomy of Comets*, also in 1705.

It included bright comets sighted between 1337 and 1683. Halley pointed out that the orbits of the comets of August 1531, October 1607, and September 1682 were so similar that they probably were the same comet. Many had supposed that comets traveled in straight lines or in parabolic orbits. In either of those cases, the comet would pass close to the Sun only once, and then vanish back into interstellar space. According to Halley's calculations, some cometary orbits were highly elongated ellipses, which meant that they orbited the Sun and should return again and again.

Halley calculated that the comet of 1682 should return near the end of the year 1758, and while Halley did not expect to live long enough to see the comet return, he hoped that if it did return at the predicted time the world would recall that its return had been predicted by an Englishman. As time passed, Halley tried to calculate the effects of Jupiter on the comet's orbit. Such effects, along with one unknown to Halley—the jetting of matter from the nucleus—make precise predictions of comets' orbits impossible. (Modern calculations, which take into account the effects of planets, show that the period of Comet Halley has ranged from 68 to 79 years over three millennia.)

Impact

After a long and productive life, Halley died in 1742. The year 1758 produced a flurry of activity as astronomers and mathematicians tried to refine calculations of where and when Halley's comet would reappear. It was first seen on Christmas evening by Johann Georg Palitzsch, a young German astronomer. Believing he saw a faint bit of fuzz about where the comet was expected, he set up his telescope and confirmed that it was a comet, most likely the comet. The news of Halley's successful prediction spread quickly. Within ten years it became known as Halley's comet, the first comet named for a person. Modern convention calls it Comet Halley.

The second (1713) edition of Newton's *Principia* included Halley's prediction. It stands as a remarkable prophecy of an event over fifty years in the future based on mathematical analysis of a physical model. Perhaps more important, it testifies to Halley's key role in the history of physics: Without Halley's urging, ongoing encouragement, and diplomacy, the *Principia* would not have been written. Once written, it would not have been published without Halley's corrections, editing, and funds, and once published, its worldwide acceptance would have occurred more slowly without Halley's prediction and its confirmation by the spectacular return of Comet Halley.

See also Brahe's Supernova; Cassini-Huygens Mission; Extrasolar Planets; Galileo Mission; Greek Astronomy; Heliocentric Universe; Herschel's Telescope; Hubble Space Telescope; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mars Exploration Rovers; Mass Extinctions; Moon Landing; Nebular Hypothesis; Oort Cloud; Planetary Formation; Pluto; Saturn's Rings; Solar Wind; Van Allen Radiation Belts; Voyager Missions.

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—*Charles W. Rogers*

HAND TRANSPLANTATION

THE SCIENCE: In 1999, a team of surgeons performed a successful hand transplant operation in Louisville, Kentucky, enabling the recipient to perform twisting and gripping functions and to feel sensation in the hand.

THE SCIENTISTS:

Warren C. Breidenbach, lead hand surgeon, head of surgical team

Jon W. Jones, Jr., lead transplant surgeon

A COMPLEX AND RISKY PROCEDURE

Hand transplant surgery is an extremely complex procedure. Unlike a solid organ transplant, a hand transplant involves multiple tissues: bones, tendons, cartilage, muscle, fat, nerves, blood vessels, and skin. After the difficult surgery is performed, a major possible complication is rejection, the natural response of the patient's immune system not to accept the alien hand.

An early hand transplant was attempted in 1964 in Ecuador in South America. The transplant was rejected within two weeks. By the 1980's, scientists had refined therapies using drugs called immunosuppressants, which prevent rejection of transplanted tissue or organs by suppressing the body's immune system. These drugs make organ transplants more practical, but carry risks for the recipient, including possibly fatal infections and an increased risk of developing cancer among other conditions. Because of the side effects of immunosuppressive drugs, transplants at first were limited to life-saving procedures, such as heart or liver transplants. Because a hand transplant is not a life-saving procedure, the risks were considered to outweigh the potential benefits.

Advances in immunosuppressive therapies in the 1990's allowed transplants to be performed for conditions that were not life-threatening. A multidisciplinary team of researchers and physicians, including transplant immunologists, hand surgeons, and micro-surgeons from Jewish Hospital in Louisville, Kentucky, and the University of Louisville developed a pioneering hand transplant program that was granted the first approval for a program of its kind in the United States in July, 1998.

The hand transplant procedure was primarily intended for healthy individuals who had experienced the loss of a hand or forearm because of trauma such as accident or amputation, rather than for congenital abnormalities (individuals born without a hand). Replacement hands would come from donors who met the criteria of total and irreversible brain damage, with the consent of their families.

A hand transplant operation was performed on an Australian man in Lyons, France, in September, 1998, by a group of doctors flown in from around the world. This was widely acknowledged to be the world's first hand transplant.

The First U.S. Hand Transplant

The first hand transplant procedure in the United States was performed at Jewish Hospital in Louisville, Kentucky, on January 24-25, 1999. The recipient was Matthew Scott, a thirty-seven-year-old paramedic from New Jersey. Scott lost his dominant left hand in a fireworks accident at the age of twenty-four. He had been using a prosthesis (artificial hand) and had relearned many activities necessary for daily living. However, an artificial hand does not allow twisting motions, has limited gripping ability, and has no feeling. The transplant included about two inches of forearm, to allow a functioning wrist. The donor was a brain-dead fifty-eight-year-old man.

The surgery lasted for fourteen hours and was performed by a team that included Warren C. Breidenbach, lead hand surgeon, and Jon W. Jones, Jr., lead transplant surgeon. After surgery, Scott was placed on a combination of immunosuppressive drugs at a reduced dosage to lower the risks of cancer and infection associated with antirejection medication. This lower dosage of antirejection drugs was innovative. Because the hand transplant was not a life-saving procedure, the drug treatment could be less aggressive than with organ transplant patients.

Scott remained in the Louisville area for three months, for follow-up bi-

The Ethics at Hand

Hand transplantation presents an ethical issue that characterizes much of modern medicine: Do the benefits of a hand transplant outweigh the risks? Advocates of transplantation say that the improvement in daily living and the increased motion, function, and feeling in a transplanted hand as opposed to a prosthesis—coupled with the psychological benefits of a warm human part—make the risk of immune suppression worth it. Opponents of the procedure question the ethics of performing a procedure with potentially life-threatening risks in a case where a life is not threatened. James Herndon of Harvard Medical School, who questions the ethics of the hand transplant operation, suggests that the procedure be limited to patients who are already taking immunosuppressive drugs for a life-threatening problem or those who have lost both hands, while the medical community waits for further advances in immunosuppressive therapy.

In November, 2003, Drs. W. P. Andrew Lee, Dennis B. Phelps, and David M. Lichtman articulated the position of the American Society for Surgery of the Hand as follows:

> Preliminary clinical experience based on fourteen patients has underscored the importance of patient motivation and compliance, intensive hand therapy, and close post-transplantation surveillance. Acceptable functional and cosmetic outcomes, particularly for bilateral amputees, have been achieved and are similar to hand replantation at equivalent levels. However, major return of two-point discrimination or intrinsic muscle function is not to be expected.
>
> At present, ongoing heavy immunosuppression is required for allograft survival with unknown long-term risks. Although there have been no life-threatening adverse events, complications include allograft rejection and loss, tissue necrosis, and osteomyelitis. Furthermore, the effects of chronic rejection on the allograft function and survival have not yet been determined. Because there are many significant contraindications to both the surgical procedure and the immunosuppressive protocol, careful preoperative, medical and psychological screening is mandatory.

Source: Quotation from "Hand Transplantation: Current Status." First prepared September, 2001, and revised November, 2003. American Society for Surgery of the Hand. Available at www.assh.org. Accessed September, 2005.

opsies and laboratory evaluations to monitor immunosuppressive drug therapy, to watch for possible episodes of rejection, and to begin intensive physical therapy. A year after surgery, he had good hand function, range of motion, grip, and sensation, allowing him to tie his shoes, turn the pages of a newspaper, and throw a baseball, among other actions. He could sense hot and cold and feel pain. He would continue watching for rejection and monitoring of the effects of immunosuppressive drugs for the rest of his life.

Impact

The most significant impact of Scott's hand transplant surgery in January, 1999, is the advance in immunosuppressive drug therapy that made its success possible. Many people felt that the hand would be rejected almost immediately, or that Scott would not be able to live with the risk of infection and side effects of the antirejection drugs.

Clint Hallam, the Australian man who received the hand transplant in France in 1998, did not fare as well. He began having difficulties with rejection and stated dramatically that he had no feeling in his "dead man's hand." Eventually, the new hand was amputated by one of the surgeons on the transplant team. The transplant team stated that Hallam had not followed through with the antirejection drug therapy nor did he remain under the regular care of his physicians after the transplant.

Subsequent hand transplants have been considered successful, including double hand transplants for individuals who have lost both hands in accidents. However, the hand transplant procedure is controversial. Discussion centers on whether hand transplants are ethical or wise, because limb transplants, unlike heart or liver transplants, are not essential to life, and the drugs that must be taken to prevent rejection by the immune system carry the risk of serious side effects. A transplant recipient must take these immunosuppressive drugs for the rest of his or her life.

See also Blue Baby Surgery; Heart Transplantation.

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—*Susan Butterworth*

HEART TRANSPLANTATION

THE SCIENCE: In December, 1967, Dr. Christiaan Barnard transplanted the first human heart, opening a new era in medicine.

THE SCIENTISTS:

Christiaan Barnard (1922-2001), South African heart surgeon

Louis Washkansky (1914-1968), the recipient of the first transplanted human heart

A HEART FOR LOUIS

In 1967, many surgeons in medical centers throughout the world were on the verge of performing the first human heart transplant. Since 1954, when the first successful kidney transplant had been achieved, surgeons had performed innumerable heart transplants on dogs, calves, and monkeys in preparation for the first attempt on humans. Major obstacles had to be overcome. For example, the immune systems of heart recipients tended to reject the new hearts. This problem had not yet been solved. There were also moral, legal, and emotional problems with transplanting a heart into a human.

Nevertheless, on December 3, 1967, Christiaan Barnard and the thirty members of his team transplanted the heart of Denise Darvall into the body of Louis Washkansky at the Groote Schuur Hospital in Cape Town, South Africa. Even though Washkansky lived for only eighteen days after the operation, a whole new medical frontier had been entered.

Washkansky had suffered several major heart attacks since 1960. His coronary vessel, which sends blood to the heart muscle, was almost completely destroyed, and both ventricles (the lower chambers of the heart) were also failing.

Beginning in November, 1967, Barnard's team got themselves and Washkansky ready for the transplant. Marthinus Botha, the immunologist, would have to make sure that the new heart matched Washkansky's body. Arderne Forder, a bacteriologist, looked for any dangerous bacteria, not only in Washkansky but in all the team members as well. Washkansky was washed many times to remove any germs, and a germ-free recovery room was prepared. The biggest risk was that the doctors might not be able to tell the difference between rejection of the new heart and an infection.

Washkansky's health was getting worse every day. On November 23, a possible heart was found, but it failed before the parents of the donor could be reached for permission. On the afternoon of December 2, twenty-five-year-old Denise Darvall and her mother, Myrtle, were hit by a car as they were crossing a street. Myrtle Darvall was killed instantly. Denise Darvall was taken to Groote Schuur Hospital, but her skull was fractured in many

CHRISTIAAN BARNARD: TAKING RISKS

Dr. Christiaan Barnard was born in South Africa, where his father was a missionary in the hot, dry Karroo scrubland. As a boy, he recalled pumping the bellows for the mission's church organ while his mother played it and his father preached for a "coloured" (mixed-race) congregation. The system of apartheid—a severe, brutal form of segregation—was in place and enforced by the Nationalist Party, which ran the government. Barnard's father taught his son, however, that the government was wrong and that he should not tolerate prejudice.

(Library of Congress)

When young, Barnard was more interested in mechanical engineering than medicine, but his interests took a turn and he became a general practitioner, later studying surgery at the University of Minnesota. One day he was asked to work on a heart-lung machine and became fascinated by open-heart surgery. He returned to South Africa to open his own cardiac surgery unit. He recalled that his father had once shown him a cookie with a boy's teeth marks in it; they were those of one of Barnard's brothers, who died when only a few years old: "I realized that he died of a heart problem and that had he lived in my time as a cardiac surgeon I probably could have cured him."

Barnard maintained that the 1967 heart transplant "wasn't such a big thing surgically. The technique was a basic one. The point is that I was prepared to take the risk. . . . My philosophy is that the biggest risk in life is not to take a risk."

Source: Quotations from an interview with Peter Hawthorne published in *Time* magazine (© 2005 Time Inc. and Time Warner Publishing).

places, and the doctors knew there was no hope. By 5:30 P.M., her brain was dead. A machine was used to keep her heart beating, and after a few hours Botha found that her heart would match with Washkansky's. Edward Darvall, Denise's father, gave permission for her heart to be given to Washkansky.

EIGHTEEN DAYS OF SUCCESS

By 1:30 A.M., on December 3, the team was ready. Washkansky was anesthetized in one room, while in another room Darvall's heart was taken off the machine. Fifteen minutes later, her heart stopped beating. It was then chilled to keep it from decaying, and a drug was used to prevent the blood from clotting. Darvall's heart was then removed from her body by Barnard and his surgical team.

Barnard then prepared to remove Washkansky's diseased heart. There was a moment of crisis when he found that one of the arteries was hardened, making it difficult to attach the heart-lung machine that would keep the patient alive while his heart was taken out. While the team hurried to try to connect the machine, Washkansky's blood spilled out on the floor.

When everything was ready, Washkansky's heart was removed by Barnard. Meanwhile, Darvall's heart was bathed in Washkansky's blood. Two hours later, the heart was fully connected. The next major problem came in trying to get the heart to beat. Almost an hour later, at 6:24 A.M., the first human heart ever transplanted began to beat strongly in Washkansky. The patient was rushed to the germ-free recovery room and given drugs to stop his body from rejecting his new heart.

Once the press was told of the operation's success, reporters began climbing trees to peek inside Washkansky's window. Some tried to go into the sterile room, and others demanded press conferences with Barnard and his team.

Washkansky was known as a brave, feisty, uncomplaining person, but for the next eighteen days, his health went up and down. The doctors had weakened his immune system so that, even though it tried, it could not reject the new heart. Unfortunately, it was also too weak to fight germs. He was exhausted by the drug and radiation treatments, and his heart raced.

By December 9, though, he felt better. His oxygen tent was removed, and he was given sterilized newspapers and a radio. His heart was working normally, and he was allowed visits from adult family members. He was even allowed to sun himself on the balcony.

The struggle began again on December 15, with weakness, a rising fever, and chest pains. The thirty-member team met for long hours every day, trying to figure out whether his body was fighting an infection or his new heart. Finally, on December 21, Washkansky died of bacterial pneumonia in both lungs. After his death, there was no sign that his body had rejected Darvall's heart. The doctors had mistakenly fought too hard against rejection and not hard enough against infection.

Washkansky's death was a crushing blow to Barnard. Yet he and his team had learned that heart transplants were possible and quickly began planning ways to use this hard-won knowledge to save others.

Impact

It had been expected that the first heart transplant would take place in the United States, where doctors had been preparing for it for decades. Barnard took the knowledge he had learned from the Americans and with courage—some say arrogance—went ahead and did a transplant. As soon as he did, other doctors, who had been waiting cautiously, followed his lead. Five heart transplants took place in the next two months, and 170 in the next three years.

However, of the first 170 transplant operations, 50 recipients died from rejection of the heart, 30 died from infections, and others died for other reasons. After four tries, Barnard gave up. Almost no transplants were done during the 1970's; the rejection problem needed to be taken care of first.

In 1969, Jean-François Borel discovered cyclosporine, which not only killed any immune cell but also killed the T lymphocytes that spread to fight any foreign tissue, such as a transplanted heart. Cyclosporine became widely used after 1983, when it was finally approved by the U.S. Food and Drug Administration, and doctors once again began transplanting hearts.

Although many legal, moral, and emotional questions surrounding heart transplants remained, and although the numbers of people waiting for hearts outnumber the numbers of available hearts that are usable, heart transplantation was established by the end of the twentieth century as a medical procedure, in large part thanks to the actions of Barnard and his team. By 2003, more than two thousand transplant operations were being undertaken annually in the United States alone.

See also Blue Baby Surgery; Hand Transplantation; Immunology.

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—*Grace Dominic Matzen*

HEISENBERG'S UNCERTAINTY PRINCIPLE

THE SCIENCE: Werner Heisenberg showed that, in the new quantum theory, objects could not be thought of as having both location and motion at the same time.

THE SCIENTISTS:
Werner Heisenberg (1901-1976), German physicist
Niels Bohr (1885-1962), Danish physicist
Arnold Sommerfeld (1868-1951), German physicist
Max Born (1882-1970), German physicist

THE SATURNIAN ATOM

After the end of World War I in 1918, the "Saturnian" model of the atom made impressive gains. This model was named after the planet Saturn because the idea of negatively charged electrons orbiting a positively charged nucleus resembled the satellites that orbit the planet Saturn.

Proposed by Niels Bohr in 1913, the Saturnian model was especially good at predicting the colors (frequencies) of light emitted from atoms whose electrons "jumped" from one orbit to another. Bohr thought that electrons orbited nuclei only in specific orbits that have a constant energy level. When an electron "jumped" to an orbit of lower energy, energy was radiated; when it "jumped" to an orbit of higher energy, energy was absorbed.

Along with the successes of Bohr's theory, however, came an increasing number of puzzles. In the laboratory, the behavior of the more complicated atoms did not follow the model's predictions. For example, atoms with many electrons, or atoms in a magnetic field, emitted light of the "wrong" colors, or frequencies. In theory, the model could not account for the stability of the atom. A disturbance of a moon of Saturn would wreck its orbit, but the electrons in a disturbed atom would stubbornly keep to their Bohr orbits. In the postwar years, many scientists, including Bohr himself and the young German physicist Werner Heisenberg, tried to refine the Saturnian model to repair its defects.

HEISENBERG'S QUANTUM MECHANICS

In 1925, Heisenberg shuttled from one university to another, trying to get help in understanding electron theory. He often attended seminars by the great physicists: Albert Einstein in Berlin, Bohr in Copenhagen, and particularly Arnold Sommerfeld in Munich. Sommerfeld, an expert in both atomic theory and astronomy, taught Heisenberg methods of describing satellites in complicated orbits. By tinkering with the equations for possible electron orbits, Heisenberg was finally able to match the jumps of the electrons with the colors of light emitted by the atoms.

He took his work to his adviser, Max Born. Along with Pascual Jordan, the two of them published the now famous treatise "Matrix Mechanics" in 1915. Heisenberg was awarded the Nobel Prize in Physics in 1932 for his discovery, and Born won the prize in 1954 for applying the theory to electrons in metals.

These ideas were quickly combined with the wave-mechanical theory of Erwin Schrödinger to create "quantum mechanics." The new theory, however, had some puzzling features. One problem arose when Heisenberg calculated either the speed of the electron or its location in a piece of its orbit. If he chose a speed and calculated a position, the result he obtained was different from the result he obtained if he first picked

Werner Heisenberg. (The Nobel Foundation)

EINSTEIN'S CERTAINTY

At the Fifth Solvay Congress in Brussels in 1927, Werner Heisenberg announced his famous uncertainty (or indeterminacy) principle, which clarified the theoretical limitations imposed by quantum mechanics upon certain pairs of variables that constantly interact with each other, such as position and momentum. He asserted that in their new classifications as conjugate observables (an interrelated pair of measurable quantities), indeterminacy dictated that no quantum mechanical system could simultaneously possess an exact position and exact momentum. Although indeterminacy affects all phenomena, large and small, its significance is usually confined to subatomic particles.

At the conference, Albert Einstein, the famous theoretical physicist and author of the theory of general relativity, raised serious objections. He believed that a fundamental theory should predict precise values, not averages. Einstein and Neils Bohr argued about the validity of Heisenberg's ideas for the rest of their lives. The issue was philosophical, not experimental, because Heisenberg's methods worked very well in practical electronic calculations. The argument was over the question of principle. Was uncertainty merely a part of Heisenberg's method, which would someday be replaced by a more accurate method, or was it a fundamental fact of nature? Einstein argued against uncertainty as an underlying principle of the universe: "I shall never believe that God plays dice with the world."

the same position and then calculated the speed. This meant that the theory required a mathematics in which $x \times y$ does not give the same result as $y \times x$.

Heisenberg and others soon expanded quantum mechanics to cover more complicated problems. They also argued that the theory did not apply only to electrons. In fact, they could describe any object—even a planet—by using quantum mechanics. In cases of objects much larger than atoms, however, the differences between quantum calculations and ordinary physics were far too slight to be measurable.

INDETERMINACY

In every case, the peculiar "indeterminacy" (as Heisenberg called it) of the simultaneous position and speed was an inevitable result of the calculated motion. Born argued that this meant that numbers calculated in this way must represent only "average values." Heisenberg came to believe that he had discovered a fundamental principle of physics: The simultaneous speed and motion of an object cannot be measured precisely because they do not even "exist." It was in talking to Bohr that Heisenberg first thought of a reason for this. Perhaps only those things in nature exist that can be described by physics. If that is true, then there will always be uncertainty regarding the speeds and positions assigned to theoretical objects. The predicted values will only be averages; therefore, measuring these quantities will be difficult even in identical experiments.

Impact

With the development of radar after World War II ended in 1945, it became possible to make extremely fast and accurate measurements of electron motions. In this new era of electronics, Heisenberg's principle became noticeable. In some cases, the formula made it possible to imagine electrons "avoiding" locations within a metal or a semiconductor. Transistors, tunnel diodes, and other devices of "quantum electronics" now often show indeterminacy as their electron currents flow in places and in ways that are impossible to imagine using classical physics.

Heisenberg extended his principle to apply not only to position/motion "pairs" but also to an indeterminate energy-change/time-elapsed "pair." It is now possible to imagine very fast particles that require very high energy changes to dislodge them from nuclear interiors. Using Heisenberg's principle, modern particle theorists have explained the behavior of subatomic forces, which have been confirmed spectacularly in high-energy physics and cosmology.

Despite Einstein's objections, Heisenberg's principle is now regarded as a basic principle of nature. Calculations by John Sebastian Bell in 1964 and experiments conducted by Alain Aspect in 1982 have confirmed that Heisenberg did indeed discover a principle of nature.

See also Compton Effect; Electrons; Quantum Mechanics; Schrödinger's Wave Equation; Wave-Particle Duality of Light.

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—*Peter D. Skiff*

HELIOCENTRIC UNIVERSE

THE SCIENCE: In 1632, Galileo confirmed Copernicus's heliocentric model of the solar system, which led to an inevitable clash between scientific inquiry and the traditional geocentric beliefs of Aristotelian philosophy and the established Church.

THE SCIENTISTS:

Galileo Galilei (1564-1642), Italian mathematician who accepted Copernicus's theories

Tycho Brahe (1546-1601), Danish astronomer who modified the geocentric system of planets

Nicolaus Copernicus (1473-1543), Polish astronomer who developed the heliocentric system

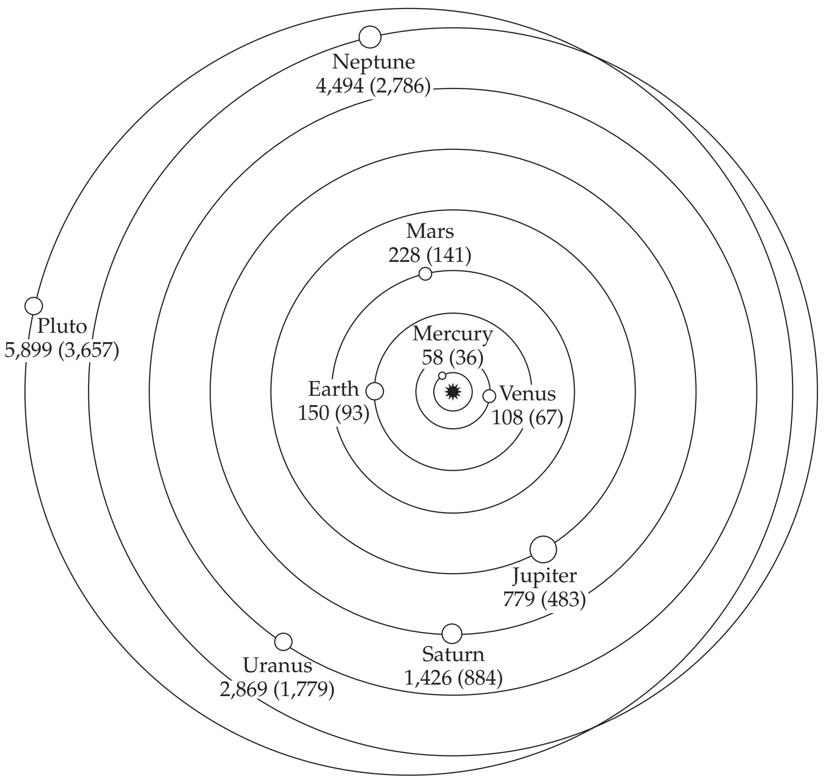
Johannes Kepler (1571-1630), German astronomer who formulated new laws of planetary motion

Sir Isaac Newton (1642-1727), English physicist whose laws of motion supported the heliocentric system

THREE SYSTEMS

Although the publication of Galileo's *Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano* (1632; *Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*, 1661) was condemned by the Roman Catholic Church and placed on the Index of Forbidden Books, it fueled the Scientific Revolution and led to increasing acceptance of the heliocentric (Sun-centered) system of Nicolaus Copernicus, culminating in the Newtonian synthesis and the eighteenth century Enlightenment. The classic Greek system of the planets was completed by Ptolemy in about the

Distances of the Planets from the Sun in Millions of Kilometers (Miles)



year 150. This Ptolemaic system was geocentric (Earth-centered) and could accurately account for the positions of the planets by a complicated combination of circles known as epicycles. It was further developed by Arabic scientists and was incorporated into Catholic theology by Thomas Aquinas in the thirteenth century.

The heliocentric system was developed by Copernicus and published in 1543 as *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*, 1939; better known as *De revolutionibus*), in an attempt to simplify astronomy. However, it still required complicated combinations of circles to achieve the accuracy of the Ptolemaic system, and it provided no explanation of how Earth could rotate on its axis and revolve around the Sun. The annual revolution of Earth about the Sun implied that the positions of the stars should shift as Earth moves, but no such shifting of the stars was observed. Because motion of the Earth also seemed to contradict the philosophical and theological ideas of the time, only a few astronomers gave serious consideration to the Copernican system.

The last great astronomer before the introduction of the telescope was Tycho Brahe. By building very large instruments for measuring celestial positions, he increased the accuracy of astronomy about ten times over that of the Greeks. However, he was still unable to measure the annual shifting of the stars required by the Copernican system. He recognized the mathematical advantages of heliocentric astronomy but could not accept the idea of a moving Earth. Thus, he proposed a compromise system in which the Sun revolved around a stationary Earth, but all the other planets revolved in circular orbits around the Sun. The Tychonic system gained a significant following among astronomers, so that by the end of the sixteenth century there were three competing systems of the world: the Ptolemaic (geocentric) system, the Copernican (heliocentric) system, and the Tychonic (combined geo-heliocentric) system.

Elliptical Orbits

The two great champions of the Copernican system at the beginning of the seventeenth century were Galileo and Johannes Kepler, even though neither was able to detect direct evidence of the Earth's motion. Kepler became Tycho's assistant in 1600. A year later, Tycho died and Kepler began to develop the Copernican system using the accurate data Tycho had accumulated. In 1609, he published his analysis of the orbit of Mars in his *Astronomia nova* (*New Astronomy*, 1992), which established that the planets move in elliptical orbits. This simplified the Copernican system, because only a single ellipse was required to account for the motion of each planet rather than a complicated combination of circles.

Although Galileo corresponded with Kepler and shared many of his heliocentric views, he never endorsed elliptical orbits and retained a strong emphasis on the importance of circles in astronomy. Galileo was born at Pisa in northern Italy in the same year that Michelangelo died. His father, Vincenzo Galilei, was a musician whose book *Dialogo della musica antica, et della moderna* (1581; *Dialogue of Ancient and Modern Music*, 2003) was used by Kepler in his attempt to apply the principles of harmony to astronomy. In 1581, Galileo went to the University of Pisa in the Republic of Venice to study medicine, but after four years he had to drop out for lack of funds. After further private study of mathematics, he was appointed as a professor of mathematics at the University of Pisa in 1589. Conflict with Aristotelian colleagues led him to resign after three years and take an appointment at the University of Padua, where he concentrated on the study of motion.

THE TELESCOPE: NEW VISTAS

Galileo interrupted his work on motion in July of 1609 when word reached Venice about a magnifying tube made with a combination of lenses by a Dutch lens grinder, Hans Lippershey. After hearing these reports, Galileo ground lenses and tried several arrangements before finding a combination that gave a magnifying power of about thirty. When he presented one of his telescopes to the Venetian senate, they renewed his professorship for life and doubled his salary. He loaned another telescope to Kepler, who worked out the geometry of image formation by two lenses. Galileo recognized that the primary value of the telescope was in astronomy, opening up new vistas of space. Few of his contemporaries realized how valuable this would be for astronomy, and some even opposed its use as deceitful. In 1610, Galileo published his initial discoveries, including the four largest moons of Jupiter, in a small booklet called *Sidereus nuncius* (*The Sidereal Messenger*, 1880; also known as *The Starry Messenger*). This success led to his appointment as chief mathematician of the University of Pisa and recognition in Rome by Pope Paul V.

Galileo's successes with the telescope led him into a bolder polemic for the Copernican system, bordering on propaganda. Although none of his observations provided conclusive evidence for a moving Earth, taken together they began to turn the tide toward its wider acceptance.

A DANGEROUS POSITION

Resistance to Galileo's ideas began to build. In 1616, he was warned by the Holy Office in Rome that the idea of the moving Earth was expressly condemned. After the election of Pope Urban VIII in 1623, Galileo went to Rome, where he had several audiences with the new pope and received permission to write about the motion of the Earth as a scientific hypothesis. During the next six years, he worked on his masterpiece, the *Dialogue Concerning the Two Chief World Systems*. Supposedly an evenhanded comparison of the Copernican and Ptolemaic systems, it proved a highly persuasive book in favor of the heliocentric system while largely ignoring the Tychonic system. To make matters worse for him, Galileo wrote it in vernacular Italian, accessible to a wide audience, instead of the usual scholarly Latin.

Galileo submitted his manuscript to the chief censor at Rome in 1630. After several delays and minor revisions, permission was finally granted in both Rome and in Florence, where it was published in 1632. The closing paragraph of the dialogue included a statement suggested by Pope Urban that the Copernican theory was "neither true nor conclusive" and that no one should "limit the divine power and wisdom to one particular fancy of his own." Unfortunately, Galileo put these words in the mouth of the character in his dialogue to whom he had assigned the Aristotelian viewpoint, Simplicio, who is obviously characterized as a close-minded traditionalist. Sale of the book was stopped and Galileo was summoned to Rome.

In the winter of 1633, the gravely ill Galileo was carried by litter to

A Galilean Dialogue

In Dialogue Concerning the Two Chief World Systems *(1632), Galileo uses the dialectical form of Plato to develop his arguments through the voices of three persons: Simplicio, the traditional Aristotelian, who subscribes to the Ptolemaic universe; Salviati, the scientist, who argues for the Copernican universe; and the open-minded Sagredo. This exchange is typical of Galileo's art of persuasion: The "neutral" Sagredo finds the Copernican Salviati's arguments persuasive, whereas Simplicio relies on dogma rather than his own observation and understanding.*

Sagredo: For my part, so far as my senses are concerned, there is a great difference between the simplicity and ease of effecting results by the means given in this new arrangement [the heliocentric solar system] and the multiplicity, confusion, and difficulty found in the ancient and generally accepted one. . . . I must confess that I have not heard anything more admirable than this, nor can I believe that the human mind has ever penetrated into subtler speculations. I do not know how it looks to Simplicio.

Simplicio: If I must tell you frankly how it looks to me, these appear to me to me some of those geometrical subtleties which Aristotle reprehended in Plato when he accused him of departing from sound philosophy by too much study of geometry. . . .

Salviati: . . . please tell me what absurdities or excessive subtleties make this Copernican arrangement the less plausible so far as you are concerned.

Simplicio: As a matter of fact, I did not completely understand it, perhaps because I am not very well versed either in the way the same effects are produced by Ptolemy. . . . Aristotle's axiom that to a simple body only one simple motion can be natural appears to be sufficient. Here three movements, if not four, are assigned to the Earth, a simple body. . . . My mind feels a great repugnance to this.

Source: Excerpted from Galileo Galilei, *Dialogue Concerning the Two Chief World Systems*, translated by Stillman Drake, annotated and condensed by S. E. Sciortino. Available at http://www.math.dartmouth.edu/~matc/Readers/renaissance.astro. Accessed September, 2005.

Rome. After trial by the Inquisition, in which he vigorously denied that he had intended to teach the truth of the heliocentric system, he was judged guilty and the *Dialogue Concerning the Two Chief World Systems* was totally forbidden. He was then sentenced to house arrest at his country estate near Florence, with no visitors allowed except by special permission.

IMPACT

Although Galileo lost his eyesight in the last decade of his life, he returned to the study of matter and motion, which was eventually developed by Sir Isaac Newton to establish the physical basis for the Copernican system. Galileo's astronomical observations—and, perhaps equally important, his clear articulation of the heliocentric solar system in the face of established authority—paved the way for the acceptance of the new cosmology. Galileo was certainly among those to whom Newton would later refer when he stated, "If I have seen further than other men, it is because I stood on the shoulders of giants."

See also Brahe's Supernova; Copernican Revolution; Falling Bodies; Gravitation: Newton; Greek Medicine; Herschel's Telescope; Kepler's Laws of Planetary Motion; Mayan Astronomy; Medieval Physics; Saturn's Rings; Scientific Method: Aristotle; Scientific Method: Bacon; Scientific Method: Early Empiricism; Speed of Light; Stellar Evolution.

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—*Joseph L. Spradley*

HERSCHEL'S TELESCOPE

THE SCIENCE: In 1787 William Herschel completed construction of a 40-foot-long telescope, which he used to discover two of Saturn's moons and to observe nebulae and identify galaxies like the Milky Way. Herschel's telescope was the largest in the world for more than fifty years.

THE SCIENTISTS:
William Herschel (1738-1822), German-born astronomer
Caroline Lucretia Herschel (1750-1848), astronomer who assisted her brother William

AMATEUR ASTRONOMERS

In 1773, William Herschel, a German musician living in Bath, England, began to spend more and more time studying astronomy. He read books on astronomy and purchased a quadrant, an instrument used to measure angles between the stars, as well as some lenses and mirrors. His first telescope is believed to have been a small, compact reflector of the type designed by the Scottish astronomer James Gregory. This telescope, however, was too small to satisfy Herschel. He wanted a bigger instrument, which would gather more light and allow him to see fainter stars, but the large lenses or mirrors were very expensive. Herschel therefore decided to make his own.

By 1774, he had developed techniques to cast and polish mirrors superior to any that had been made previously. Herschel constructed more than four hundred telescopes, which he used to observe the planets and their moons, the stars, and unusual objects called nebulae, which appeared as luminous patches in the night sky. With his large telescopes, Herschel could resolve the individual stars in nearby nebulae, and he proposed that the nebulae that seemed like clouds were so far away that even his telescopes could not separate the individual stars. Herschel therefore theorized that the nebulae were groups of stars, gathered together over long periods of time by the force of gravity, and that our own Milky Way was one of these galaxies.

Herschel's sister, Caroline, became his assistant, standing beside his telescope and recording his observations as well as helping him grind and polish the mirrors for his new telescopes. Later she became a noted astronomer herself. She is frequently referred to as the first important woman astronomer; she discovered eight comets and three nebulae.

Herschel and his sister gave their last public musical performance in 1782, after which they devoted themselves to astronomy. Between 1786 and 1802 Herschel published three catalogs giving the positions and characteristics of nebulae. These observations were performed mainly with Herschel's 20-foot telescope (an instrument with a focal length of 20 feet and a diameter of 18.8 inches).

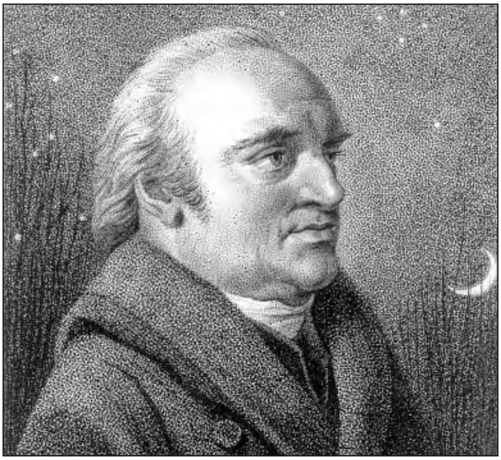
Bigger and Better

Herschel was not satisfied with the magnifying power of his 20-foot telescope. Therefore, in 1784 he decided to build a much larger telescope, with a tube having a length of 40 feet. This project was far more expensive then he could afford. He was unable to begin construction at his home and observatory in Slough, England, until King George III of England granted him £2,000 for constructing the 40-foot telescope. The king provided an annual stipend of £200 for operating expenses and repairs.

The construction of Herschel's 40-foot telescope was a major project. As many as forty workers, some removing trees—some digging and preparing the ground, and others laying the brick foundation for the telescope—performed different tasks for the new telescope. Another group prepared the tools for shaping and polishing its mirror. During this time, Herschel and his sister made observations using the smaller telescopes during the night and supervised construction of the giant telescope during the day.

Mirror, Mirror

After about two years of work, Herschel's largest telescope, with a focal length of 40 feet and a mirror with a diameter of 48 inches, seemed to be complete. On February 19, 1787, Herschel tried to use the new telescope for the first time. However, he was not satisfied with the quality of the mirror, which weighed about one thousand pounds and was so thin that it distorted under its own weight, compromising the quality of the image. He ordered a new mirror disk to be cast, but this one broke while it was cooling. Only



Sir William Herschel. (Library of Congress)

with the third mirror did Herschel achieve success. This mirror was 3.5 inches thick, twice as thick as the first mirror, so it did not distort significantly.

The telescope saw "first light" (an astronomer's term for the first attempt to observe through a new telescope) on August 28, 1789. The extraordinary power of Herschel's new telescope was immediately apparent. That first evening Herschel quickly discovered Saturn's sixth moon, Enceladus. On September 17, 1789, he discovered Saturn's seventh moon, Mimas.

Herschel was one of the most important and influential astronomers of the eighteenth century. His most significant research was conducted with his two largest telescopes, the 20-foot telescope and the 40-foot telescope. In addition to discovering two of Saturn's moons, he became famous for his discovery of the planet Uranus. He determined the rotational period of Saturn and used the same techniques to study the rotation of other planets. He also observed the motion of double stars and concluded they are held together by gravitation, revolving around a common center. Thus he confirmed the universal nature of Newton's laws of gravity. He cataloged more than eight hundred double stars.

The 40-foot telescope was never Herschel's favorite telescope, for two reasons. First, it required a great deal of maintenance and the mirror needed to be repolished quite frequently. Second, and even more problematic, was that the mounting which allowed the the telescope to be aimed at different spots on the sky, was difficult to handle. Herschel therefore continued to make most of his observations with the 20-foot telescope, which he used to discover two moons of Uranus, named Titania and Oberon. Possibly because of these difficulties, Herschel's 40-foot telescope remained the world's largest telescope for more than fifty years. It was not until 1845 that William Parsons, the third earl of Rosse, built a larger telescope, which Parsons called the Leviathan. Had Herschel's 40-foot telescope been easier to aim, he might have discovered even more cosmic phenomena, such as the spiral nebulae, a discovery made by Lord Rosse.

In recognition of his achievements, the musician from Germany was knighted, becoming Sir William Herschel. In 1820, he helped found the Astronomical Society of London, which later became the Royal Astronomical Society. A piece of the tube of Herschel's 40-foot telescope is on display in the garden of Greenwich Observatory in London, but the mirror seems to have been lost.

IMPACT

Before Herschel, only about one hundred nebulae were known, but the 1828 edition of his catalog, completed after Herschel's death by Caroline, listed about twenty-five hundred nebulae. His research in the field of nebulae suggested that new worlds might begin from gaseous matter, which is now a widely accepted theory of the origins of solar systems. Herschel also concluded that our entire solar system is moving through space, and he was able to determine the direction of its motion.

The research Herschel began on stellar astronomy and nebulae continued into the twentieth century. Although Herschel's large telescope possessed excellent optics, the instrument had no mechanical drive to keep it aimed on the moving sky, so he simply adjusted his telescope to a particular angle above the horizon and watched objects that crossed through his field of view. Herschel's inability to track stars with his 40-foot telescope demonstrated the need to couple superior optics with well-designed steerable mounts, so greater attention was given to telescope mounts following Herschel's difficulty. Herschel was honored by the astronomical community when a crater on the Moon and a crater on Mimas were named after him.

See also Brahe's Supernova; Copernican Revolution; Hubble Space Telescope; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mayan Astronomy; Optics; Saturn's Rings; Scientific Method: Aristotle; Scientific Method: Bacon; Scientific Method: Early Empiricism; Speed of Light; Stellar Evolution.

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—*George J. Flynn*

HILBERT'S TWENTY-THREE PROBLEMS

THE SCIENCE: David Hilbert proposed twenty-three problems that motivated and directed mathematical research, ushering in the modern period of mathematics.

THE SCIENTIST:
David Hilbert (1862-1943), German mathematician

THE FOUNDATIONAL PERIOD

By the end of the nineteenth century, most of the foundations of classical mathematics had been formulated. The fundamental groundwork of mathematical analysis had been established. The axiomatic approach, which involves using definitions, assumptions, and deductions with proofs, had become standard. (Axioms are mathematical statements that are assumed to be true.) Calculus and the theory of functions were formalized in this manner. "Abstract" algebra had developed throughout the nineteenth century. The basis of set theory had been laid out by Georg Cantor (1845-1918). Logic was in a rudimentary stage, in spite of its long history. New geometries and theories of curves had been conceived. With the foundations of mathematics solidified and new theories continually being proposed, the time had come to explore the deeper aspects of these theories.

David Hilbert, one of the major mathematicians of this period, established the groundwork for many of these theories. Among his published papers and monographs were complete treatises on number theory, logic, and geometry. Hilbert was known for presenting lectures that stimulated research, especially among his students at Göttingen, Germany. Many of his students would become great researchers and founders of schools of mathematics. The concise description of complex, original problems introduced by means of an interesting and motivating development of ideas was Hilbert's style. His address to the international mathematical congress was a fine example of this style.

HILBERT'S CHALLENGE TO MATHEMATICIANS

Hilbert's celebrated address to the International Mathematical Congress of 1900, entitled "Mathematical Problems," presented ten of a total of twenty-three problems in topics at the forefront of mathematical research. Hilbert challenged the audience to solve these problems. Later, all twenty-three problems were published, translated into several other languages, and distributed widely. Generations of mathematicians have worked on solving those problems. In mathematics, such work involves formally proving a theorem, not merely discovering patterns or confirming hypotheses with further evidence.

The first problem asked whether infinities exist that are larger than the set of all whole numbers (for example, {1, 2, 3, 4, . . . }) yet smaller than the set of all real numbers (the real numbers are all positive numbers, all negative numbers, and zero). It went even further, asking about the nature of the structure of the set of real numbers. A partial solution was found by Kurt Gödel (1906-1978) in 1940, and Paul Cohen (b. 1934) solved the problem completely in 1963.

David Hilbert. (Library of Congress)

The second problem was to determine whether the axioms of arithmetic were consistent. Could false conclusions be reached by using the assumptions of arithmetic? This is the basic issue for all mathematics. Gödel proved in 1931 that the answer to this question is yes.

Hilbert's third mathematical problem involved three-dimensional geometric figures. It was promptly solved. Problem four asked about the nature of geometries that are similar to the standard model of the universe. By changing the basic assumptions of space, what new properties and conclusions could be proved about that system? Some problems were very broad. The sixth problem asked for the formulation of a collection of axioms from which physical laws in general could be derived. Hilbert may have hoped that such an elegant "core" of assumptions could be used to derive mathematical physics.

The seventh problem dealt with numbers raised to the power of other numbers whose digits have no simple pattern. Even when this problem was solved, it led to many other problems that are still unsolved. In mathematics, even simple operations can generate difficult questions.

Some problems were not original but resulted in a resurgence of interest and new attempts to solve them. The eighth problem is a historic problem dating back to Bernhard Riemann (1826-1866). It deals with the frequency and distribution of prime numbers (prime numbers are numbers that can be divided only by themselves and 1).

Some problems originated in antiquity but have modern applications. Hilbert's tenth problem, "Determination of the Solvability of a Diophantine Equation," asks whether an important category of equations has a solution as a finite sequence of arithmetic operations resulting in integer (the integers are zero and the negative and positive whole numbers) answers. Although it is quite old, this problem has applications in such areas as factory production scheduling.

Not all of Hilbert's problems have been solved in the conventional sense. In the last third of the twentieth century, Hilbert's tenth problem was shown to be unsolvable. Even if all future human and computer effort were applied to this one problem, no general answer would ever be achieved. This is particularly ironic, because Hilbert seemed to hope that all mathematics could be reduced to a concise set of assumptions and methodically derived by deductive proof.

IMPACT

After Hilbert's twenty-three problems were published, the wheels of progress turned with a focused purpose. Hilbert's questions ushered in the modern period of mathematics. The progress in twentieth century mathematics that was made in attempts to solve these problems is significant in both quality and quantity. These questions required new methods and systems of reasoning, methods of greater abstraction, and more careful construction. These features characterize modern mathematics, in which small sets of assumptions prove very general results. Several of Hilbert's problems had the effect of reducing and clarifying key issues in mathematics.

Whole new fields of mathematics were created to build the powerful tools and deductions needed to find answers to these problems. In May, 1974, a symposium reviewed the new subdisciplines created in the process of resolving Hilbert's problems. Progress in many fields can be measured in terms of the degree of success that has been achieved in solving Hilbert's problems in those fields.

The most profound results of Hilbert's problems (and perhaps of all modern mathematics) were "negative solutions." The answer to Hilbert's second problem was Gödel's famous incompleteness theorem, which states that arithmetic cannot be proved to be consistent. Basically, this means that some questions are unanswerable. These problems cannot be solved by humans and computers, not for any mystical reason, but because they are infinitely complex. Hilbert's legacy is rich indeed.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*John Panos Najarian*

HORMONES

THE SCIENCE: Sir William Maddock Bayliss and Ernest Henry Starling proved that chemical integration can occur without assistance from the nervous system.

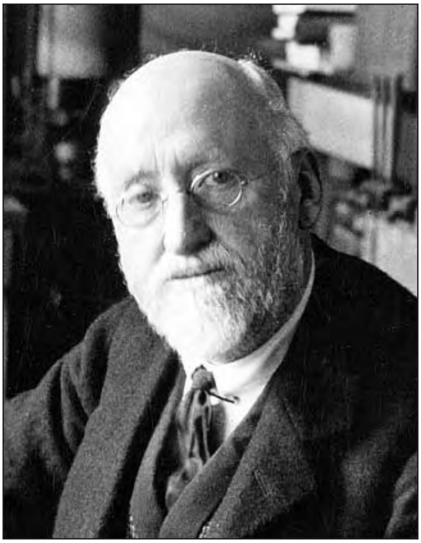
THE SCIENTISTS:

Sir William Maddock Bayliss (1860-1924), English physiologist
Ernest Henry Starling (1866-1927), English physiologist who coined the term "hormone"
Sir Frederick Grant Banting (1891-1941), Canadian physiologist
Arnold Berthold (1803-1861), German physiologist
Ivan Petrovich Pavlov (1849-1936), Russian physiologist

BYPASSING THE BRAIN

In the human body, food is digested by being dissolved and broken down chemically into simple chemical compounds that can be easily absorbed and used for nourishment. The process begins the moment food is chewed and swallowed and continues all the way down through the stomach and the small and large intestines. As the food reaches the stomach, the gastric glands in the stomach lining secrete gastric juices. These juices contain substances such as enzymes and hydrochloric acid, which break down food and aid digestion. The food then enters the small intestine, triggering the action of other glands, including the pancreas. The pancreas also secretes digestive substances such as enzymes. It also produces insulin, the hormone that enables the body to store and use sugar.

At the beginning of the twentieth century, two English physiologists, Sir William Maddock Bayliss and Ernest Henry Starling, were interested in discovering what triggered the pancreas to release digestive juices as soon as food arrived in the small intestine. In 1902, they set up an experiment to find out whether a nerve signal from the intestine was ordering the pancreas to release these juices. The investigators took an animal and cut the nerve system controlling its small intestine. They then injected stimulating material such as food from the stomach into the intestine. To their astonishment, pancreatic juices poured promptly into the intestine. With all the nerves cut, some mysterious signal must have reached the pancreas and roused it to action. Bayliss and Starling discovered that the signal was chemical in nature, not nerve-related. Arrival of hydrochloric-acid-laden food from the stomach had caused the intestinal wall to secrete a substance called "secretin," which oozed into the bloodstream, eventually stimulating the pancreas.



Sir William Maddock Bayliss. (Library of Congress)

The Role of Hormones

In 1905, Starling first used the word "hormone" (from Greek *hormon,* meaning "exciting" or "setting in motion") with reference to secretin. Today, physiologists know that hormones may inhibit as well as excite, and it is now understood that hormones do not initiate metabolic transformation but merely alter the rate at which these changes occur. The hormone disappears rapidly from circulation owing to the destructive action of an enzyme called "secretinase." Small amounts of the hormone are excreted in the urine. Many materials other than hydrochloric acid stimulate the release of secretin: water, alcohol, fatty acids, partially hydrolyzed protein, and certain amino acids are all effective.

The discovery by Bayliss and Starling of how hormones trigger the operation of other bodily systems influenced the research of others. Ivan Petrovich Pavlov, a Russian scientist and great pioneer in the study of conditioned reflexes, repeated the work of Bayliss and Starling in 1910 and obtained similar results. Subsequently, S. Kopec demonstrated in 1917 that a hormone from the brain controlled pupation in certain invertebrates (insects), which illustrated for the first time that central nervous structures could perform hormonal roles.

In other areas, important medical research focused on the islets of Langerhans. These are the small, scattered endocrine glands in the pancreas that produce insulin. They are named after Paul Langerhans, the German pathologist, who discovered them in 1869. If the islets, or islands, of cells fail to release enough insulin into the bloodstream during

Ernest Henry Starling. (Library of Congress)

HORMONES AND DIABETES

Diabetes begins when the body is unable to utilize its food properly. If food is not correctly metabolized, excess sugar accumulates in the blood and the body cannot access the energy needed to perform day-to-day functions. When the kidneys are unable to keep up in the extraction of excess sugars from the body's waste fluids, sugars tend to concentrate in the urine. Urine flow is abnormally increased, and the diabetic is constantly thirsty and consumes much fluid. Hunger and fatigue are constant companions as the body's demands for energy go unmet. In advanced cases, the diabetic suffers other symptoms: blindness, infections of the extremities that can lead to gangrene, and a higher incidence of other maladies, including heart disease. Without control of any kind, the diabetic faces a dismal future; for children without treatment, the normal life expectancy following diagnosis is only a year or two.

The role of the pancreas in the process of digestion gradually became clear in the mid-nineteenth century. French physiologist Claude Bernard discovered the role of the liver in the processes of digestion, and some suspected that it played a role in diabetes. Degenerative damage to the pancreases of diabetics led some to speculate that the pancreas, too, must play a role in the disease. Microscopic studies of pancreatic tissue by the German student Paul Langerhans revealed the presence of two distinct types of cells: those that secrete the ordinary digestive enzyme, and islands of cells whose appearance was quite different and distinctive. The islands of cells came to be known as the Islets of Langerhans. There was a growing sense that the powerful protein-destroying capacity of the external secretion might be involved in the destruction of the internal secretion in diabetics.

Such was the situation in October, 1920, when Fred Banting, a part-time lecturer in surgery at Western University who was interested in carbohydrate metabolism, formulated the idea of causing the death of the digestive juice cells and isolating their internal secretion to test its effectiveness against high blood sugars. Banting contacted John J. R. Macleod, a professor of physiology at the University of Toronto, to propose his research idea. Along with Macleod and their assistant Charles H. Best and later physician James Bertram Collip, they finally isolated the hormone insulin and prepared an injectable form for treatment of diabetes. On January 23, 1922, it was tested on a fourteen-year-old boy dying of diabetes. The injection controlled the boy's blood sugar, and his life was saved.

digestion, diabetes may result. The bodies of people who have diabetes are unable to process properly the sugar in the food they eat. Since insulin regulates the body's ability to process sugar, diabetics must take in additional dosages of it. The condition can be fatal if not carefully controlled.

Discovery of Insulin

In 1920, Sir Frederick Grant Banting was intrigued by the possibility that the operation of the pancreas might somehow be related to the onset of diabetes. Previous medical evidence seemed to suggest that the islands of Langerhans were important in directly releasing into the bloodstream something that prevented the disease. He set out to study these islands in the hope of finding what the "something" was.

By 1921, a team led by Banting had succeeded in extracting a quantity of insulin from the embryos of animals. The insulin extract was next injected experimentally into dogs and then humans. It was found to be effective in relieving the symptoms of diabetes. For his discovery of insulin, Banting shared the 1923 Nobel Prize.

Impact

Many scientists have built on the work of Bayliss and Starling. In one set of experiments, Arnold Berthold castrated six young cockerels, then returned a single testicle to the body cavity of each of the birds. Berthold observed that the host birds continued to exhibit the sexual behavior of normal young roosters. At autopsy, he found that the nerve supply of the grafted testes had not been reestablished. Hence, Berthold concluded that, since maintenance of sexual behavior and appearance could not have been accomplished by the nerves (which were severed), the results must have been caused by a contribution of the testes to the blood and then by the action of the added substance throughout the body.

In 1962, Donald G. Cooley, an American physiologist, published a manuscript entitled, "Hormones: Your Body's Chemical Rousers," in which he reviewed the experiments of Bayliss and Starling and presented an updated, salient summary concerning the mechanism of hormone action. The article appeared in the November, 1962, issue of *Today's Health*.

Strong evidence that a virus can cause juvenile-onset diabetes was reported in May, 1979, by scientists at the National Institute of Dental Research in Bethesda, Maryland. Ji-won Yoon, Marchall Austen, and Takashi Orodern isolated the virus, called "Coxsackie B4," from the pancreas of a ten-year-old boy who had died of a sudden and severe case of diabetes. The researchers grew the virus in cultures and injected it into mice. Some strains of mice then developed diabetes. This evidence indicated that the Coxsackie virus somehow interferes with the pancreas's ability to produce enough insulin, thus causing some cases of diabetes.

Hormones have even been implicated in many types of cancer, notably breast cancer but other forms as well. In 2003, the Framingham study, which involved thousands of women followed over many years, concluded that the therapeutic use of the female hormone estrogen to fight the effects of aging on the heart and bones was ill-advised. For certain groups of women, the hormone was associated with increased incidences of cancer and demonstrated no significant protection against heart disease, the number one killer of women in the United States.

See also DNA Sequencing; Insulin; Vitamin D.

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—*Nathaniel Boggs*

HUBBLE SPACE TELESCOPE

THE SCIENCE: The Hubble Space Telescope has provided astronomers with clear images of distant objects in the universe.

THE SCIENTISTS:

Hermann J. Oberth (1894-1989), German rocket scientist
Edwin Powell Hubble (1889-1953), American astronomer
Steven A. Hawley (b. 1951), STS-31 mission specialist
Richard O. Covey (b. 1946), STS-61 commander
Kenneth D. Bowersox (b. 1956), STS-61 pilot
Kathryn C. Thornton (b. 1952), STS-61 mission specialist
Claude Nicollier (b. 1944), STS-61 mission specialist
Jeffery A. Hoffman (b. 1944), STS-61 mission specialist
F. Story Musgrave (b. 1935), STS-61 mission specialist
Thomas D. "Tom" Akers (b. 1951), STS-61 mission specialist

EARTH VS. SPACE TELESCOPES

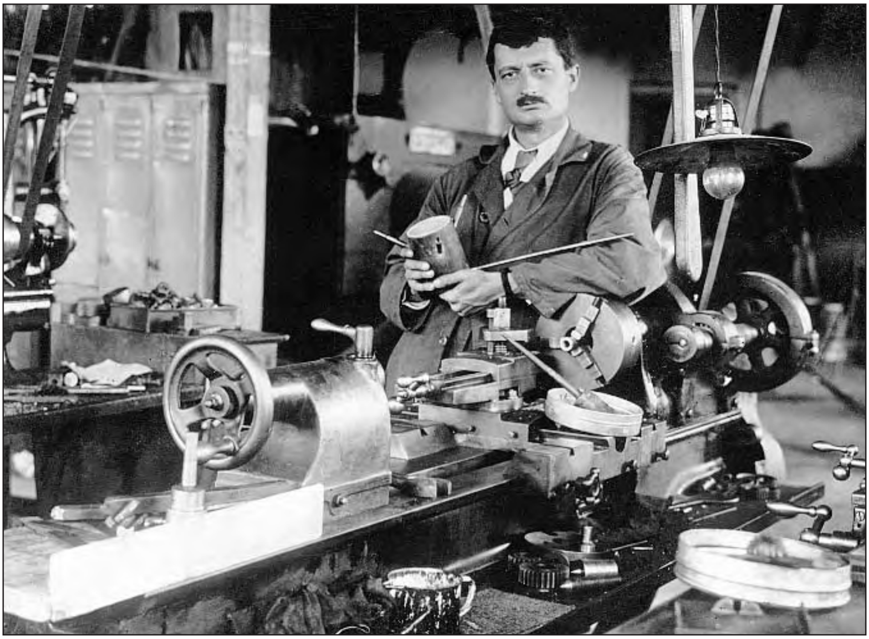
Since the early twentieth century, when American astronomer Edwin P. Hubble began a study of galaxies using the Hooker telescope at the Mount Wilson Observatory in California, astronomers on Earth have built bigger observatories with larger mirrors in order to see fainter and more distant celestial objects. However, they continued to be hindered by what they could see through the haze and turbulence of the Earth's atmosphere. Placing an optical telescope above the atmosphere in orbit about Earth originally was suggested in the 1920's by the German rocket scientist Hermann Oberth. Oberth's suggestion was not acted upon until NASA began a study in 1962. Fifteen years later, Congress approved the plan of a space telescope and it became an official NASA project. The proposed space telescope was named the Hubble Space Telescope in honor of Edwin P. Hubble's important contributions to astronomy.

The Hubble Space Telescope (HST) was designed by astronomers and engineers to function somewhat like an Earth-based reflecting telescope. While the telescope orbited Earth, two solar panels on HST pointed toward the Sun to provide energy for scientific instruments. A door at one end of the telescope opened and light struck the larger (primary) mirror, which was 2.4 meters in diameter. This mirror reflected light toward the smaller (secondary) mirror, which was 0.3 meter in diameter. From there, the light was again reflected and passed through a hole in the primary mirror. The focused light was converted into an electrical signal that was transmitted by satellite to White Sands, New Mexico, and then to the Goddard Space Flight Center and Space Telescope Science Institute, both in Maryland.

The original instruments of HST included the Wide Field/Planetary Camera 1, the Faint Object Spectrograph, the High Resolution Spectrograph, the High Speed Photometer, the Faint Object Camera, and Fine Guidance Sensors. All of the instruments were built to be modular in design so that they could be replaced in case of a system failure or during routine upgrading of equipment. These instruments allowed HST to measure infrared and ultraviolet radiation as well as visible light.

HUBBLE LAUNCH INTO ORBIT

HST weighed approximately 11,000 kilograms when it was loaded into the cargo bay of the space shuttle *Discovery*. It was launched into orbit from Cape Canaveral on April 24, 1990. The following day, the telescope was deployed by American Astronaut Steven A. Hawley, using the 15-meter (50-foot) mechanical arm of the shuttle.



German rocket scientist Hermann Oberth envisioned space stations and space telescopes in the early twentieth century. (Library of Congress)

The primary mirror on the HST was designed at the Perkin-Elmer Corporation (later renamed Hughes Danbury Optical Systems) in Danbury, Connecticut. Several months after deployment, astronomers on Earth discovered that technicians had made it slightly too curved, which caused much of the starlight to be out of focus. Once the defect was identified, specialists planned a mission during which astronauts would replace an optical component in HST and allow light to be focused as originally planned.

The flaw in the mirror was only one of several problems with HST. The devices that help align the observatory with targets, the gyroscopes, were not reliable; one failed in 1990 and two failed in 1992. Astronomers would not be able to point the telescope at any object if another gyroscope failed. These units would either have to be replaced or repaired.

The two solar arrays, which provided energy to power the telescope's instruments, also had a problem. The material used in the arrays expanded when HST was facing the Sun and contracted when the telescope was entering darkness. The temperature reaction of the panels caused HST to vibrate uncontrollably, which further blurred the images. Engineers on Earth had to develop new software to try and compensate for the jitter. Even with the software, there were certain times when observations could not be made because of the erratic motion.

SERVICING MISSIONS

Engineers from Ball Aerospace and Communication Group in Colorado developed a solution for the problem with Hubble's primary mirror. They studied technical drawings of the telescope and determined that a set of corrective lenses could compensate for the flaw. The lenses would have to be placed along the internal path of light. Their solution was to replace Hubble's photoelectric photometer with the Corrective Optics Space Telescope Axial Replacement (COSTAR) optics units. Once in place, small robotic arms would move the mirrors into position to refocus the fuzzy light.

On December 2, 1993, the space shuttle *Endeavour* and its STS-61 crew lifted off from Cape Canaveral. Upon achieving orbit, American astronauts Kenneth D. Bowersox and Richard O. Covey maneuvered *Endeavour* so that its path would intersect the orbit of HST. Two days later, Swiss astronaut Claude Nicollier used the shuttle's robotic arm to reach out and grapple HST. The telescope was then moved onto a special turntable inside the shuttle's cargo bay so that the astronauts could repair or replace the malfunctioning instruments.

To repair HST, astronauts had to wear space suits during extravehicular activity (EVA). While outside the shuttle, the astronauts moved using a combination of tethers (rope) and holding on to the railing on HST. An astronaut inside the shuttle operated a mechanical arm that was used to move some of the EVA astronauts toward HST. During the first day of repair, astronauts restored the malfunctioning gyroscopes to operational condition and inspected the solar panels, discovering that one panel was severely bent. The other panel was mechanically rolled up, leaving the bent panel still unfurled against HST. During the second EVA, Astronaut Kathryn C. Thornton successfully detached the bent solar panel from HST. Next, astronauts removed the HST's original Wide Field/Planetary Camera 1, WFPC1. In its place, they installed the new state-of-the-art WFPC2.

The final job was to correct the flawed optics of HST. To make room for COSTAR, astronauts removed the photoelectric photometer, the least-used scientific device on HST. With the photometer out, COSTAR fit like a glove into HST. Scientists on Earth positioned a series of internal mechanical arms that moved the corrective lenses in front of the mirror like a pair of eyeglasses.

The HST was released back into orbit on December 10, 1993. Astronomers on Earth were able to confirm the success of the repair mission a few weeks later. The new optics worked perfectly. In February, 1997, the space shuttle *Discovery* returned to Hubble for a second servicing mission during STS-82. Two advanced instruments—the Near Infrared Camera and Multi-

Object Spectrometer (NICMOS) and the Space Telescope Imaging Spectrograph—were swapped out with the two first-generation spectrographs. The astronauts also replaced or enhanced several electronic subsystems and patched unexpected tears in the telescope's shiny, aluminized thermal insulation blankets.

During subsequent servicing missions—in December, 1999, on STS-103, and in March, 2002, on STS-109—astronauts replaced faulty gyroscopes, added a new high-tech computer and a data recorder, and installed new equipment: solar arrays, the Advanced Camera for Surveys, a new power control unit, and a new cryocooler for NICMOS.

Amazing Images, Precious Data

The HST has provided new and unprecedentedly sharp images of objects within our solar system. Storms on the gas giant planets (Jupiter, Saturn, Uranus, and Neptune) have been observed. Huge storms were seen on Jupiter and Saturn. In July, 1994, HST observed the fragments of Comet Shoemaker-Levy 9 slam into the atmosphere of Jupiter. In 1995, HST took images of Saturn as its rings appeared "edge on" from our perspective on Earth. S1995S3, a newly discovered moon orbiting Saturn, was seen. Peering outside the solar system, HST returned stunning images of stars at various stages of their lives; protoplanetary disks in the Orion nebula surrounded by gas and dust; columns of cool interstellar dust and gas; an elusive brown dwarf star, known as G1229B, that orbits a red dwarf star and is the faintest object ever seen around a star beyond the Sun; the globular star cluster M4 with its white dwarf stars; unstable stars such as Eta Carinae; the debris of Supernova 1987A; the elliptical M87 galaxy in Virgo; and Cepheid variable stars, which are being used by cosmologists to estimate more accurately the rate at which the universe is expanding.

A Replacement for Hubble?

As of 2005, HST was awaiting a fourth servicing mission, which had been postponed after troubles with the shuttle beginning with the 2003 *Columbia* tragedy in which seven astronauts lost their lives upon reentry into Earth's atmosphere. At the same time, the James Webb Space Telescope, Hubble's next-generation replacement, was being planned for launch in 2011.

The Webb Space Telescope (JWST)—a large, infrared-optimized space telescope scheduled for launch in August, 2011—would study the earliest galaxies and some of the first stars formed after the big bang. The Webb telescope's instruments would work primarily in the infrared range of the electromagnetic spectrum, with some capability in the visible range.

JWST will have a large mirror, 6.5 meters (20 feet) in diameter, and a sunshield the size of a tennis court. Neither the mirror nor the sunshade can fit onto the rocket fully open, so both will fold up and open only once JWST is in outer space. JWST will reside in an L2 Lissajous orbit, about 1.5 million kilometers (1 million miles) from the Earth. L2 is one of five Lagrangian points where the pulls of the Earth and Sun combine to form a point at which a third body of negligible mass—a satellite—would be stationary relative to the two bodies. Achieving this point precisely is difficult, so a special Lissajous orbit (a periodic orbit in which there is a combination of planar and vertical components) called a "halo" orbit will be used. A halo orbit is one in which a spacecraft will remain in the vicinity of a Lagrangian point, following a circular or elliptical loop around that point.

Mission goals are to determine the shape of the universe, explain galaxy evolution, understand the birth and formation of stars, determine how planetary systems form and interact, determine how the universe built up its present chemical/elemental composition, and probe the nature and abundance of dark matter.

A Replacement for Hubble

In 2004, facing the worst federal deficit since the Hoover administration as well as ongoing problems with the space shuttle, NASA eliminated all space shuttle flights not directly supporting the International Space Station. These included scheduled servicing missions to the Hubble Space Telescope. NASA had planned to visit Hubble one last time in 2006 to change out instruments and replace its gyroscopes with the intent of keeping the telescope in service until at least 2011, when its successor, the James E. Webb Space Telescope was expected to launch.

The Webb telescope is a large, infrared-optimized space telescope designed to study the earliest galaxies and some of the first stars formed after the big bang. The new telescope will have a large mirror, 6.5 meters (20 feet) in diameter, and a sunshield the size of a tennis court. Mission goals are to determine the shape of the universe, explain galaxy evolution, understand the birth and formation of stars, determine how planetary systems form and interact, determine how the universe built up its present chemical composition, and probe the nature and abundance of dark matter.

IMPACT

According to the Space Telescope Science Institute in Baltimore, Maryland:

> In its first ten years of surveying the heavens, the Hubble Space Telescope . . . made 330,000 exposures and probed 14,000 celestial targets. It has whirled around Earth 58,400 times, racking up 2.4 billion kilometers, approximately equal to making eight round trips to the Sun. The orbiting observatory's observations have amounted to 3.5 terabytes of data. Each day the telescope generates enough data—3 to 5 gigabytes—to fill a typical home computer.

See also Gamma-Ray Bursts; Herschel's Telescope; Jupiter's Great Red Spot; Optics; Pulsars; Quasars; Radio Galaxies; Radio Maps of the Universe; Saturn's Rings; Space Shuttle; Very Long Baseline Interferometry; X-Ray Astronomy.

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—Noreen A. Grice, updated by Russell R. Tobias

HUMAN ANATOMY

THE SCIENCE: In the sixteenth century, scientists began making detailed studies of the human body that produced a new level of accuracy in anatomical studies and formed a foundation for modern medicine.

THE SCIENTISTS:

Andreas Vesalius (1514-1564), professor of anatomy

Bartolommeo Eustachio (c. 1524-1574), anatomist whose ideas rivaled those of Vesalius

VESALIUS'S ANATOMY

Andreas Vesalius, known as the father of modern anatomy, is also regarded as one of a small group of individuals who initiated the scientific revolution. He was born in Brussels and studied medicine at the Universities of Louvain and Paris, conservative schools that stressed medical teaching according to the writings of Galen (129-c. 199), the Roman physician whose work was regarded as authoritative in Vesalius's time.

Vesalius taught anatomy at the Universities of Pavia, Bologna, and Padua, where he adopted the technique of lecturing along with demonstrations in dissection done by him in person. He became a popular lecturer, and his methods of instruction became the model for the teaching of anatomy in other schools.

Andreas Vesalius. (Library of Congress)

In 1543, Vesalius presented his masterpiece, *De humani corporis fabrica* (*On the Fabric of the Human Body*, books I-IV, 1998; better known as *De fabrica*), published in Basel by the printer Johannes Oporinus. In this book, Vesalius followed Galen in many inaccuracies as well as in true observations. The illustrations in the book, however, were drawn to a level of accuracy never before achieved in the study of human anatomy. Without the drawings, the book would have done little to excite interest in further anatomical research and could not be regarded as a milestone in the history of science. The illustrations were made probably in the studio of the Italian painter Titian, the supervisor of a number of artists including Vesalius and a fellow countryman, Jan Steven van Calcar. Van Calcar previously had collaborated with Vesalius in the production of six large plates illustrating anatomical nomenclature.

Muscles, Tendons, Bones, and Joints

The drawings in Vesalius's work achieved more than mere naturalism. They show, among other things, the dissection of muscles, so that the relations between the structure and functions of muscles, tendons, bones, and joints are clearly visible. These drawings were the most detailed and extensive illustrations of the systems and organs of the body up to this time, and they include a large number of new observations the anatomist had made on the veins, arteries, and nerves. In addition, the study of the brain presented remarkable new insights about that organ.

The work is divided into seven parts or books, each of which is devoted to a group of organs of the human body; Book V, for example, describes the abdominal viscera. The explanations in physiology follow Galen closely, and not all of the books are of equal value. However, included in the text is an emphasis on the need for introducing the scientific method into anatomical studies, and the overall value of the work far outweighed its deficiencies. In 1555, Vesalius produced a new edition, considerably revised, but then he gave up teaching and research to become court physician to Holy Roman Emperor Charles V.

Eustachio's Anatomy

The work of Vesalius was paralleled by a contemporary and rival, Bartolommeo Eustachio, a citizen of Rome. His work, similar to that of Vesalius, was completed in 1552 but was not published until 1714. He was engaged with the same problems as Vesalius, and in some respects his anatomical drawings are more accurate. He introduced the study of anatomical variations, with his most successful work being done on the sympathetic nervous system, the kidney, and the ear. His name has been given to the eustachian tube, the narrow canal connecting the ear and throat.

As has often happened in the history of science, the two men were seeking knowledge in the same area. Had it not been for the fact that Vesalius published his book before Eustachio had even finished his illustrations, the latter might be known today as the father of anatomy.

Impact

Vesalius insisted that human anatomy be studied through hands-on dissection and observation, an insistence that led to his being included as one of world history's greatest physicians. *De fabrica* is the culmination of Vesalius's observations in all their detail, and it stands as the foundational text in human anatomy.

See also Blood Circulation; Blood Groups; Contagion; Galen's Medicine; Germ Theory; Greek Medicine; Human Genome; Neurons; Ova Transfer; Pulmonary Circulation; Stem Cells.

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—*Robert F. Erickson*

HUMAN EVOLUTION

THE SCIENCE: In 1871, Charles Darwin published *The Descent of Man and Selection in Relation to Sex*, which continued his earlier work, *On the Origin of Species by Means of Natural Selection*. Darwin argued that humans are evolutionarily derived from lower animals, and the features typically used to distinguish humans from animals originated by natural or sexual selection. This work provided the impetus to more materialistic views of humanity as well as scientific investigations into the origins of human nature.

THE SCIENTISTS:

Charles Robert Darwin (1809-1882), English naturalist and originator of the theory of organic evolution

Thomas Henry Huxley (1825-1895), English comparative anatomist and chair of Natural History at the Royal School of Mines in London

Sir Charles Lyell (1797-1875), eminent geologist who encouraged Darwin to publish his speculations

Erasmus Darwin (1731-1802), Charles's grandfather, an English physician

Alfred Russel Wallace (1823-1913), Scottish naturalist who in 1858 independently originated the theory of natural selection

John Lubbock (1834-1913), English banker, statesman, and naturalist

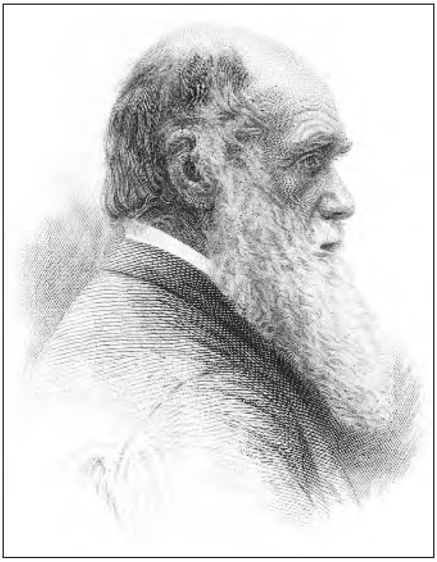
Edward B. Tylor (1832-1917), English anthropologist

Ernst Haeckel (1834-1919), German biologist

HUMANS AS PRIMATES

Charles Darwin's *On the Origin of Species by Means of Natural Selection* (1859) postulated that all life on Earth evolved from a common ancestor by means of natural selection. This theory released a flood of controversy, since it implied that humanity also arose from lower animals by purely naturalistic mechanisms rather than through supernatural means. Even though Darwin scrupulously avoided the human origins question in his first book, it generated most of the controversy over his theory. Darwin, however, was eager to apply his theory to humans, and from 1859 to 1871 he gathered valuable information by corresponding with scientists all around the world and conducting his own experiments. What he learned during this time provided material for his book on human evolution entitled *The Descent of Man and Selection in Relation to Sex* (1871).

Darwin began *The Descent of Man* by asserting that there were no fundamental qualitative differences between the anatomy or development of hu-



Charles Darwin. (Library of Congress)

mans and higher mammals. Comparative anatomical work on humans and nonhuman primates by Thomas Huxley, Darwin's friend and most loyal defender, tended to support a common ancestry for these two groups. Darwin depended on Huxley's *Evidence as to Man's Place in Nature* (1863) for this first section of his book. Darwin utilized Huxley's extensive anatomical data to show that there are no distinctively human structures and to argue that humans are more closely related to apes than apes are to monkeys. This shrank the physical gulf between humans and nonhuman primates. Darwin also argued that human populations possessed great variability and that natural selection could operate upon these differences.

Human Cultural Traits

Darwin further argued that human mental capacities differed only in degree, not in essence, from those of animals. He provided several, admittedly anthropomorphic, anecdotal examples of animal behavior to support this claim. He believed that the origin and development of characteristics thought to distinguish humans from the animals—like religion, language, or morality—could be reasonably explained by evolutionary mechanisms.

Some found Darwin's line of argumentation convincing because by the late 1850's, people had begun to believe that humanity was more ancient than previously presumed. To establish the ancient age of humanity, Darwin relied on research from three English scientists: Archaeologist John Lubbock, anthropologist Edward B. Tylor, and geologist Sir Charles Lyell.

Lubbock, another friend and defender of Darwin, subdivided the Stone Age into the Neolithic and Paleolithic periods according to progressive improvements in toolmaking, with the oldest remains of human activity displaying the most primitive levels of technology.

Darwin regularly corresponded with Edward Tylor, whose studies suggested that cultural differences between Europeans and non-European societies were well explained by an evolutionary model of inheritance, diffusion, and independent innovation. Based on Tylor's work, Darwin hypothesized that humans developed religious beliefs out of a primitive need to find a cause for those phenomena that evade simple explanation.

Yet another friend and sometime defender of Darwin, Charles Lyell, author of *The Geological Evidences of the Antiquity of Man, with Remarks on the Theories of the Origin of Species by Variation* (1863), cataloged—in great detail and with tremendous clarity for any educated Victorian—the accumulated evidence for the antiquity of humankind. His book was the first after Darwin's to cause a reevaluation of what it meant to be human.

These discoveries made degenerationism—the popular belief of the time that human culture had originated at a relatively high level of social organization and sophistication, after which some cultures degenerated to simpler states while others advanced to more complex states—untenable. They also made evolutionary accounts of the rise of modern humans from more primitive ones seem much more plausible.

With respect to language, Darwin referenced the evolutionary genealogy of Indo-European languages constructed by August Schleicher. Schleicher's analyses intimated that all modern languages had evolved from earlier ones. Darwin postulated that human language originated from social sounds, like those produced by apes, which gradually expanded when primitive humans began to imitate natural sounds. To explain the origin of morality, Darwin argued that right and wrong were relative and learned by children when they were young; there was no innate sense of morality in humans. Darwin used many examples from "uncivilized" peoples and their practices to corroborate his claims.

HUMAN ANCESTORS?

Darwin was unsure of the identity of the actual biological ancestor of humanity, as he knew almost nothing about fossil primates. He suspected that the Old World monkeys gave rise to humans, but he had little evidence other than anatomical similarities to support this contention. Darwin referred to the embryological work of Ernst Haeckel, the most enthusiastic promoter of Darwinism in Germany, to unite the evolutionary ancestors of primates with those of marsupials, monotremes (egg-laying mammals like the duck-billed platypus), reptiles, amphibians, and fishes. Darwin suggested that the ancestor of the vertebrates was the lowly tunicate (ascidian), whose larval stage possesses a notochord—the dorsally located cartilage rod found in the embryos of all vertebrates—that serves as the embryological precursor to the backbone that is lost upon metamorphosis to the adult form in tunicates.

Social Darwinism

Perhaps more profoundly than any other work, Charles Darwin's *On the Origin of Species by Means of Natural Selection* (1859) and its sequel, *The Descent of Man and Selection in Relation to Sex* (1871), shaped the development of modern biology and, more broadly, the modern view of human nature. No longer was it possible to accept uncritically the biblical view of creation, with the implied special place of humankind in the divine order. Human beings became creatures among creatures, with a traceable evolution and descent from earlier hominid forms.

Darwin's ideas exerted a wide cultural influence, diffusing into politics, literature, and class relations, especially through Herbert Spencer's Social Darwinism. It was not Darwin but Spencer—a laissez-faire economist and an ironically fragile individual—who coined the misleading phrase "survival of the fittest." However, this misapplied evolutionary perspective was current before Darwin produced his famous work. Spencer was simply the most dogmatic in applying the principles of evolution and natural selection to society. Moreover, Spencer's writings on competition in business had influenced Darwin.

Unfortunately, Social Darwinism became embedded in much of the popular imagination. Darwin's ideas were often mistakenly used to justify racism, discrimination, and repressive economic practices. Although Darwin drifted toward agnosticism and did not believe in a divinely sanctioned morality, neither did he condone a world of amoral violence and brute struggle for domination. A gentle man who abhorred violence and cruelty, he would have been horrified at the political and social misapplications of principles linked with his name. At the same time, Darwin was not a Victorian liberal and accepted many of the unenlightened views of his age concerning "primitive" cultures.

During his lifetime, Darwin faced formidable challenges to his evolutionary theory, first from the scientist Fleeming Jenkin, who argued that fortuitous adaptations would be "swamped" and disappear in larger populations, and later from Lord Kelvin, who mistakenly questioned Darwin's estimate of the geological age of the Earth on the basis of the laws of thermodynamics. These challenges led Darwin to revise his work and to back away from some of his earlier claims about the long eras needed for slow evolutionary changes to take place. Darwin had no way of knowing that Gregor Mendel's discoveries in genetics—made in 1865 but not fully recognized until 1900—would have answered many of his doubts about the sources of variation and the mechanisms of inheritance.

Sexual Selection

Darwin also devoted the latter part of *The Descent of Man* to the concept of sexual selection. Original to Darwin, sexual selection postulates that the evolution of particular traits is driven by competition for mates between individuals of the same sex. Darwin theorized that human beings, like the animals, possessed a variety of superfluous traits that existed because they aided reproductive success. With sexual selection, Darwin attempted to explain most of the geographical and behavioral distinctions of humanity. Differences in appearance such as skin color, hair texture, and body size, as well as divergent behavioral traits such as bravery, social cohesion, maternal feelings, propensity for hard work, obedience, and altruism, could be explained by applying the principles of sexual selection to humans. Like almost all Europeans of his day, Darwin believed that men were intellectually superior to women and that European society, where men set the evolutionary direction for humanity, was the most advanced kind of society.

Impact

By the time of Darwin's death (1882), his theory of common descent, which included humans, enjoyed almost universal acceptance among scientists, but his mechanism of evolutionary change, natural selection, was heavily disputed and widely disbelieved. In 1891, Dutch anthropologist Eugène Dubois discovered a skullcap near Trinil in central Java. This fossil human seemed to possess anatomical features that were intermediate between apes and modern humans. Dubois named it *Pithecanthropus erectus* (its modern distinction is *Homo erectus*), and it became known as Java man. Though disputed at first, Dubois's find was eventually viewed as a vindication of Darwin's theories and initiated other efforts to find fossil human ancestors.

The Descent of Man dealt with questions regarding humanity's origins that had never been asked before, so in this regard the book was truly pioneering, even if some of its arguments were less than satisfying. Darwin's book also spurred scientific investigation into the origin of humanity, particularly in areas that were formerly thought to be outside the purview of science. Biological investigations of human reasoning, consciousness, and moral motivations had their inauguration with *The Descent of Man*.

Darwin's ideas also generated great controversy, since many people were appalled by the thought that they had descended from apelike creatures. In the United States, this controversy culminated in the 1925 Scopes trial. The application of Darwin's theories to social sciences and humanities stimulated new avenues of research but also dehumanized them to some extent, which caused much of the controversy that surrounded, and still surrounds, Darwin's theories.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Michael A. Buratovich*

HUMAN GENOME

THE SCIENCE: Two scientific research teams announced that they had finished the first complete reading of the human genetic code, fueling hopes that this breakthrough would lead to rapid medical advances but also raising ethical concerns as to how the information would be used.

THE SCIENTISTS:

Francis Collins (b. 1950), physician and head of the National Human Genome Research Initiative

J. Craig Venter (b. 1946), scientist and president of Celera Genomics

THE HEREDITARY MATERIAL

On June 26, 2000, U.S. president Bill Clinton hosted a ceremony at the White House at which a momentous announcement was made. The human genome—the genetic material in every person—had been sequenced. The announcement by Francis Collins, director of the National Human Genome Research Initiative and head of the publicly funded international effort to sequence the genome, and J. Craig Venter, president of the private company Celera Genomics, was regarded as one of the most significant advances ever made in biology.

The human genome is made of the chemical deoxyribonucleic acid (DNA) and is located inside the nucleus of nearly every cell of the body. DNA is the hereditary material passed from parent to child. DNA consists of four elements called bases, designated as A, T, C, or G. There are about three billion bases of DNA in the human genome, divided into twenty-three rod-shaped structures called chromosomes located in the nucleus of the cell. The sequence of the DNA bases contains information that is converted into proteins, molecules that have an impact on most human structures and biochemical processes. Because human traits, as well as diseases, can be encoded in the DNA, it was believed that understanding the complete sequence would be the key to understanding human health and disease.

DECIPHERING THE SEQUENCE

The dedicated effort to sequence the entire human genome was begun in 1990 with the creation of the National Human Genome Research Initiative (NHGRI), a collective of many U.S. and five international research centers. This group of institutions expected to complete the sequencing in 2005. In May of 1998, however, J. Craig Venter and his company Celera Genomics announced that with newly developed technology they would complete the project in three years. Rather than work independently, the two groups became partners in sequencing the genome, sharing results and technology.

To sequence the genome, NHGRI researchers followed an orderly process of breaking the genome into large pieces, localizing them to particular sites on chromosomes, and then breaking the large pieces into smaller pieces. Automated sequencers were then used to establish the DNA sequence of the smaller pieces. Computer programs were used to arrange these short sequences so that they overlapped. As a final step, researchers called "annotators" located and identified genes, again aided by computers.

Celera used a different technique for sequencing the genome, one called "whole genome shotgun sequencing." The genome was shattered into thousands of short fragments. The ends of these fragments were sequenced and powerful computers were used to do literally trillions of computations to identify the overlapping regions of the fragments. These overlapping fragments were then arranged, and the entire genome sequence was reconstructed.

The genome sequencing proceeded at a much faster rate than either initiative could have accomplished alone. The June, 2000, announcement of the nearly completed sequence occurred five years earlier than originally anticipated. At the time of the announcement, it was estimated that 99.9 percent of the human genome sequence was completed, but significant gaps and inaccuracies existed, which both groups continued to resolve.

On February 10, 2001, Collins and Venter announced the completed sequencing of the human genome. Their initial analysis of the genome indicated that the human genome contained 30,000 genes—small segments of DNA that code for proteins—far fewer than expected by most scientists. In fact, later investigations have found this number to be even lower, on the order of 22,000. The result has been interpreted to mean that the human complexity is caused by the modification of the protein products of genes and the interaction of proteins after they have been produced.

Impact

The news of the near completion of the deciphering of the human genome was met with both great excitement and caution. The medical community looked to the discovery for rapid advances in enhancing health and curing disease, and others regarded the announcement with apprehension because of the possibility of misuse of genome information.

By comparing the sequence of genes in the human genome with the genomes of other organisms, scientists have localized suspected human disease genes in other animals. For example, the fruit fly has long been a research organism that has led to advances in understanding human genetics. In April, 2000, the sequencing of the fruit fly genome was completed. Scientists compared 289 human genes suspected to be involved in disease with the fly genome. More than 60 percent of these human genes had similar counterparts in the fly. Because genes are much easier to study in the fly, study of these human gene counterparts may lead to rapid understanding of disease processes in humans.

Scientists are also beginning to compare single nucleotide polymorphisms (SNPs) between individual humans. Humans differ from one another in about one nucleotide per thousand bases, for example, an A instead of a T at a particular site. Although the vast majority of these differences are of no consequence, some may be involved in disease, or in the body's response to a particular medication. By identifying these SNPs and establishing a database of these variations, researchers can use the information to identify disease genes and drug companies can tailor medications to an individual patient.

Access to the genome information of an individual also has multiple and complex ethical implications. For example, many genetically based diseases can be identified with diagnostic tests, and additional ones will be identified. Life and health insurance companies, as well as employers, may require genetic testing of their subscribers and employees. Individuals with a particular genetic makeup could be denied or dropped from insurance or employment. Genetic discrimination is a reality that must be dealt with by society.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Karen E. Kalumuck*

HUMAN IMMUNODEFICIENCY VIRUS

THE SCIENCE: Discovery of the human immunodeficiency virus, which leads to AIDS, helped researchers design therapies to mitigate the disease and prolong human life.

THE SCIENTISTS:
Robert C. Gallo (b. 1937), the leading U.S. AIDS researcher
Luc Montagnier (b. 1932), French medical researcher
Jonas E. Salk (1914-1995), American medical research scientist and Nobel laureate

A NEW RETROVIRUS

Robert Gallo's initial medical research at the National Cancer Institute (NCI) in Bethesda, Maryland, focused on retroviruses, mystifying organisms that present mirror images of themselves genetically. As early as 1910, such retroviruses were identified as a cause of cancer in hens. Later, scientists established a link between retroviruses and cancer in other animals.

During the early 1970's, Gallo, spurred by generous governmental funding for medical research that could lead to a cure for cancer, searched for a link between retroviruses and cancer in humans. By 1975, he had isolated HL-23, a human retrovirus taken from the blood of a leukemia patient. Others in the scientific community questioned and disparaged his findings when they were unable to replicate his results; such critics suggested that his results were invalid, possibly because of contamination of Gallo's sample.

Late in 1978, researchers at the NCI discovered an atypical T-cell cancer in the lymph node of a patient and identified it as reverse transcriptase—seemingly a retrovirus—which they cultured and grew for the next two years. They tried to find the same retrovirus in other patients; two, from a large patient population, also tested positive for it. Gallo labeled this virus human T-cell lymphoma virus, or HTLV. It seemed identical to the adult T-cell lymphoma virus, ATLV, isolated in Japan.

Controversy and Cooperation

In 1981, the acquired immunodeficiency syndrome (AIDS) was becoming a medical fact of life in the United States. James Curran of the Centers for Disease Control talked about it at the National Institutes of Health (NIH) in that year. Gallo, focusing on his own research, however, had little

Robert C. Gallo on HIV/AIDS

Born March 23, 1937, Robert C. Gallo became interested in medicine at a very young age, when his six-year-old sister died of leukemia. He would discover the first human retrovirus (a cause of leukemia) and the human immunodeficiency virus, the cause of AIDS. After working at the National Cancer Institute for thirty years, Gallo founded the Institute of Human Virology (IHV) at the University of Maryland Biotechnology Institute, becoming its director in 1996.

In the same year, Gallo published his discovery that chemokines, a class of naturally occurring compounds, can block HIV and halt the progression of AIDS; the achievement was recognized by *Science* magazine as one of the top scientific breakthroughs of 1996. Chemokines are still being researched and might lead to a vaccine, although such a possibility is still in the distant future.

Gallo's career has not been without controversy, however—as might be expected in connection with the emotional issue of AIDS. He was depicted critically in Randy Shilts's book *And the Band Played On* (1987) and in John Crewdson's book *Science Fictions: A Scientific Mystery, a Massive Cover-Up, and the Dark Legacy of Robert Gallo* (2002). Gallo has nevertheless devoted his life and considerable skills to finding both treatments and cures, and in 2000 his team was awarded a grant from the International AIDS Vaccine Initiative to develop a genetically encoded oral vaccine.

In 2001, in an interview occasioned by the twentieth anniversary of the discovery of HIV, Gallo noted the status of AIDS research. His sobering comments are a reminder of the need for education in safe sex, especially for youth as well as those struggling under gender oppression:

> Sure, we have drugs that will treat AIDS, but these drugs are in no way a cure. . . . These drugs can suppress the virus, but you must take them for the rest of your life and they are expensive, which makes them a nightmare for the Third World. We also see a lot of toxicity with these drugs, and through overuse they can cause the virus to mutate. We are working hard to create a vaccine and less toxic treatments, but we aren't there yet.

Source: Quotation from "AIDS at 20: A Look Back, a Look Ahead with World-Renowned Scientist Dr. Robert Gallo." Interview by Noel Holton for the University of Maryland Medical System. Available online at www.umm.edu. Accessed September, 2005.

interest in what Curran presented. When Curran returned to the NIH in 1982 with the suggestion that AIDS attacks T-cells, Gallo became intrigued and involved, surmising that a link might exist between AIDS and HTLV, which also attacks T-cells.

Early in 1983, Luc Montagnier of the Pasteur Institute in Paris called Gallo to share information about a retrovirus identified in an AIDS patient there. Montagnier requested that Gallo send him some antibodies of HTLV for comparison with this patient's cells. This marked the beginning of what ultimately led these two scientists to the joint discovery of the human immunodeficiency virus (HIV).

The discovery of HIV—and the assignment of credit for it—was marked by considerable rancor on the parts of the two men most directly involved in the research. Gallo, obviously pursuing a Nobel Prize, was accused of plagiarizing important research findings related to the Pasteur Institute's lymphadenopathy-associated virus (LAV). The personal and professional relationship between Gallo and Montagnier cooled. Gallo publicly badgered Montagnier when he presented some of his findings at international scientific meetings.

Despite this contention, after considerable public wrangling and after revelations that cast suspicion on Gallo's scientific honesty, Jonas E. Salk, representing a group of Nobel Prize winners, became a shuttle diplomat between the United States and France, seeking some accord in this discordant affair. On March 31, 1987, U.S. president Ronald Reagan and French prime minister Jacques Chirac made a joint announcement that made public a French American agreement declaring Gallo and Montagnier codiscoverers of the human immunodeficiency virus. This meant that the royalties from all HIV blood tests would be shared equally by both scientists.

Impact

Regardless of the issues involved in ascribing credit for the discovery of HIV, the achievement was monumental. It provided a vital link for discovering the means of preventing, treating, and controlling one of the most threatening of human diseases. The isolation of HIV enabled subsequent researchers to focus upon means of dealing with the virus. Although AIDS has not yet been defeated medically, the identification of HIV provided the necessary initial step.

In *AIDS and Its Metaphors* (1989), essayist Susan Sontag noted that AIDS had become the most dreaded disease of its day, replacing cancer as the most dreaded incurable disease. AIDS has a maximum incubation period of a decade or more. Those detected as HIV-positive face not only the almost certain possibility of developing full-blown AIDS but also discrimination in the workplace, in health insurance coverage, and in countless interpersonal relationships.

Without the discovery of HIV, nevertheless, the research path that may ultimately lead to immunization against the disease and possible cures for it would undoubtedly be blocked. For HIV-positives, the discovery was in many ways a mixed blessing. Many equate their status with certain death when the seemingly inevitable onset of AIDS occurs. On the other hand, knowing their status enables HIV-positives to embark on courses of treatment that can delay the onset of AIDS.

As investigation into AIDS has progressed, the relationship between HIV and AIDS has been questioned. Studies, however, have concluded that HIV infection is an absolute concomitant for the development of AIDS. Although quibbling over salient details continues, the impact of the Gallo/Montagnier discovery of HIV has been enormous. Their findings became the all-important first step in understanding what causes AIDS and in moving toward its control.

See also AIDS; Immunology; Oncogenes; Viruses.

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—*R. Baird Shuman*

Hybridomas

The Science: When a mouse cell that makes antibodies is joined with a fast-growing human tumor cell, the resulting hybrid cell, or hybridoma, grows rapidly and produces large amounts of antibodies.

THE SCIENTISTS:

César Milstein (b. 1927), Argentinean biochemist
Georges J. F. Köhler (b. 1946), German immunologist and cell biologist
Niels K. Jerne (1911-1994), Swiss immunologist

LYMPHOCYTES AND ANTIGENS

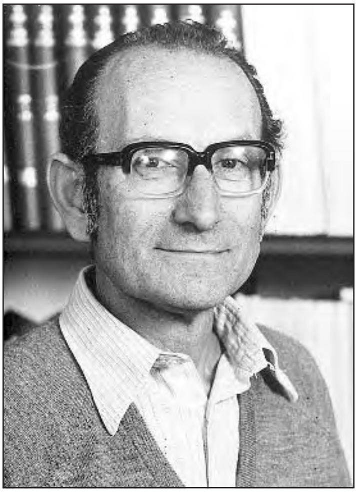
Antibodies are special proteins that recognize dangerous chemicals, viruses, and bacteria that get inside the body. Antibodies are made by blood cells called lymphocytes. When foreign substances, which are called antigens, enter the body from outside, several lymphocytes respond, each of which begins to make antibody molecules. Each antibody molecule attaches tightly to an antigen molecule, which is the first step in making the antigen harmless.

The human body can make about a million kinds of antibodies, but each lymphocyte makes only one kind. Because many lymphocytes respond to each antigen that enters the body, however, many slightly different kinds of antibodies will be made that can attach to each antigen. Each lymphocyte can grow and divide itself a few times to make more antibody-producing lymphocytes, but they soon stop working, so not very much of each kind of antibody is actually made.

Antibodies are very useful for medical purposes and can also be used in scientific research that examines how the body works. Unfortunately, the use of antibodies for these purposes is limited, because people and animals make mixtures of antibodies and therefore little of any one antibody is produced. It was realized that the ability to make large amounts of a single, pure antibody would be very useful, and in the early 1970's, scientists were able to manufacture living cells, containing both human and mouse components, that could make pure antibodies.

WORKING WITH LYMPHOMAS

Many people worked hard in the 1950's and 1960's to learn why antibodies are produced when a lymphocyte recognizes an antigen. The Swiss biologist Niels K. Jerne was a pioneer during this period in developing theories about how antibodies are made and how they work. César Milstein, another leader in these early studies, was, along with other scientists, able to devise excellent experiments to test Jerne's theories. Milstein used tissue culture methods in his research. In other words, he removed lymphocytes and other cells from animals (mostly mice and humans) and kept them alive in dishes in his laboratory so that he could study them in great detail.



César Milstein. (The Nobel Foundation)

Some of the cells that he and his colleagues studied were abnormal lymphocytes that they obtained from human tumors called lymphomas. These tumor cells were very easy to keep alive: They duplicated themselves quickly in tissue cultures, and they made large amounts of antibodies. Unfortunately, the scientists could not control the kinds of antibodies made by the tumor cells. Georges J. F. Köhler, a brilliant young immunologist, was working with Milstein at the time trying to understand why it was impossible to control the kinds of antibodies produced by the tumor cells. By the early 1970's, Milstein and Köhler realized that what they needed was a new kind of cell that had both the excellent growth properties of the lymphoma tumor cells and the ability of normal lymphocytes to make specific kinds of antibodies in response to specific antigens.

Lymphocyte + Lymphoma = Hybridoma

The two scientists realized that it would be possible to engineer such a cell by means of a method called cell fusion. By treating mixtures of different cells with certain chemicals, they could join these cells. After several years of hard work, Milstein and Köhler succeeded in producing hybrid cells (hybridomas) that combined a lymphoma tumor cell from a human being and a single normal lymphocyte cell from a mouse. These hybrid cells had the best features of their human and mouse parents. They grew well to make more hybridoma cells, and they made large amounts of antibodies—called monoclonal antibodies—of the kind expected based on the lymphocytes that were used.

Impact

Hybridomas and the monoclonal antibodies produced by them have since been perfected and are now used in hundreds of laboratories around the world by scientists and physicians who require large amounts of pure antibodies. The great scientific importance of the immunologists' hard work was recognized in 1984, when Milstein, Köhler, and Jerne were awarded the Nobel Prize in Physiology or Medicine.

MONOCLONAL ANTIBODIES

Late in 1974, Georges Köhler, a postdoctoral student at the University of Cambridge Medical Research Council Laboratory of Molecular Biology, was formulating a project to develop a cell that would produce antibodies for specific antigens. His idea was simple: He planned to fuse a myeloma (bone-marrow tumor cell) with a normal lymphocyte. Lymphocytes are found in the spleen, where they produce immunoglobulin that attacks a particular site on an invading antigen. The resulting combination of a lymphocyte and a myeloma, if successful, would create a hybrid cell with the properties of both parent cells. It was hoped that the new hybrid would produce the same single antibody as the lymphocyte parent but be immortal like its myeloma parent.

Köhler designed an experiment to expose a mouse to a specific antigen, remove its spleen, mix the lymphocytes formed by the spleen with myeloma cells, and then attempt to create as many hybrids as possible. In discussing the experiment with César Milstein, director of the laboratory, Köhler foresaw two possible mechanisms for failure: Lymphocytes were bad fusers, and the chance of producing the desired antibody and identifying it was statistically thin. They decided that Köhler would have to make and screen nearly one thousand hybrids.

During his first experimental trial, Köhler injected a mouse with antigen, consisting of red blood cells from a sheep. For the myeloma parent, he used an azaguanine-resistant P3 myeloma line he had created with earlier cell fusion experiments. The parent cells successfully fused, and after several days Köhler identified the development of hybrids in the culture. In December of 1974, Köhler ran a plaque assay on the hybrids. If any hybrid cells were making antibodies specific for sheep red-blood cells, they would form halos in the culture surrounding the hybrids.

The assays were a success: Halos appeared around the hybrid cells. The experiment had produced the first myeloma-lymphocyte hybrid: a hybridoma. This cell had both the "immortality" of the myeloma cell and the antibody activity of the lymphocyte. Each hybrid cell was producing a clone of identical daughter cells, each creating the same immunoglobulin molecule—a monoclonal antibody. Köhler and Milstein called this type of antibody "monoclonal" because it was produced by a clone of one type of B lymphocyte (*monos* is a Greek work meaning "one").

The implications of such a discovery were monumental. Milstein contacted the British government in an attempt to secure a patent on the hybridoma technique. The patent office did not respond. On August 7, 1975, Köhler and Milstein published a three-page article in *Nature* outlining their findings. This short article revolutionized immunology, and, with its publication, the British government lost all chance of patenting the hybridoma technique.

Before hybridomas became available, antibodies were widely used in medicine and in research, but they were expensive and difficult to obtain and prepare. The availability of cells that continue making antibodies ceaselessly made it much easier to use antibodies, which thereafter were put to work in new ways.

They are helpful in studying cell-surface and tumor antigens. Because antibodies and antigens recognize one another so precisely, antibodies can be used to detect tiny amounts of antigens and to measure how much antigen is present. Physicians can use antibodies to test for viruses, bacteria, and various other poisonous or normal antigens in tiny amounts of blood. Therefore, antibodies have been very helpful in diagnosing diseases.

Antibodies are also widely used for ABO blood typing; to remove antigens quickly and completely from blood that is to be used for transfusions; and to prepare pure antibodies that are used to inoculate people and animals to protect them from dangerous viruses and bacteria. All these uses, and more that are being developed, have had a major impact on modern biology and medicine.

See also Blood Groups; Immunology.

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—Howard L. Hosick

HYDROSTATICS

The Science: Archimedes' theoretical and practical discoveries in hydrostatics as well as mathematics led to innovations in technological inventions as well as theory.

THE SCIENTIST:

Archimedes (c. 287-212 B.C.E.), mathematician and inventor

EUREKA!

The beginning of hydrostatics—the study of fluids at rest and under pressure by immersed objects—is attributed to the Greek mathematician Archimedes. The legend is passed down by Vitruvius, a Roman architect under Emperor Augustus.

King Hieron, grateful for the success of one of his ventures, wanted to thank the gods by consecrating a golden wreath. On delivery, the wreath had the weight of the gold supplied for it, but Hiero suspected that it had been adulterated with silver. Unable to make the goldsmith confess, Hiero asked Archimedes to devise some way of testing the wreath. Because it was a consecrated object, Archimedes could not subject it to chemical analysis. He pondered the problem without success until one day, when he entered a full bath, he noticed that the deeper he descended into the tub, the more water flowed over the edge. This suggested to him that the amount of overflowed water was equal in volume to the portion of his body submerged in the bath. This observation gave him a way of solving the problem, and he was so overjoyed that he leapt out of the tub and ran home naked through the streets, shouting: "Eureka! Eureka!"

Archimedes. (Library of Congress)

Vitruvius then goes on to explain how Archimedes made use of his newly gained insight. By putting the wreath into water, he could tell by the rise in water level the volume of the wreath. He also dipped into water lumps of gold and silver, each having the same weight as the wreath. He found that the wreath caused more water to overflow than the gold and less than the silver. From this experiment, he determined the amount of silver admixed with the gold in the wreath.

MATHEMATICAL ELUCIDATIONS

As amusing and instructive as these legends are, much more reliable and interesting to modern historians of science are Archimedes' mathematical works. These treatises can be divided into three groups: studies of figures bounded by curved lines and surfaces, works on the geometrical analysis of statical and hydrostatical

LEGENDS OF ARCHIMEDES

Few details are certain about the life of Greek mathematician Archimedes, born in the third century B.C.E. Ancient writers agree in calling him a Syracusan by birth, and he said his father was the astronomer Phidias. He may have been an aristocrat who participated in the Syracusan court; he certainly was friendly with King Hiero II and Hiero's son Gelon, to whom he dedicated one of his works.

Archimedes traveled to Egypt once or possibly twice to study in Alexandria, then the center of the scientific world, where he made friends with Alexandrian scholars and may have worked on the construction of dikes and bridges. He may have visited Spain before returning to Syracuse, where he then spent his time working on mathematical and mechanical problems.

Stories multiplied about him. Archimedes became a symbol of the learned man: absentminded and unconcerned with food, clothing, and the other necessities of life. He was depicted as the quintessential sage, with a heavily bearded face, massive forehead, and contemplative mien. He had a good sense of humor. He often sent his theorems to Alexandria, but to play a trick on some conceited mathematicians there, he once slipped in a few false propositions so they would fall into the trap of proposing impossible theorems.

Unfortunately, many stories about Archimedes are doubtful. For example, he is supposed to have invented an early water pump, but this device—now called the Archimedean screw—antedates its supposed inventor. In a well-known story from Plutarch, Archimedes boasted to King Hiero that, if he had a place on which to stand, he could move the Earth. Hiero urged him to make good this boast by hauling ashore a fully loaded, three-masted ship of the royal fleet. Using a compound pulley, Archimedes, with modest effort, pulled the ship out of the harbor and onto the shore. The compound pulley may have been Archimedes' invention, but the story is fiction. Perhaps the most famous story is that Archimedes jumped naked from a bathtub shouting "Eureka! I have found it!" upon realizing the principle of water displacement, the basis for modern hydrostatics. Although the foundations may lie with Archimedes, the story is apocryphal.

When the Roman army attacked Syracuse, Archimedes is said to have helped defend the city with missile launchers and cranes. One more story relates that he was so focused on a geometrical diagram he had drawn in the dirt that he ignored an approaching Roman soldier, who killed the mathematician with a sword.

problems, and arithmetical works. The form in which these treatises have survived is not the form in which they left Archimedes' hand: They have all undergone transformations and emendations. Nevertheless, one still finds the spirit of Archimedes in the intricacy of the questions and the lucidity of the explanations.

In *Peri ochoymenon* (c. 230 B.C.E.; *On Floating Bodies*, 1897), Archimedes' cool logic contrasts with the legendary emotion upon discovery of the buoyancy principle. In this work, Archimedes proves that solids lighter than a fluid will, when placed in the fluid, sink to the depth where the weight of the solid will be equal to the weight of the fluid displaced. Solids heavier than the fluid will, when placed in the fluid, sink to the bottom, and they will be lighter by the weight of the displaced fluid.

IMPACT

Archimedes' achievements went beyond the initiation of hydrostatics to include significant contributions to geometry, statics, optics, astronomy, and engineering. He proves the law of the lever geometrically and then puts it to use in finding the centers of gravity of several thin sheets of different shapes. By center of gravity, Archimedes meant the point at which the object could be supported so as to be in equilibrium under the pull of gravity. Earlier Greek mathematicians had made use of the principle of the lever in showing that a small weight at a large distance from a fulcrum would balance a large weight near the fulcrum, but Archimedes worked this principle out in mathematical detail. In his proof, the weights become geometrical magnitudes acting perpendicularly to the balance beam, which itself is conceived as a weightless geometrical line. In this way, he reduced statics to a rigorous discipline comparable to what Euclid had done for geometry.

In his own lifetime, Archimedes' works were forwarded to Alexandria, where they were studied and dispersed. Two major Greek collections of Archimedes' works made by the mathematical schools of Constantinople were later passed on to Sicily and Italy, and then to northern Europe, where they were translated into Latin and widely published after the sixth century C.E. Because none of the Greek collections is complete, Arabic collections and associated commentaries were used to tabulate the works attributed to Archimedes.

Knowledge of Archimedes' ideas multiplied during the Renaissance, and by the seventeenth century his insights had been almost completely absorbed into European thought and had deeply influenced the birth of modern science. For example, Galileo was inspired by Archimedes and tried to do for dynamics what Archimedes had done for statics. More than any other ancient scientist, Archimedes observed the world in a way that modern scientists from Galileo to Albert Einstein admired and sought to emulate.

See also Ballistics; Stratosphere and Troposphere.

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—Robert J. Paradowski

HYDROTHERMAL VENTS

THE SCIENCE: John B. Corliss and Robert D. Ballard discovered deep-sea hot springs and collected previously unknown life-forms from them.

THE SCIENTISTS:
Robert D. Ballard (b. 1942), marine geologist
John B. Corliss (b. 1936), oceanographer
John M. Edmond (b. 1943), marine geochemist

THEORIES OF SEAFLOOR SPREADING

Coincidence and science often work together. Some of the truly great scientific discoveries have been made when researchers stumbled onto a new insight or fact while they were working toward an unrelated goal. A group of previously unknown life-forms in the deep sea were discovered by just this sort of serendipity, or happy coincidence.

Earth scientists' idea of how the Earth works changed dramatically in the mid-1960's, when the theories of seafloor spreading and plate tectonics began to make sense to many scientists. The Earth's surface is made up of a number of rigid plates, which move away from each other along spreading centers. These centers are located mostly in the major ocean basins; for example, one of them stretches down the length of the Atlantic Ocean. A spreading center looks like a long valley running between a matching pair of deep-sea mountain ridges.

At their outer edges, the Earth's plates collide with one another; these edges are called "convergent boundaries." Mountains and active volcanoes often form along these boundaries; the Andes Mountains of South America are an example.

Long ago, earth scientists understood that the force needed to push or pull these plates across the Earth's surface must be phenomenal. According to the theories, circulation "convection cells" of molten rock rise from deep in the Earth toward the surface (at a spreading center). The molten rock makes cracks in the plate and then forces its way into the cracks. The older, rigid rocks on either side of the cracks are pushed away from the central valley. New rock is continually being formed in the central valley, while old rocks are pushed aside, and everything on the plates on either side of the spreading center moves away from the ridge. This process takes millions of years.

Earth scientists realized that the concentration of molten rock in the central valleys should heat the water in the cracks between the rocks in the valley floor. Some thought there might be hot springs (like those in Yellowstone Park) deep in the ocean.

A Voyage to the Depths

In 1977, a group of oceanographers went to an area of the Pacific Ocean near the Galápagos Islands to search for hydrothermal (hot water) springs. The team towed a remotely operated camera and a sled carrying other instruments behind their ship, the deep submersible *Alvin*. The sled carried temperature sensors that could detect any slight increase in water temperature at the ocean floor.

The team included Robert D. Ballard, who worked at the Woods Hole Oceanographic Institute near Boston. He had already used *Alvin* and the instrument sled to study other ridge systems in the ocean. John B. Corliss of Oregon State University and John M. Edmond of the Massachusetts Institute of Technology were also part of the team, along with marine geologists and other oceanographers.

The remote instruments did detect some temperature variations, and photographs showed that there tended to be large clam shells in places

A Titanic Undertaking

After Robert D. Ballard completed his Galápagos expedition, he began to think that an old dream of his might become a reality: With improvements to the deep-sea submersible *Alvin* continually being made, he might be able to locate the giant ship *Titanic* on the ocean floor. *Titanic*, which had sunk in 1912 on its first voyage from England to New York City, was thought to lie some 13,000 feet below the surface of the Atlantic Ocean—too far for divers or previous submersibles to reach.

Ballard was able to gather funding and the support of the Navy, and in 1982 he established the Woods Hole Deep Submergence Laboratory (DSL), which developed *Argo*, a sophisticated video sled about the size of a car, with floodlights and three cameras, and *Jason*, a smaller tethered robot vehicle that could be sent into the ship's tight spaces. The *Argo-Jason* system enabled a research crew onboard a ship to send and steer cameras into the dark ocean depths.

When testing of *Argo-Jason* was completed, Ballard and a team of French scientists launched a joint effort to locate the *Titanic*. The French, with their sophisticated sonar technology, would map the ocean floor in the area where the *Titanic* was thought to rest in order to determine a smaller area for *Argo* to search. For five frustrating weeks, the French covered a 100-mile target area but did not locate the ship. A few days before the French left the area, Ballard and his team arrived. Drawing on the French data, the Americans limited their search to a narrower area and located the *Titanic* late in the night of August 31, 1985. A year later, Ballard returned to *Titanic*, this time sending *Jason* into the ship itself to photograph the interior. The pictures of the ship, with its recognizable central staircase and unopened bottles of wine, captured the imaginations of viewers around the world.

The search for famous shipwrecks continued: In 1989, Ballard established the JASON Project, a program that sent live images from *Jason* video robots to students at museums and science centers so that they could experience some of the wonders of the undersea world. In the 1990's, he located and photographed the German battleship *Bismarck*, American and Japanese warships sunk during World War II at Guadalcanal, the luxury ship *Lusitania*, and several trading ships from the Roman Empire—some as old as two thousand years. Thereafter, Ballard dedicated his time to expanding the field of underwater archaeology, founding the Institute for Exploration in 1997.

where the temperature was different from normal. The scientists brought *Alvin* closer to investigate.

At the bottom, more than 2,500 meters below the ocean's surface, they found clear evidence of hot springs. In fact, the water near the rocky bottom was shimmering because of the difference in temperature between the normal bottom water and the water that came out of cracks on the seafloor. The scientists also noticed that many of the rock surfaces in these areas were dusted lightly with a white material.

The researchers decided that the hot water coming out of the rocks must be carrying minerals that remained dissolved in hot water but "froze" once the hot water began mixing with the very cold bottom water. In a few places, the hot water was coming out in a concentrated jet so that as the minerals solidified, they formed a hollow chimney. As a result, some of the hydrothermal areas looked like factories with smokestacks (and were nicknamed "black smokers").

Deep-Sea Colonies

Around the vents, the scientists discovered fascinating biological communities that included gigantic clams, tube worms, and crabs, as well as some organisms that were new to science. Investigating further, the researchers discovered some inactive vents that were surrounded by re-

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mains of similar creatures. This made it clear that the organisms were finding their nourishment in the environment of the vents.

Most of what is known about biological communities comes from environments on or near the Earth's surface, where the Sun provides energy and where the photosynthesis of green plants is the final source of most nutrients. In the hydrothermal vent communities on the deep-sea floor, however, scientists had come upon an ecosystem whose basic food chain was a mystery.

Water samples were taken from near the vent and analyzed; they proved to contain high concentrations of a type of dissolved sulfur called "sulfide." When the water was filtered and the filters were examined, chemists found large quantities of a kind of bacteria that use dissolved sulfide as the basis of their biochemistry. When clams and worms from these areas were examined, they were found to contain this kind of bacteria.

The researchers concluded that in this deep-sea world without sunlight, there are thriving communities that use the Earth's internal heat as their basic energy source. The food chain in these communities is based on chemicals leached out of the heated rocks and carried up on water jets to the seafloor surface, where bacterial colonies live. It seems that the vents are not permanent (they may last only thirty or forty years), and when they no longer supply the sulfide-rich water, the communities collapse.

Impact

After the hydrothermal vents and deep-sea communities were discovered near the Galápagos Islands, researchers began searching around the world for similar deep-sea vent systems. The original research team had not included a biologist, so the geologists on the team found themselves trying to answer the many questions that marine biologists in different parts of the world were asking. Scientists have continued to try to understand how the organisms in the deep sea find their way to new hot-water vents to form communities. Many questions remain.

See also Amino Acids; Continental Drift; Earth's Core; Earth's Structure; Geomagnetic Reversals; Microfossils; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating; Seafloor Spreading.

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—*Richard W. Arnseth*

IMMUNOLOGY

THE SCIENCE: The concept of phagocytosis as a defense mechanism of the body and the mechanism of action by antitoxins and cell receptors provided the springboard for advances in immunology.

THE SCIENTISTS:

Élie Metchnikoff (1845-1916), Soviet biologist, microbiologist, and pathologist who advanced phagocytosis as a defense mechanism of the animal body in the inflammatory response

Paul Ehrlich (1854-1915), German research physician and chemist who advanced the concepts of acquired and passive immunity

Carl Claus (1835-1899), Austrian zoologist, keenly interested in the phagocytosis theory

INFECTIOUS DISEASE

In 1796, Edward Jenner introduced the first vaccination against smallpox—so named to distinguish it from syphilis, the "great" pox—by employing cowpox pustule exudate as the inoculant. By so doing, he used a principle of animal biology that he and other scientists did not yet fully understand. Jenner's success rested on the principle of immunity, the body's own ability to attack and prevent disease.

Immunity can be defined simply as the state of protection against disease, particularly infectious disease. It is the response of the animal body and its tissues to an assault by a variety of disease-causing agents, or antigens. In the context of present-day knowledge, understanding, and research in the field of immunity, the definition is as uninformative as a definition of life. The weakness of the definition is not in what it covers, but rather what it leaves out for the sake of brevity.

In the context of late nineteenth century science, the field of immunity, aside from being young, was fraught with seemingly incongruous results. Élie Metchnikoff and Paul Ehrlich, who shared the 1908 Nobel Prize in Physiology or Medicine for their work in immunity, provided two significant insights that opened the door to the understanding and direction of research in immunity. Their work paved the way for the effective development and use of vaccination, chemotherapeutic treatment of infectious disease, and even organ transplants.

Paul Ehrlich. (The Nobel Foundation)

METCHNIKOFF: UNDERSTANDING PHAGOCYTOSIS

Metchnikoff correctly interpreted and advanced the concept of phagocytosis as a major mechanism by which the animal organism combats foreign particles and disease organisms invading the body. He first used the term "phagocyte," derived from the Greek, in Carl Claus's *Arbeiten* (1893; work). Metchnikoff was educated as a zoologist, but his studies led him increasingly into the field of pathology. In 1865, he made the first observation that would lead to his concept of phagocytosis as a disease-fighting mechanism. Metchnikoff examined the intracellular digestion in the round worm *Fabricia*, which compared with that of protozoans. Although this phagocytic-type process was originally discovered and noted in 1862 by Ernst Haeckel, it was Metchnikoff who correctly interpreted the relationship between phagocytic digestion and phagocytic defense mechanisms.

In 1882, while studying transparent starfish larvae, Metchnikoff observed mobile cells engulf foreign bodies introduced into the larva. He noted that these cells arose from the mesoderm layer (middle layer of the embryo) rather than the endoderm layer, which is associated with the digestive system. Metchnikoff examined the degeneration of the tadpole tail and observed that it occurred by the phagocytic process also. These observations led him to spend the next twenty-five years in developing and advancing his theory of phagocytosis. The need for phagocytosis in an actively diseased animal led him to study a fungus infection of the water flea, *daphnia*.

Metchnikoff demonstrated that human white blood cells also develop from the mesodermal layer and serve the role of attacking foreign bodies, particularly bacteria. These ideas were revolutionary because, at the time, one school of thought held that the leukocytes were responsible for nurturing and spreading bacterial infection throughout the body. Indeed, the observation of many white blood cells in the blood of patients who died of infection added resistance to Metchnikoff's phagocytosis theory. As advanced by Julius Cohnheim, the inflammatory response was believed to be operative only in higher animal life that possessed a cardiovascular system. Metchnikoff had demonstrated the principle of inflammatory response in lower life-forms devoid of such a system.

It was in the study of the higher animal systems that Metchnikoff faced his most significant challenge in understanding phagocytosis and disease. His choice of infection was the anthrax bacillus. His observations appeared to conflict because phagocytosis seemed to be limited, depending upon the virulence—very virulent bacillus were not attacked while weaker bacillus were. Complicating the study was the observation that resistant animals exhibited active phagocytosis, while susceptible stock displayed no phagocytosis. Metchnikoff was up against the multifaceted complexity of immunity—the humoral versus cellular dichotomy—and the basis of his day's confusion and controversy in immunity studies.

Beginning in 1883, Metchnikoff's ideas were published in Rudolf Virchow's *Archiv für pathologische Anatomie und Physiologie, und für klinische Medizin* (archives for pathological anatomy and physiology and clinical medicine). By 1892, phagocytosis in combating disease was established and published in *The Comparative Pathology of Inflammation*. Metchnikoff wrote a comprehensive book in French in 1901, *L'Immunité dans les maladies infectieuses*, reviewing both comparative and human immunology, which proved a defense of his phagocytosis theory. The book was translated in 1905 under the title *Immunity in Infective Diseases.*

Ehrlich: Toxins and Antitoxins

While Metchnikoff wrestled with establishing phagocytosis as a mechanism of defense in disease, Ehrlich studiously examined antitoxins. His first major accomplishment was the improvement of the effectiveness of the diphtheria antitoxin discovered and developed by Emil von Behring. He also performed fundamental experiments leading to his views on active and passive immunity. His research on antitoxin and immunity led to the development of his side-chain theory, a concept of specific cellular responses toward toxins and antitoxins. This theory led to the concept of cell receptors—the basis of the cell's chemical specificity for certain chemical substances.

Whereas Metchnikoff studied the factors associated with phagocytosis and thus the cellular aspect of immunity, Ehrlich studied the factors associated with the humoral aspects of immunity—immunity embodied in the body fluids. Ehrlich's research of toxins and antitoxins aided later studies and the development of an understanding of antigens and antibodies (immunoglobulins). Ehrlich's accomplishments were the introduction of quantification and graphical representations of the relationships existing between toxins and antitoxins.

Additionally, he introduced practical and appropriate in vitro systems within which to study these complex associations, selecting erythrocytes as the simplest case in test-tube experiments. Ehrlich reproduced essentially the same effects in these test-tube experiments as observed in the animal body, particularly in the case of the plant toxin ricin. Most important, a complex series of experiments established that the lethality of a toxin and its ability to bind to an antitoxin are two separate and independent properties of the toxin.

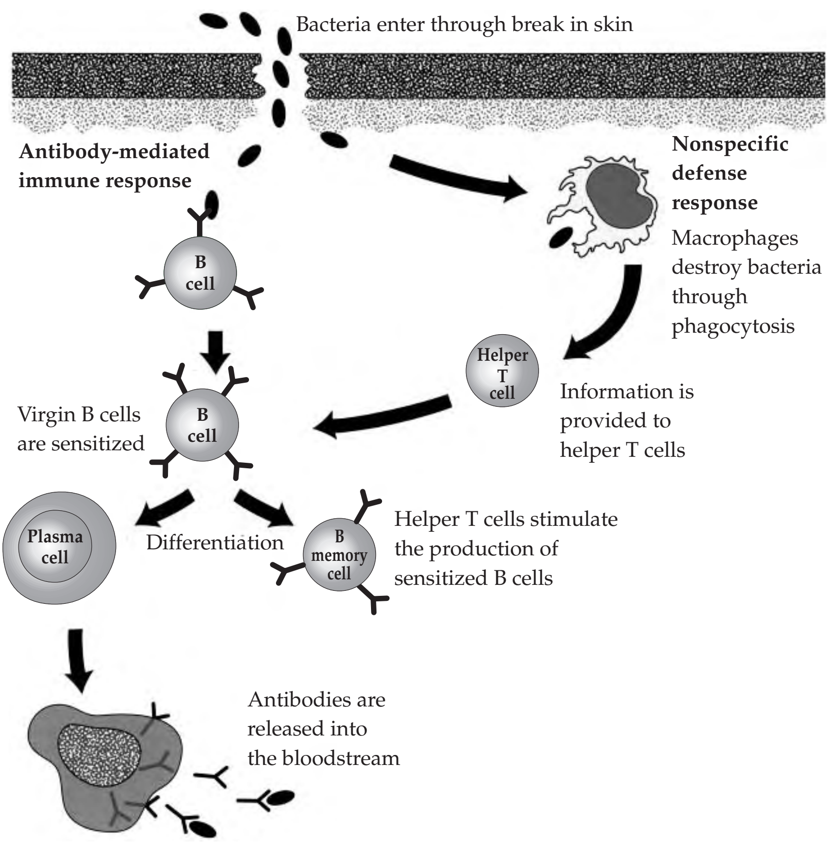
Ehrlich's work with ricin established that animals can build an immunity to such toxic substances by administration of initially minute doses, gradually increasing over time. Furthermore, he demonstrated in mice the transference of this immunity to the offspring through maternal milk. From his work on diphtheria toxin, he developed a quantitative standardization method for antitoxin dosage characterization.

Ehrlich's work in immunity arose from his study of blood, particularly staining with various dyes. These studies convinced him that the cell does bind certain dyes by distinct chemical affinities. The variously discovered blood components and the differential staining methods he developed not only prepared him for his immunity research but also marked Ehrlich as the founder of modern hematology. Additionally, the Wassermann test for syphilis, developed by August von Wassermann in 1906, was a direct outgrowth of Ehrlich's immunological research and views.

IMPACT

Prior to the phagocytosis doctrine advanced by Metchnikoff, the commonly held view was that resistance to bacterial infection resided in chemical properties of the blood. This view enjoyed reinforcement because antibodies in blood had been demonstrated. In 1903, the English scientists Sir

The Response of the Immune System to Bacterial Infection



(Hans & Cassidy, Inc.)

Almroth Edward Wright and Stewart Douglas demonstrated the presence of substances in blood, called opsonins, that seem to prepare bacteria for phagocytosis by white blood cells by binding to the bacterial surface. Thus, the phagocytosis doctrine appeared to require a precondition, a pre-coated bacterium that was engulfed. In the ensuing years, the role of phagocytosis and antibody formation became better defined. Phagocytosis is but one mechanism of defense offered by the host against infection. Its activation depends upon whether the infective organism is within the cell (intracellular) or outside the cell (extracellular).

Phagocytosis is most pronounced in acute (extracellular) infection, although bacteria protected by a capsular coat are not readily attacked. Phagocytosis is of limited importance in the case of intracellular infections, such as viruses. In the early stages of infection, antibody production has not yet begun. Thus, phagocytosis is the first defensive action initiated against foreign microorganisms. The administration of antibiotics slows bacterial growth and multiplication, permitting phagocytic blood cells to kill these small populations.

Present-day knowledge of defense against infection lists several types of cells involved. A division of labor exists in which some cells detect byproducts of infectious organisms and release immunoglobulins to inactivate the toxic properties of these antigens. Cells of this type are B cells and usually are short-lived. Cells that kill foreign cells are known as T cells. Cytotoxic, or killer T cells, eliminate foreign cells directly. TH cells assist B cells to differentiate and proliferate. TA cells amplify differentiation and proliferation of the T cells. T cells suppress the immune response and are important in policing the body's own attack on itself.

Ehrlich's work in immunity had far-reaching consequences for general medicine. His studies provided the earliest methods of standardization of bacterial toxins and antitoxins that are still employed and are unaltered essentially from his original methods. He demonstrated further that the lethal action of toxin and its antitoxin-binding potential are actually two separate and distinct properties of the toxin. Additionally, with ricin, Ehrlich demonstrated that a lag-time exists between exposure to a toxin and the manufacture of antibodies against it. Furthermore, Ehrlich distinguished clearly between the concepts of active immunity and passive immunity during his studies of immunity transmission through milk and placenta.

Through these studies—all of which rested on Ehrlich's fundamental belief in chemical affinities between a cell and chemical substances—he went on to study ways of curing disease by chemical means. His early work and successes with trypanosome infection utilizing trypan-red and Atoxyl derivatives led to his most celebrated application of Salvarsan, an arsenical, as a cure for syphilis.

Armed with new knowledge, understanding, biotechnology, and insight into the mechanics of immunity and chemotherapy, modern medicine can fight microorganisms now on their own ground—the molecular level—and win.

See also AIDS; Human Immunodeficiency Virus; Smallpox Vaccination.

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—*Eric R. Taylor*

IN VITRO FERTILIZATION

THE SCIENCE: When Lesley Brown gave birth to the first "test-tube baby," aided by the pioneering efforts of Drs. Robert Geoffrey Edwards and Patrick Christopher Steptoe, a new area of medicine opened, reproductive medicine.

THE SCIENTISTS:

Patrick Christopher Steptoe (1913-1988), the obstetrician who delivered Louise Joy Brown

Robert Geoffrey Edwards (b. 1925), biologist who designed the methods of in vitro fertilization and early embryo development

Jean M. Purdy, laboratory technician who designed the apparatus for retrieving the egg cells

HELP FOR INFERTILE COUPLES

As a medical student in the 1930's, Patrick Christopher Steptoe was concerned about the plight of women coming to his clinic with blocked reproductive tubes that prevented fertilization and travel of an embryo to the uterus for development. After moving to a position at Oldham General Hospital in 1951, he developed the technique of laparoscopy to study the internal abdominal area. He used a flexible source of cool light and fiber optics to visualize, move, and even take samples from the ovaries and other organs through a small incision in the naval.

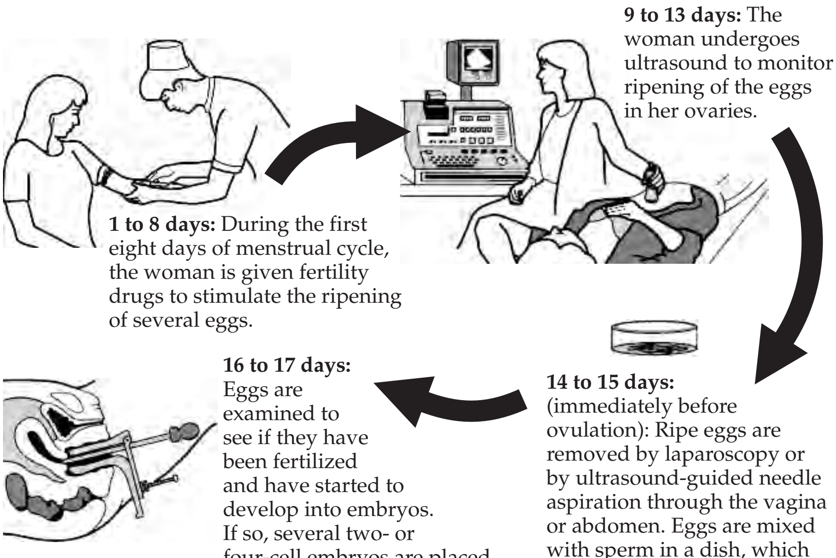
In the 1950's, Robert Geoffrey Edwards was a student in zoology, and, later, genetics, working on the immunology of reproduction and on embryos. Edwards and Steptoe met at a scientific meeting in 1968 in London. They spent the next several years working on perfecting the techniques of oocyte ripening and fertilization in the culture dish.

In 1969, they published a paper in the journal *Nature* about the ripening of twenty-four of fifty-six human oocytes and subsequent fertilization of some of them in the culture. It was at this point that they began to involve patients. Steptoe obtained by laparoscopy already ripe oocytes from the ovary follicles, areas of the ovary where oocytes matured. Edwards and Jean M. Purdy, who designed the apparatus to retrieve the oocytes, would attempt to fertilize the oocyte using the husband's spermatozoa. Within a short time, they had routine fertilization and some development of the embryo in the culture dish, called "in vitro fertilization."

Joyous Success

In 1971, they moved their research to Kershaw's Cottage Hospital in Royton, near Oldham, and in 1972, they started transplanting embryos into female patients. They were not successful until the summer of 1975. The elation of those early weeks was ended when the pregnancy developed prob-

The Process of In Vitro Fertilization



1 to 8 days: During the first eight days of menstrual cycle, the woman is given fertility drugs to stimulate the ripening of several eggs.

9 to 13 days: The woman undergoes ultrasound to monitor ripening of the eggs in her ovaries.

14 to 15 days: (immediately before ovulation): Ripe eggs are removed by laparoscopy or by ultrasound-guided needle aspiration through the vagina or abdomen. Eggs are mixed with sperm in a dish, which is then incubated.

16 to 17 days: Eggs are examined to see if they have been fertilized and have started to develop into embryos. If so, several two- or four-cell embryos are placed in the woman's uterus.

(Hans & Cassidy, Inc.)

lems and had to be terminated at seven weeks. The report of their results, however, made medical history after being published in the journal *The Lancet* on April 24, 1976. A few more pregnancies occurred and ended prematurely on their own before Edwards and Steptoe, revising the process, decided to use the natural reproductive cycles instead of hormone treatment.

Finally, true success occurred in late 1977. Lesley Brown was the second patient to go through the regime of urine collection every three hours to check natural hormones in order to decide when the oocyte would be ready to be ovulated. A ripe oocyte was collected on the first try and was fertilized without problems. The embryo was placed into her uterus just after 12 A.M. on November 13, 1977. In three weeks, Lesley Brown was informed that the hormone level screening from urine and blood tests was positive for pregnancy.

A cesarean section was planned and carried out with health officials filming and the world almost literally watching. At 11:47 P.M. on July 25, 1978, Louise Joy Brown—at five pounds and twelve ounces, the world's first "test-tube baby"—was born. Months later, Steptoe and Edwards were greeted by a standing ovation at the Royal College of Obstetricians and Gynecologists as they presented their work.

IMPACT

The controversies and acclaims over in vitro fertilization techniques began in 1966 and have not ended, although today the technique is well established and widely used, leading to the births of tens of thousands of babies. Arguments in favor of the technique include an expected increase in the number of successful test-tube babies, the growth of cells that might be used to replace defective tissues or organs in humans, and the understanding of normal human development that may help doctors prevent defective births.

One of the major concerns of early critics was over "informed consent." Edwards and Steptoe always stated how they explained that the methods, being experimental, "might" result in a pregnancy. Gena Corea, in her book *The Mother Machine* (1985), gave evidence that many of the women in the early experiments were treated more like research subjects than patients, and she doubted that Edwards and Steptoe understood this. She concluded that these women would have subjected themselves to anything to have a child. Corea cautioned that their consent resembled coercion caused by societal and family pressures to have a child.

There were also those who argued that in vitro fertilization is unnatural and could lead to genetic screening for certain perfect offspring and the destruction of others for increasingly trivial reasons, including being the "wrong" sex. Such issues have become increasingly important in the discussions of ethics committees connected with hospitals and clinics.

See also Ova Transfer.

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—*Judith E. Heady*

INCOMPLETENESS OF FORMAL SYSTEMS

THE SCIENCE: Kurt Gödel proved that certain formal systems of mathematical axioms (large enough to model arithmetic) were not complete; that is, all true statements in such systems could not be derived from axioms.

THE SCIENTISTS:

Kurt Gödel (1906-1978), Austrian mathematician
Bertrand Russell (1872-1970), English logician
David Hilbert (1862-1943), German mathematician

THE TROUBLE WITH GEOMETRY

In the nineteenth century, logicians and mathematicians were eager to make the foundations of mathematics more formally exact than had previously been possible. The discoveries that had produced this energy were in geometry and logic. Around the middle of the century, Georg Riemann (1826-1866) and others had invented new geometries. Their axioms and rules of deriving theorems were the same as those of Euclid, the ancient Greek geometer, except that one axiom had been altered.

This axiom required that "through a point outside a line only one parallel line can be drawn." For hundreds of years mathematicians had been unsuccessfully trying to determine whether this axiom could be derived from the others or was truly an independent statement. In the new geometries, the axiom was replaced by a "transplant." Some new choices included allowing "parallel lines to meet at infinity."

Logicians tried to find methods of determining whether a proposed system of axioms was consistent and complete. To be consistent, the system could not be used to derive contradictory statements. David Hilbert and others proved that the new geometries (and the old one) were consistent. To be complete, there had to be enough axioms to derive all true statements (theorems) from them. Proofs of the completeness of the geometry, and even arithmetic, were not so successful. In 1900, Hilbert proposed that proofs of completeness should be a priority for future research. His student, Kurt Gödel, took up the challenge.

Methods of proving things had improved in the nineteenth century because of the invention of ways to "model" the arguments of one system in another. For example, geometric statements, such as "these two lines cross," could be modeled by algebraic statements, such as "these two equations have a common number as a solution." Statements in simple logic, such as "x and y cannot both be true," could be modeled in a kind of local arithmetic: x "plus" y equals "zero." Hilbert's suggestion was to model statements about axioms of geometry ("this system is inconsistent" or "this system is complete"). Then proofs in the model language would equal proofs in the system. He got as far as showing that the geometries were consistent and complete if arithmetic was complete. Now, what about arithmetic?

Image Not Available

Gödel's Proof

Late in the nineteenth century, Bertrand Russell had devised a logical calculus with which he hoped to formalize mathematics. His famous book (written with Alfred North Whitehead) was called *Principia Mathematica* (1910-1913). In it, he had shown that, mirrored in his symbols and their calculus, arithmetical arguments could be made precise. It took hundreds of pages to prove that "one plus one equals two." Mathematicians then tried to make equally exact statements regarding the completeness of arithmetic. Their method was to try to show that if valid statements could not be derived (proved) from axioms, then those statements were axioms themselves. If they found a statement that was neither an axiom nor a derivable theorem, the system was incomplete. Famous examples of this method date from antiquity. One such argument—that of finding a man from Crete who says that "all Cretans are liars"—is in every elementary logic book. The statement is both true and false, and hence "formally undecidable." It is not an axiom. Unless one is to doubt logic, one must reject the statement as an improperly formed piece of nonsense. Russell made this clear in the *Principia Mathematica*.

Gödel's proof involved finding a "Cretan-like" statement about mathematical proof expressed in Russell's symbols. He did this by assigning a "Gödel number" to each statement about arithmetic. The Gödel number was constructed by assigning prime numbers to each symbol and multiplying together all the numbers in the statement. Thus each statement had a unique "code" number. In fact, each argument (proof) had a code number. The Gödel numbers were made of primes, so they could be decoded exactly into their logical equivalents.

By manipulating his numbered arguments, Gödel found some valid statements that could not, he proved, be derived from axioms. These were statements about the completeness of the axiom system, not axioms themselves. They were "formally undecidable." Thus, in this way of modeling, arithmetic was not complete. Gödel showed that it was impossible to fix this by adding an axiom. If one did so, the new system would not be consistent. Arithmetic's axioms could be either complete or consistent, but not both. Gödel titled his famous 1931 paper "On Formally Undecidable Propositions in the Calculus of *Principia Mathematica*."

Impact

This new insight into mathematical logic has had many consequences. Some mathematicians think that the incompleteness results from the method of modeling, not the axioms themselves. They hope that new axioms or a better way to model the old ones will be possible. If not, then there will be undecidable theorems—even ambiguous "truths"—hidden in exact mathematics. Necessary theorems may not be derivable from the system. If needed, they then must be found by imagination, luck, or intuition. If so found they may not be provable, and the argument in which they appear can be doubted.

Through the work of Gödel, it has become clear that computer "logic" (particularly the method of "trial and error"), although it usually works, is not fully understood. New kinds of logic and subsequent new kinds of arithmetic, geometry, and calculus are arising either to adjust to Gödel's limitations or to bypass them. For example, "fuzzy" logics have been used to design autofocusing systems in cameras. Like an undecidable proposition, a focus setting can be "right" (in focus) and "wrong" (out of focus) at the same time. One must hope that the part of the picture that is in focus is the one that the user wants.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Peter D. Skiff*

Independence of Continuum Hypothesis

The Science: Paul Cohen proved that Georg Cantor's continuum hypothesis is independent of the axioms of set theory.

The Scientists:
Georg Cantor (1845-1918), German mathematician
Paul Joseph Cohen (b. 1934), American mathematician
Kurt Gödel (1906-1978), Austrian logician

The Continuum

Georg Cantor was one of a number of nineteenth century mathematicians (including Karl Weierstrass and Richard Dedekind) who provided the first adequate analyses of the real numbers, which are collectively known as "the continuum." He also proved that there are more real numbers than there are integers.

An integer is a number that can be expressed as the sum or difference of two natural numbers. The natural numbers, which are also known as the counting numbers, are 1, 2, 3, and so forth. The numbers –3, –2, and –1 are negative integers, and 1, 2, and 3 are positive integers. Rational numbers are those numbers than can be expressed as a ratio of two numbers, and the real numbers consist of all rational and irrational numbers.

It is not at all obvious that there are more real numbers than there are integers. For example, it would appear that there are more positive integers than there are even positive integers. If one counts the even numbers, however, using all the positive integers to keep track of the count, one soon sees that there are infinitely many even positive integers and an equal number of integers. Therefore, the set of all positive integers and the set of all even positive integers are the same size—in technical terms, the two sets have the same "cardinality."

Cantor proved that the set of integers and the set of real numbers have different cardinalities; indeed, he proved that the infinity of real numbers is larger than the infinity of integers. The set of real numbers is called "uncountable" for that reason. The number of integers, the smallest infinity, is referred to as "aleph null." Cantor proved that, for each infinite cardinal aleph$_{a}$, there is a bigger one that can be designated aleph$_{a+1}$. Furthermore, he proved that, for a set of cardinality aleph$_{a}$, the set of all of its subsets has the larger cardinality of 2^{alepha}. This means that there are two different ways of producing an infinite sequence of infinities. Finally, Cantor proved that the number of real numbers is $2^{\text{alephnull}}$. He also speculated—but could neither prove nor disprove—that $2^{\text{alephnull}}$ was equal to aleph$_1$, which is the next largest infinity after that of the number of integers. This speculation became known as the continuum hypothesis (CH).

Fate of the Continuum Hypothesis

Kurt Gödel showed in 1938 that the continuum hypothesis could not be disproved by using the basic axioms of set theory, which are known as "ZF" (these axioms provide the foundation of mathematics). Gödel's proof left the status of the hypothesis in doubt: Mathematicians did not know whether CH could be proved by means of the set-theory axioms or was independent of those axioms. Many mathematicians attempted to resolve the problem.

Finally, in 1963, Paul Cohen invented a new way of building mathematical models, which was known as "forcing." In the same way that the scale model of a bridge may reveal the structural integrity of its design, a mathematical model produced for a set of propositions can demonstrate that that set might be true (consistent). Using his forcing technique, Cohen produced models of both ZF with CH and ZF with the negation of CH. This showed that the axioms of set theory together with CH are consistent and also that those axioms together with the negation of CH are consistent. In other words, Cohen proved that the continuum hypothesis is independent of the axioms of set theory.

Because the continuum hypothesis can be neither proved nor disproved, one response to it is to accept it or reject it as a matter of convention. A similar situation arose in the nineteenth century in the field of geometry. Traditionally, the basic axioms of mathematics were deemed to be true on the basis of intuition. Euclid's geometry was based upon the "parallel postulate," which states that two parallel lines will never meet. Many mathematicians thought that this postulate was less likely to be true than Euclid's other axioms. After repeated attempts to prove it by using Euclid's other axioms, the parallel postulate's independence from those axioms was established, which led to the development of non-Euclidean geometries that denied the postulate in various ways. Non-Euclidean geometry has become a major field of study, and it is central to Albert Einstein's theory of relativity.

There is no agreement regarding the proper view of the continuum hypothesis. Gödel, for example, believed it to be false. He could not prove that his view was correct, but he pointed out that if new axioms based upon an intuitive understanding of sets were added, those new axioms would alter the formal concept of sets—possibly to the point at which the continuum hypothesis or its negation would become provable.

IMPACT

As Gödel's argument suggests, the ZF axioms are intuitively incomplete, and there is no agreement about how to extend them. Cohen's forcing method has been applied particularly to the building of models for new propositions about sets—especially propositions involving higher-order infinities. The models are used to explore the interdependencies of those propositions. Although some of those propositions do, in fact, entail either CH or its negation, none has come to be widely regarded as obviously true. So long as that is the case, one can put forward CH or its negation as a proposition that further refines the modern concept of sets.

Because set theory concerns the foundations of mathematics (it is used to define such basic concepts as "number" and "function"), the acceptance or rejection of CH does not appear to have immediate consequences for physical theory, unlike the acceptance or rejection of Euclid's parallel postulate in geometry. This means that physical theory offers no help in settling the debate. The nature of the higher-order infinities, and thus the nature of the sets used to construct them, is one of the great unresolved issues in mathematics.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Kevin B. Korb*

INFLATIONARY MODEL OF THE UNIVERSE

THE SCIENCE: Alan Guth proposed a new theory of cosmology that says that the current slow, linear expansion of the universe was rapid and exponential for a very brief period near the beginning of time.

THE SCIENTISTS:
Alan Guth (b. 1947), American physicist
A. D. Linde (b. 1926), Russian physicist
Paul J. Steinhardt (b. 1952), American physicist
Andreas Albrecht (b. 1927), American quantum chemist

THREE SERIOUS PROBLEMS

According to the big bang theory, the present universe emerged out of a region of space smaller than a proton 13.7 billion years ago. Originally, it was too hot for material particles to form. As the universe cooled, however, elementary particles were able to crystallize out of the high-energy sea; further cooling allowed these particles to form atoms, then molecules, then clouds, then stars and planets, and finally living beings.

There are at least three serious problems with the standard model of the big bang theory: the horizon problem, the smoothness problem, and the flatness problem. The horizon problem exists because the standard model of the big bang theory cannot explain why the universe is so uniform over such great distances. If the different parts of the universe are so separated that they cannot communicate with one another, even at the speed of light, then why do they look exactly the same? Just as animals on widely separated continents evolve differently, so should different parts of the universe evolve differently.

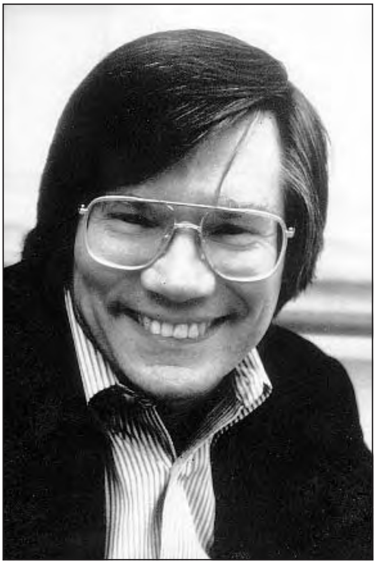
The smoothness problem is the opposite of the horizon problem. In an otherwise uniform universe, how were galaxies formed? These deviations from perfect uniformity must have arisen from tiny irregularities in the very early universe. The problem lies in the fact that ten billion years later, even tiny deviations from perfect smoothness in the early universe will result in enormous nonuniformity. Galaxies represent relatively minor disturbances in the uniformity of the universe.

The flatness problem relates to the energy density (or, equivalently, the mass density) of the universe. If the energy density is only slightly higher than a particular "critical value," the big bang will reverse eventually and be followed by a big contraction. If the density is slightly lower than this critical value, the current expansion will continue forever. If the density is exactly equal to the critical value, corresponding to a "flat" universe, the expansion will continue, but at a gradually slowing rate. Measured values of the present energy density yield results that are very close to the critical value. The flatness problem exists because any initial deviation from perfect flatness in the early universe is magnified tremendously by the subsequent expansion of the universe. To account for the current measured flatness of the universe, the early universe must have been flat to within one part in a thousand trillion (10^{15}). This is an unbelievable constraint on the allowed values for the initial flatness.

The horizon, smoothness, and flatness problems are dealt with in the standard model of the big bang model by simply assuming the specific initial conditions necessary to account for the present observed features of the universe. The fact that these conditions are assumed without any theoretical basis makes them arbitrary, which is considered to be a weakness in a physical theory. A good physical theory explains things; it does not assume them.

The Bubble Universe

The "inflationary model" of the big bang theory was proposed by Alan Guth in 1980 in an attempt to explain the horizon, smoothness, and flatness problems. Guth suggested that the very early universe, which he called a "bubble," underwent an initial, very rapid exponential expansion that was much faster than the linear expansion of the standard universe. This bubble inflated to become the present observable universe, which is thus embedded in a much larger unobservable universe. This exponential expansion increased the size of the universe by a factor of 10^{50}, from smaller than a proton to larger than a softball. Inflation began at 10^{-35} seconds after the big bang and ended at 10^{-33} seconds.



Alan Guth. (MIT News Office)

According to the inflationary model, the observable universe grew out of a region of space—the inflationary bubble—that was much smaller than was formerly believed. The material in this small primordial bubble was thus very densely packed and able to interact mutually for a longer period, homogenizing itself so that when it began to separate, all of it would evolve in the same way, thus solving the horizon problem. When the inflation occurred, the universe expanded dramatically, maintaining its newly established homogeneity, thus solving the smoothness problem. The flatness of the universe increased with the size of the universe, just as the flatness of a square drawn on a balloon increases as the balloon is blown up. By viewing the entire universe as being much larger, inflation explains successfully why the visible portion is so flat.

Furthermore, the inflationary model is able to explain the approximate distribution and size of the galactic clusters that populate the universe. In the original primordial bubble, the homogeneity would have been limited by the laws of quantum mechanics, which state that there will be small fluctuations even in a perfectly uniform region of space. These small fluctuations were magnified dramatically by inflation until they became the large structures that are seen as galaxies.

There were a few problems with Guth's original formulation. The most serious was the length of the inflationary epoch, which was too short to produce a universe of adequate size. In 1984, A. D. Linde, Paul J. Steinhardt, and Andreas Albrecht solved this problem and improved the inflationary theory, which is now widely accepted as the most likely explanation for the observed features of the present universe.

IMPACT

The inflation theory has helped to explain the actual origin of the universe itself, one of the deepest mysteries in science, which has repercussions for philosophy and religion. In a remarkable application of quantum theory, Guth has calculated that the tiny fluctuations present even in a vacuum—an empty region of space—might be adequate to initiate the process of inflation. According to quantum theory, which is very well established, a vacuum is not completely inactive. There must be a small energy field present that is fluctuating about zero. There is a probability that one of these fluctuations could erupt and produce a new universe. The laws of physics permit this because a universe such as Earth's has almost no net energy in it. The positive energy associated with all matter (Einstein's $E = mc^2$) is balanced by the negative energy associated with the gravitational force. If the universe is indeed flat, which both measurements and inflationary theory seem to suggest, then it has no net energy, indicating that it could have erupted from an empty vacuum—from nothing—without violating the law of the conservation of energy.

See also Big Bang; Black Holes; Cosmic Microwave Background Radiation; Expanding Universe; Galaxies; Quarks; Spectroscopy; String Theory; Wilkinson Microwave Anisotropy Probe.

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—*Karl W. Giberson*

INSECT COMMUNICATION

THE SCIENCE: Karl von Frisch discovered that honeybees returning to the hive use a so-called round dance to communicate to their comrades that food is nearby.

THE SCIENTIST:

Karl von Frisch (1886-1982), Austrian physiologist and student of animal behavior who was a cowinner of the 1973 Nobel Prize in Physiology or Medicine

BEE WATCHING

Karl von Frisch can be credited, in part, for several lines of experimentation, such as the study of color perception in bees and hearing in fish. It was his study of communication in bees, however, that brought him world fame and, in 1973, a Nobel Prize, which he shared with Konrad Lorenz and Nikolaas Tinbergen.

Many observers, including the ancient Greek philosopher Aristotle, have noticed that when honey or sugar water is placed near a hive, it may be many hours before a wandering bee discovers the food. Yet once the food is discovered, hordes of bees soon descend upon the new find. Obviously, in some way, the forager bee communicates information about the presence of food to other members of the hive. A few naturalists noticed the dancing movements of bees and speculated about what their meaning might be, but it remained for Frisch to perform the many years of exacting experiments that were needed to substantiate that dancing in bees is actually a form of communication.

Frisch's autobiography recounts the experiment that led to the most far-reaching observation of his life. At the time, he was at the Munich Zoological Institute, studying bees in a queen-breeding cage, which has glass sides so that all the bees can be seen easily. Frisch put out a dish of sugar water to feed foraging bees from the little glass-sided hive. He marked the bees that fed on the sugar water with small dots of red paint. He then removed the dish of sugar water, and the bees came less and less frequently. Finally, he once again put the sugar water out and allowed a bee to feed. He watched the behavior of the bee once it returned to the hive. As Frisch recalls in his autobiography:

Karl von Frisch. (The Nobel Foundation)

> I could scarcely believe my eyes. She performed a round dance on the honeycomb which greatly excited the marked foragers around her and caused them to fly back to the feeding place.

When Frisch and his family moved to Brunnwinkl, Austria, he continued his studies of the round dance as a form of communication in honeybees. The results of these early studies were published in 1920.

Learning to Dance

When the dancing bee performs the round dance, it moves in a tight circle to the right and then to the left, describing between one and two circles in each direction, and repeating the turning movements for half a minute or longer. The sweeter the food source, the more vigorous the dancing becomes. Typically, a group of bees surround the dancing bee and extend their antennas over the body of the dancing bee. This behavior allows the new recruits to detect odors adhering to the dancer's body. These odors enable the recruits to find the particular species of flower that is producing nectar, at distances of up to about fifty meters. During pauses in the dance, the dancer regurgitates nectar and feeds the bees around her. This nectar carries the scent of the flower that was visited.

Frisch also demonstrated that bees have color vision and can learn to seek out a given color that they have associated with food. He found that bees cannot distinguish red from black and can see ultraviolet as a distinct color. The patterns of color on flowers thus appear different to bees from the way they appear to humans. Individual bees use color vision to locate flowers they have already visited, but there is no indication that they can communicate colors to other bees.

It was another twenty years before Frisch discovered the workings of the more incredible "wagging dance" that was often performed by bees returning from a distance with loads of pollen. Upon closer inspection of bees fed four hundred meters north of their hives at Brunnwinkl in June of 1945, he discovered that this more elaborate dance communicates both direction and distance and is used for finds at more than fifty meters from the hive. The dancing bee moves in a figure-eight pattern, its movements followed by the outstretched antennae of forager bees. The greater the distance to the food, the slower the tail wagging performed by the dancing bee. If the tail wagging is in an upward direction, then the food is toward the Sun; and if the tail wagging part is downward, the food is away from the Sun. The biological clock of the bee gradually corrects the dance for changes in the apparent position of the Sun.

IMPACT

Frisch's publication of his 1919 observations on the round dance as a form of communication in bees did not result in either immediate fame or controversy, although eventually both would come. It was the steady stream of scientific papers on animal physiology and behavior, especially on fish and bees, that eventually established Frisch as the most widely known Austrian biologist. By World War II, his reputation allowed him to continue his work for a time, even though his mother was in danger for being of Jewish descent. Later, forced into isolation at Brunnwinkl, Frisch continued his research during the war years. It was there in 1943 that Frisch discovered the importance of the wagging dance.

Frisch's studies on the round dance honed the experimental techniques that he later applied to the wagging dance. The work with the round dance generally furthered Frisch's reputation, and it played a role in the development of the slowly emerging field of animal behavior.

See also Pavlovian Reinforcement; Population Genetics.

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—*John T. Burns*

INSULIN

THE SCIENCE: Sir Frederick Grant Banting and Charles Herbert Best isolated the hormone insulin, which saved the lives of countless diabetes patients.

THE SCIENTISTS:

Sir Frederick Grant Banting (1891-1941), Canadian physician who was awarded the Nobel Prize in Physiology or Medicine in 1923

Charles Herbert Best (1899-1978), graduate student in the University of Toronto's physiology department

James Bertram Collip (1892-1965), professor in the biochemistry department of the University of Alberta, Edmonton

John James Rickard Macleod (1876-1935), Scottish professor, cowinner of the Nobel Prize in Physiology or Medicine in 1923

SUGAR DISEASE

Diabetes mellitus has been known since ancient times. The disease in its juvenile form is induced by a deficiency in the "islets of Langerhans," part of the pancreas, which fail to produce the hormone insulin, a substance that is needed for the utilization of glucose by muscle cells. When deprived of their primary fuel (glucose), the muscle cells produce energy from fat, which results in high blood levels of toxic ketone bodies (acetone).

The diabetic has very high levels of glucose in the blood and urine. The patient consumes much fluid, produces much urine, and is always hungry and weak; yet, in spite of eating constantly, the patient loses weight. Once ketone bodies begin to accumulate in the blood, the brain ceases to function and the patient slips into a coma and dies.

The German histologist Paul Langerhans discovered, in 1869, some peculiar cells in the pancreas, which were later named "islets of Langerhans." The Swiss anatomist Johann Conrad Brunner, in 1682, showed that if he removed the pancreas, the experimental animals began to drink and urinate continuously. These findings, together with the realization by other scientists that there was a connection between the onset of diabetes and pancreatic lesions, led to a new era: the study of the pancreas as the causative factor of diabetes.

Thus, researchers in later years were able to produce diabetes in experimental animals by surgical removal of the pancreas. This led to the demonstration that the pancreatic islets of Langerhans are the source of the insulin necessary for the metabolism of glucose. Nevertheless, from 1910 to 1920, attempts to extract the active ingredient from the islets of Langerhans were unsatisfactory.

ISOLATING INSULIN

This was the situation when a young Canadian surgeon received an inspiration that would become the turning point in the search for the elusive

Sir Frederick Grant Banting. (The Nobel Foundation)

pancreatic hormone. On October 31, 1920, Sir Frederick Grant Banting was preparing a lecture on the pancreas for his medical class. After reading an article in the journal *Surgery, Gynecology and Obstetrics*, which reported that the blockage of the pancreatic duct caused the pancreas to shrivel, leaving the islets of Langerhans untouched, Banting had an idea. He began to see how it might be possible to isolate insulin in the pancreas of a dog. He realized that when one tried to extract the insulin from the islets of Langerhans, the pancreatic digestive juice destroyed the hormone before it could be isolated. By letting the pancreas shrivel first, there would be no digestive juice left and the hormone could be isolated intact.

Banting presented his idea to John J. R. Macleod, head of the department of physiology of the University of Toronto, and requested permission to conduct the necessary experimental work in his laboratory. Although Macleod did not believe in the existence of an islet hormone or that Banting would be able to prove otherwise, after long deliberations, he gave permission to Banting to use the facilities and provided him with a graduate student assistant, Charles Herbert Best.

Banting and Best began their experiments on dogs on May 17, 1921. On August 3, the two researchers had the first conclusive result showing that their pancreas extract lowered the blood sugar of dogs who became diabetic after their pancreases had been surgically removed. At first, Macleod was skeptical about Banting's report on the successful isolation of the antidiabetic hormone, and he made the two researchers repeat their experiments several times. After he was satisfied that the results were valid, he invited James Bertram Collip to join the group.

On December 12, Collip began working on the purification of the extract to make it injectable into humans. On January 23, 1922, it was tested on a fourteen-year-old boy dying of diabetes. The injection of the extract lowered his blood sugar and cleared his urine of ketone bodies and sugar.

The first official paper on the discovery, titled, "Internal Secretion of the Pancreas," was published in February, 1922, in the *Journal of Laboratory and Clinical Medicine* by Banting and Best. On October 26, 1923, the Swedish Nobel Committee awarded the Nobel Prize in Physiology or Medicine to Banting and Macleod for the discovery of insulin. The two winners, accompanied by Best and Collip, traveled to Stockholm two years later. On September 15, 1925, at the ceremonial presentation of the award, Banting shared his half of the prize with Best and Macleod followed suit by sharing his prize with Collip.

Impact

The importance of the discovery of insulin can be appreciated only when one considers the plight of the millions of diabetics in the pre-insulin era. In particular, one has to realize the tragic fate of diabetic children who, shortly after the onset of the disease, changed from healthy, active children into weak, drowsy skeletons who soon became comatose and died. One cannot describe the despair of parents when they were told the dreaded diagnosis of their child's disease, knowing quite well that it was the equivalent of a death sentence.

The discovery of insulin at the University of Toronto was one of the most revolutionary events in the history of medicine. Its impact was great because of the miraculous effect insulin had on diabetic patients. The most dramatic example of its spectacular power was its ability to conquer the diabetic coma. It has been estimated that at the start of the twentieth century, more than fifteen million diabetics were living who, without insulin, would have died at an early age. One of these was the American physician George Minot, a juvenile diabetic who had been saved by using insulin. As an adult, he discovered a treatment for pernicious anemia, another disease that in the past had always been lethal.

See also Diphtheria Vaccine; Hormones.

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—*René R. Roth*

INTEGRAL CALCULUS

THE SCIENCE: The introduction of algebraic expressions for curves helped mathematicians to analyze geometrical figures. Leonhard Euler's 1748 work marked a change in perspective by putting the function first and the curve second. This produces a different answer to the question of the subject matter of mathematics.

THE SCIENTISTS:

Leonhard Euler (1707-1783), Swiss mathematician who took the idea of function as central to mathematics

Johann Bernoulli (1667-1748), Swiss mathematician who first formulated the idea of function

Gottfried Wilhelm Leibniz (1646-1716), German mathematician who tried to lay a foundation for mathematics

Joseph-Louis Lagrange (1736-1813), Italian-French mathematician who transmitted Euler's work to the next generation

FROM GEOMETRY TO ALGEBRA

Mathematics traditionally concerned numbers and geometrical objects. With the work of René Descartes, there was a juxtaposition of algebra and geometry that allowed for the study of geometrical objects via algebra. It was still the geometrical object that was primary; the algebraic expression was simply a translation into equations. With the work of Leonhard Euler, however, a change began that led to mathematicians thinking of the equational representation of a curve as the primary object for study and the geometrical object itself as just a sort of illustration. This development shaped mathematical practice and attitudes for a couple of centuries.

From ancient times to the seventeenth century, the objects of study of mathematics were clearly recognized as number and figure. In other words, mathematicians sought to understand and to identify the properties of numbers (arithmetic) and shapes (geometry). The use of algebra was simply to solve arithmetic problems. Similarly, illustrations were used to solve geometrical problems: Even when it was recognized that the geometrical object itself could not be drawn on a piece of paper, the concepts of geometry could be represented by figures. Even arithmetic was sometimes considered to be a branch of geometry, as expressed in Euclid's *Stoicheia* (compiled c. 300 B.C.E.; *Elements*, 1570).

THE CARTESIAN SHIFT

In the seventeenth century René Descartes introduced an approach to geometry that was to transform the subject. A geometrical figure could be represented by an algebraic equation, and study of the algebraic equation and its properties enabled the mathematician to arrive at conclusions about the geometrical object. Thus, if one had the equation for a circle and one found that plugging in the value zero for x gave rise to an equation that had no solutions for y, then one could conclude that the circle did not cross the y-axis. This kind of property was dependent on the coordinate representation of the circle, but others dealt with intrinsic properties of the figure.

It was still the case, however, that the geometrical object of the circle was taken as prior to any algebraic representation. After all, even to write down an algebraic equation for a geometrical figure required selecting a coordinate system, and geometers should not have to resort to that choice in order to be able to make conclusions about shapes and figures. The algebraic equation was a tool for arguing about the geometrical object but was only ancillary (and was dispensable).

THE ADVENT OF THE CALCULUS

With the advent of the calculus in the late seventeenth century, however, techniques had been introduced that could apply directly to the equation for a geometric shape. For example, finding the area of a parabola by means of the calculus could take the equation for a parabola and produce a number without having to go back to the geometric definition of the curve. Mathematicians like Pierre de Fermat earlier in the seventeenth century had been able to get expressions for the area of a parabola directly by geometric means, but it was much harder to see how to extend those techniques to curves in general. The calculus offered the chance to extend results without having to think about how to do so.

The idea of a function was that of a means of obtaining values for one quantity from those for another quantity. By the seventeenth century it was recognized that some of the functions could be obtained by algebraic means (as the values of a polynomial) and some (like the sine function) could not. While the former was easy to build into a notion of function that was based on numbers as primary, the other kind of function made it harder to see what one was doing with the original values in order to get the results. Johann Bernoulli offered a characterization of a quantity obtained "in any manner" from another quantity as the basis for his idea of function, which was a term subsequently employed by Gottfried Wilhelm Leibniz.

EULER: THE FUNCTION AS "ANALYTIC EXPRESSION"

It was Euler's *Introductio in analysin infinitorum* (1748; introduction to the analysis of the infinite) that put the issue of the definition of functions squarely before the mathematical audience at large. Euler had already attained quite a reputation for his mathematical ingenuity in solving problems and benefited from the standing of Johann Bernoulli, his mathematical guide at the University of Basel, to become rapidly part of the research community. Euler was to become the most prolific mathematician of all time, at least as measured by published papers, and he moved back and forth between positions at St. Petersburg and Berlin. His influence on mathematical ideas and even notation was unmatched.

In the opening chapter of his book, Euler analyzes functions into various kinds. He defines a function generally as an "analytic expression," which puts an emphasis on the ability to represent the quantity to be obtained as part of an equational expression into which values of the known quantity are substituted. There is no need to represent the quantity to be obtained as a variable on one side of the equation, so he allows for functions defined implicitly.

He then defines algebraic and transcendental functions, the latter the kind that cannot be expressed algebraically (by which he includes polynomials and ratios of polynomials). The discussion even takes on the difference between single-valued functions and multiple-valued functions. The latter encompasses functions in which, for example, the variable to be obtained only appears as a square. Then both positive and negative values for that variable could emerge from the same value for the known variable.

In the course of the *Introductio*, Euler tackles all sorts of interesting problems about infinite series, infinite products, and continued fractions. Many of those results were put to use by Euler himself and his successors. His treatment of the idea of function at the beginning of his text, however, has perhaps been the most important legacy for mathematics. The algebraic expression has become the central subject for mathematical investigation, and the geometrical object which it describes has been demoted to second place.

IMPACT

Euler's characterization of a function as an "analytic expression" was one that even he found restrictive in the course of his later mathematical career. By the end of the eighteenth century, the mathematician Joseph-Louis Lagrange had characterized a function as a combination of operations. This allowed for an idea of a function as involving more than numbers as the quantities known in advance. In addition, one could take other sorts of mathematical objects (permutations, for example) and regard those as the ingredients to be plugged into the recipe to which the function corresponded.

The drive toward abstraction that characterized mathematics through most of the twentieth century can be seen as an outcome of Euler's treatment of function as the central idea of mathematics. The branch of mathematics called "category theory" starts with the idea of a function as being primary and is not so concerned with the sort of object on which the function acts. Even philosophy of mathematics has been influenced by the view that the nature of mathematical objects is not so important as the kind of functions that act on them.

Geometrical objects have not been entirely neglected over the centuries since Euler wrote. It remains the case, however, that students asked to demonstrate something about geometrical objects will almost always turn to the algebraic representation. In the nineteenth century, the characterization of branches of geometry was according to the kind of function that left the geometric objects unchanged. The heritage of the idea of function has cut across all branches of mathematics and continues to affect our views of its subject matter.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Thomas Drucker*

INTEGRATION THEORY

THE SCIENCE: Henri-Léon Lebesgue developed a new theory for integrating discontinuous functions, based on a more general set-theoretic concept of measure.

THE SCIENTISTS:

Henri-Léon Lebesgue (1875-1941), French mathematician
Émile Borel (1871-1956), French mathematician and politician
William Henry Young (1863-1943), English mathematician

THE PROBLEM: INTEGRATING DISCONTINUOUS FUNCTIONS

Since Euclid's *Stoicheia* (compiled c. 300 B.C.E.; *Elements*, 1570), the theory of measurements in mathematics generally was thought to encompass little more than systematically comparing the points, lines, or planes to be measured to a standard reference. With Pythagoras's discovery of geometric incommensurables (irrational numbers), it was realized gradually that the question of mathematical measurement, in general, requires more precise and comprehensive consideration of seemingly infinite processes and collections. Development of the differential and integral calculus and limit theory by Sir Isaac Newton and Gottfried Wilhelm Leibniz brought with it the realization that, for most geometric figures, true mathematical measures do not exist a priori, but rather depend on the existence and computability of strictly defined associated limits.

In 1822, French physicist and mathematician Joseph Fourier discovered that computation of sets of harmonic (trigonometric) series used to approximate a given function depended upon appropriate existence and calculations using integrals. Integration, or integral theory, concerns the techniques of finding a function $g(x)$ the first derivatives of which are equal to a given function $f(x)$. These, in turn, depend on how discontinuous the function is. A function is a mathematical expression defining the relation between one (independent) and another (dependent) variable. Although it was known that every continuous function has an integral summation, it was not clear then whether or how an integral could be defined for the many different classes of discontinuous functions—that is, those functions that are not definable at one or more specific points. A function is continuous if for every positive number, it is possible to select a corresponding positive number.

From Riemann and Jordan

In 1854, the German mathematician Georg Friedrich Riemann offered the first partial answer to the question of how to integrate discontinuous functions, based on approximating integrands having only a finite number of definitely known discontinuous points by a sum of step-functions, instead of the curve-tangent sums of earlier calculus. The sum or measure of the Riemann integral is equal to the area of the region bounded by the curve $f(x)$. Yet, one of the many classic functions of importance to mathematics and physics, for which Riemann integration cannot be defined, is the "salt and pepper" function of Peter Dirichelet, where $f(x) = 1$ if x is rational, and 0, if x is irrational. Earlier, in 1834, Austrian mathematician-philosopher Bernhard Bolzano gave examples of mathematically continuous functions that are nowhere differentiable and, thus, unintegrable by Riemann's definition, as did Karl Theodor Weierstrass in 1875. Further motivations for clarifying the notions of continuity and integration arose in 1885, when German mathematician Adolf Harnack paradoxically showed that any countable subset of the real number system could be covered by a collection of intervals of arbitrarily small total length.

As a reaction to these difficulties, between 1880 and 1885, French geometrician Jean Darboux gave a novel definition of continuity, for the first time as a locally definable (versus global) mathematical property for discontinuous functions. Likewise, Camille Jordan, in 1892, first defined analogously the more general notion of "mathematical measure," using finite unions of mathematical intervals to approximate sparse and dense subsets of real numbers. Nevertheless, the opinions of many leading mathematicians such as Henri Poincaré and Charles Hermite differed as to whether discontinuous functions and functions without derivatives were legitimate mathematical objects, as well as how to define the concept of a normal versus a "pathological" function.

Borel and Cantor

The first mathematician to infer from the above results that countable unions of intervals should be used to measure the more general entity of real number subsets was Émile Borel. In 1898, in his *Leçons sur la théorie des fonctions* (lectures on the theory of functions), Borel advocated an abstract axiomatics of "constructivistic" definitions. Constructivistic, in this case, meant that all proposed definitions should permit explicit construction of actual examples of the mathematical entities referred to. Borel redefined the "measure" of any countable union of real number intervals to be its total length and thereby extended the notion of abstract measurability to progressively more complex sets.

Borel sought to generalize Georg Cantor's set theory, as well as to explicitly study "pathological" functions definable in terms of point sets. For Borel, the main problem was how to assign consistently to each pathologic point or singularity an appropriate numerical measure, meaning a nonnegative real number precisely analogous to length, area, and volume. Starting with elementary geometrical figures, Borel sought to define constructively measures to these sets so that formal measures of a line segment, or polygon, is always the same as its Euclidean measure and that the measure of a finite or countably infinite union of non-overlapping sets is equal to the sum of the measures of all individual sets.

Cantor's set theory had expanded the definition of continuity to include not only geometric smoothness (or nonvariability) of a curve but also its pointwise mapping, or set theoretic correspondence. One of the results of Borel's studies was the well-known Heine-Borel theorem, which states that if a closed set of points on a line can be covered by a set of intervals, such that every point of this set is an interior point of at least one of the intervals, then there exists a finite number of intervals with this "covering" property. For Borel, any such set obtainable by the basic mathematical properties and operations of union and intersection of sets in principle has a measure.

LEBESGUE

With these ideas as background, in 1900, Henri-Léon Lebesgue sought to enlarge Borel's notion of measurable sets in order to apply it explicitly to the problem of integrating a wider class of pathological functions than those permitted by Riemann's integral. In the preface of his doctoral dissertation, Lebesgue outlined his motivations and methods.

In contrast to Borel, Lebesgue employed a nonaxiomatic descriptive approach, one of the key results of which was to solve the problem of defining integral measure for discontinuous functions in general, insofar as it is necessary here that an infinite but bounded set have finite measure. Lebesgue generalized Riemann's definition of the integral by applying this new definition of measure. In the second chapter of his dissertation, Lebesgue proposed five criteria necessary for sufficiently widening integration theory, including the need to contain Riemann's definition as a special case to incorporate only assumptions and results in this extension that are natural, necessary, and computationally useful. Another key insight of Lebesgue's integration theory is that every function with bounded measure is also integrable.

Perhaps the most critical property of Borel-Lebesgue measure is its property of summability, or countable additivity. In particular, Lebesgue showed that this property, of term-by-term integrability, gives a definition of the integral much wider and with more stable computational properties in the limit than Riemann's integral. For example, if the approximation to a discontinuous function $f(s)$ approaches $f(x)$, as the number of terms of the approximations approaches infinity, then the integral of this series approximates the integral of the function in the limit; in general, this property of uniform-convergence is not true for Riemann's integration.

As noted in Thomas Hawkins's *Lebesgue's Theory of Integration* (1970), much of the power of Lebesgue's integration results from judicious use of the techniques of monotonic sequences and bracketing. Substituting equivalent monotonic sequences for complicated functions simplifies convergence in the limit. The bracketing technique consists of using the integrals of two well-behaved ("tame") functions to bracket as upper and lower bounds the integral of the pathological function. Instead of subdividing the domain of the independent variable x (abscissa axis), Lebesgue subdivided the range (ordinate axis) of the corresponding function $f(x)$ into subintervals. Therefore, Lebesgue's integration replaces Riemann's integral sums in the limit as sampling intervals approach zero. Lebesgue's theory of the integral also yields other important results, such as extending the fundamental theorem of calculus.

IMPACT

Initially, Lebesgue's work met with strong and lasting controversy from Borel. The main point of contention was not so much the mathematical results as the metamathematical methods used by each. Lebesgue subsequently developed the ideas of his dissertation further, and soon published these in his two classic texts, *Leçons sur les series trigonométriques* (1906; lessons on the trigonometric series) and *Leçons sur l'integration et la recherche des fonctions primitives* (1904; lessons on integration and analysis of primitive functions). Despite the fact that it was recognized early by some as an important innovation, Lebesgue's integration was comparatively slow to be adopted by the mathematical community at large.

In 1906, Lebesgue's contemporary, the English mathematician William Henry Young, independently arrived at a somewhat more general but operationally equivalent definition of Lebesgue-type integration, using the method of monotone sequences. Most textbook discussions of Lebesgue integration have incorporated a combination of Young's notation and formalism for Lebesgue's arguments and examples.

Lebesgue's integral, despite its major advantages, did not generalize completely the concept of integration for all discontinuous functions. For example, Lebesgue integration did not treat the case of unbounded functions and intervals. Subsequently, in 1912 Arnaud Denjoy, Thomas Stieltjes in 1913, and Johann Radon and Maurice-René Fréchet in 1915 created other, more encompassing definitions of the definite integral over complicated functions. Fréchet, in particular, showed how to generalize Lebesgue's integral to treat functions defined on an arbitrary set without any reference to topological or metric concepts of measure, later leading to Hausdorff dimensional or (Mandelbrot) fractal measures. As further reformulated by Beppo Levi, Lebesgue integrable functions are those that almost always equal the sum of a series of step functions.

Many of the complicated functions of aero- and fluid-dynamics, electromagnetic theory, and the theory of probability were for the first time analytically integrable using Lebesgue's method. In his book on the axiomatic foundations of Andrey Markov's probability theory, A. N. Kolmogorov defined a number of operational analogues between the Borel-Lebesgue measure of a set and the probability of an event.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Gerardo G. Tango*

INTERNATIONAL SPACE STATION

THE SCIENCE: The International Space Station (ISS)—an Earth-orbiting facility designed to house experimental payloads, distribute resource utilities, and support permanent human habitation in space—was designed to be completed in three phases. Its first phase began in 1993.

THE SCIENTISTS:

Richard Kohrs, director of NASA's Space Station Freedom program

Eugene F. Kranz (b. 1933), NASA Mission Operations director at the Johnson Space Center

David C. Leestma (b. 1949), Flight Crew Operations director at NASA's Johnson Space Center

Bryan D. O'Connor (b. 1946), Space Station Redesign director, responsible for transforming Space Station Freedom into the International Space Station

Robert Phillips, flight director scientist of NASA's Space Station Freedom project

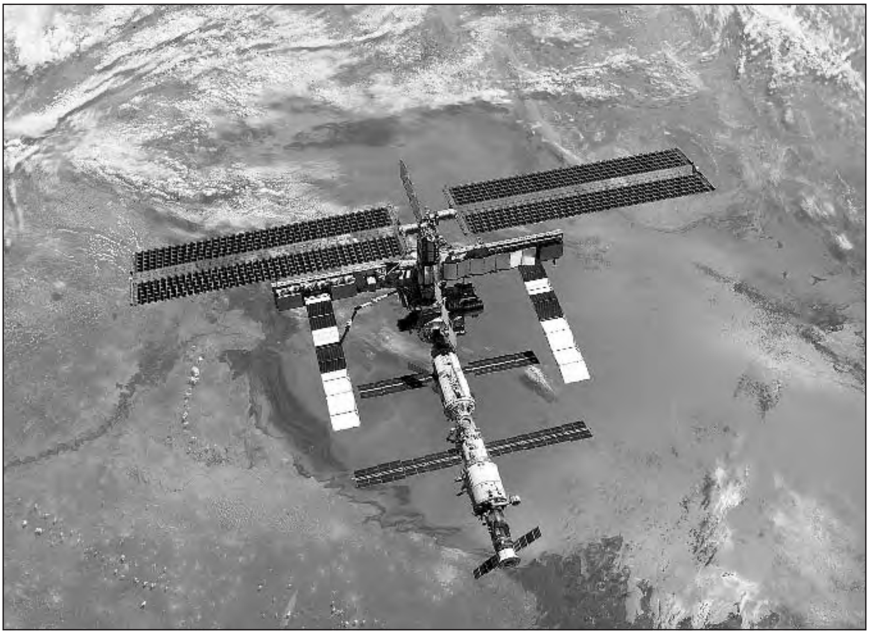
Wilber Trafton, head of the U.S. portion of the International Space Station effort

DEVELOPMENT OF THE FACILITY

The Soviet Union launched the world's first space station, Salyut 1, in 1971—a decade after launching the first human into space. The United States sent its first space station, the larger Skylab, into orbit in 1973, and it hosted three crews before being abandoned in 1974. Russia continued to focus on long-duration space missions and in 1986 launched the first modules of the Mir Space Station.

In 1993, U.S. president Bill Clinton called for a redesign of the Space Station program in order to reduce costs and include more international involvement. The National Aeronautics and Space Administration (NASA) presented three different options, of which the White House selected the one dubbed Alpha. The project thus became known as International Space Station Alpha.

The redesigning effort simplified many subsystems, resulting in a planned completion of the station assembly thirteen months earlier than originally scheduled, a permanent crew presence starting five years sooner than previously anticipated, and savings of $2 billion. A single management team replaced previously dispersed management, and an Integrated Product Team (IPT) became responsible for making decisions affecting product suitability, quality, and cost.



The International Space Station in 2005. (NASA)

When the assembly is completed, a permanent on-orbit crew of six would inhabit the ISS. The station would have an on-orbit mass of approximately 420 metric tons. The completed truss structure would measure 108.4 meters long and would hold systems requiring exposure to space, such as communication antennae, external cameras, mounts for external payloads, equipment for temperature control, transport around the station's exterior during spacewalks, robotic servicing, stabilizing, and attitude control. The truss would also support eight Sun-tracking pairs of solar arrays, providing the station with 110 kilowatts of electrical power—twice as much as the earlier space station, Freedom, was designed to have and more than ten times as much as the U.S. Skylab or the Russian Mir Complex. The total pressurized volume upon completion of the assembly was planned to be 1,200 cubic meters, with five Laboratory Modules and six crew members.

Configuration

The ISS is divided into segments defined according to the international partners' levels of responsibility. Segments include modules, nodes, truss structures, solar arrays, and thermal radiators.

Modules are pressurized cylinders of the habitable space on board the Station. They may contain research facilities, living quarters, and any vehicle operational systems and equipment the astronauts may need to access. Nodes connect the modules and offer external access for docking, extravehicular activity (EVAs), and unpressurized payloads. Trusses are girders that link the modules with the main solar power arrays and thermal radiators. Together, the truss elements form the Integrated Truss Structure. Solar Arrays collect and convert solar energy into electricity for the station and its payloads. Thermal radiators emit excess thermal energy into space.

Assembly Workflow

An assembly sequence for the ISS was developed that requires fifty assembly and utilization flights (including resupply missions) on five different launch vehicles from three countries—Russia, Japan, and the United States. The facility's development has been broken into three phases. Phase I, which operated from March, 1995, through May, 1998, was a joint program between the existing space facilities of both NASA and the Russian Space Agency (RSA), during which operational concepts required for ISS assembly were tested several times in a sort of dress rehearsal. Phase II, spanning November, 1998, to August, 2001, began the actual construction of ISS and depended on the successful endeavor of Phase I. The hardware must be flown in a particular order as the functionality of ISS is incrementally increased. Phase II would conclude after ten assembly flights, resulting in a sustainable station permanently occupied by humans and capable of continuous on-orbit payload operations. Phase III, which began in September, 2001, and was scheduled to end in 2010, will see growth of the configuration as power is increased and science platforms are added.

On February 1, 2003, NASA suffered the loss of *Columbia* and her crew of seven. After a more than two-year hiatus, the shuttle returned to the ISS in 2005 with the STS 114 mission aboard *Discovery*. The first shuttle to visit the ISS since late 2002 arrived on July 28. Shuttle and station crew members installed the Raffaello Multi-Purpose Logistics Module; set up a base and cabling for a stowage platform; rerouted power to the ISS's Control Moment Gyroscope 2; transferred water and supplies to the ISS; and replaced a 275-kilogram gyroscope on the ISS, giving the orbiting laboratory a complete, functional set of four.

Impact

After the early space stations Skylab and Mir, the ISS has provided scientists and engineers with the opportunity to design, develop, operate, and study the systems required to maintain a habitable, long-term spacecraft cabin environment. Given the microgravity environment of space, ISS provides scientists with a laboratory in which to explore the role that gravity plays in the fundamental principles that govern basic physical and biological processes—such as the burning of fuels, the solidification of metals, the growth of crystals, the life cycle from conception to old age, and the systems of the body, ranging from the musculoskeletal system to the immune system.

Scientists can use low gravity to test fundamental theories of physics with degrees of accuracy that far exceed the capability of the Earth-bound science. Observing physical processes in low gravity will expand our understanding of the structure of matter, as well as changes in states of matter (including high-temperature superconductivity), properties and behaviors of fluids, and complex combustion processes. Findings in material science alone will have very broad applications in industrial processes, including the production of semiconductors, glasses, metal alloys, polymers, and ceramics. Fundamental knowledge of fluid behavior is essential to industrial activities, ranging from energy production to material engineering.

The biological benefits to medical, agricultural, pharmaceutical, and other bioindustries will be vast. Orbital research enhances the ability to describe proteins, enzymes, and viruses at the molecular level, enabling scientists to develop new drugs and vaccines more quickly and effectively. Study of the processes controlling the growth of human tissue outside the body (tissue culturing) may lead to an improved understanding of normal and abnormal (cancerous) tissue development, with important implications for the development of new drug therapies and applications for transplant research. New insights into physiology—such as how the heart and lungs function, the growth and maintenance of muscle and bone, perception, cognition, balance, and the regulation of the body's many systems—will be gained in the low-gravity environment.

Systems of "telemedicine" (the use of telecommunications to exchange medical data and images) that have been developed to maintain astronauts' health have already proved their potential to reduce health care costs and improve the quality of health care on Earth. Human occupation of ISS inevitably necessitates such advanced life-support technologies as crop growth research capable of improving hydroponics and other controlled production systems; improved air and water quality sensors and analyzers and air revitalization systems; automatic systems for identifying microbes to detect a broad range of infectious diseases; advanced robotics and remote operation systems; improved power generation and storage systems that include particularly flexible thin-film solar arrays; and advanced waste-processing and recycling techniques to reduce pollution. For example, ISS is designed with closed-loop systems for water use and conservation of air in which about 30 liters (8 gallons) of water per astronaut will be used for hygiene and cooking, compared to an average of 606 liters (160 gallons) per person on Earth. Applied on Earth, this technology could benefit water-starved regions of the planet. Another example of potential Earth applications from the design of ISS is a more efficient burner: If engineers succeed in building a burner that is only 2 percent more efficient, and if such a burner were used routinely on Earth, the savings alone would pay the United States' costs for ISS in less than two years.

See also Space Shuttle.

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—M. A. K. Lodhi and Russell R. Tobias

INTERNET

THE SCIENCE: A worldwide network of interlocking computer systems, developed out of a U.S. government project to improve military preparedness.

THE SCIENTISTS:

Vinton G. Cerf (b. 1943), American computer scientist regarded as the "father of the Internet"

Robert E. Kahn (b. 1938), who along with Cerf invented the TCP/IP protocol, which allows information to be transmitted via the Internet

Paul Baran (b. 1926), researcher for the RAND corporation who helped develop packet switching

A COLD-WAR BIRTH

In 1957, the world was stunned by the launching of the satellite Sputnik 1 by the Soviet Union. The international image of the United States as the world's technology superpower and its perceived edge in the Cold War were instantly brought into question. As part of the U.S. response, the Defense Department quickly created the Advanced Research Projects Agency (ARPA) to conduct research into "command, control, and communications" systems. Military planners in the Pentagon ordered ARPA to develop a communications network that would remain usable in the wake of a nuclear attack.

The solution, proposed by Paul Baran, a scientist at the RAND Corporation, was the creation of a network of linked computers that could route communications around damage to any part of the system. Because the centralized control of data flow by major "hub" computers would make such a system vulnerable, the system could not have any central command, and all surviving points had to be able to reestablish contact following an attack on any single point. This redundancy of connectivity (later known as "packet switching") would not monopolize a single circuit for communications, as telephones do, but would automatically break up computer messages into smaller packets, each of which could reach a destination by rerouting along different paths.

ARPA then began attempting to link university computers over telephone lines. The historic connecting of four sites conducting ARPA research was accomplished in 1969 at a computer laboratory at the University of California at Los Angeles (UCLA), which was connected to computers at the University of California at Santa Barbara, the Stanford Research Institute, and the University of Utah. UCLA graduate student Vinton Cerf played a major role in establishing the connection, which was first known as ARPAnet. By 1971, more than twenty sites had been connected to the network, including supercomputers at the Massachusetts Institute of Technology and Harvard University; by 1981, there were more than two hundred computers on the system.

The World's Biggest Machine

Because factors such as equipment failure, overtaxed telecommunications lines, and power outages can quickly reduce or abort ("crash") computer network performance, the ARPAnet managers and others quickly sought to build still larger "internetting" projects. In the late 1980's, the National Science Foundation built its own network of five supercomputer centers to give academic researchers access to high-power computers that had previously been available only to military contractors. The NSFnet connected university networks by linking them to the closest regional center; its development put ARPAnet out of commission in 1990. The economic savings that could be gained from the use of electronic mail (e-mail), which reduced postage and telephone costs, were motivation enough for many businesses and institutions to invest in hardware and network connections.

The evolution of ARPAnet and NSFnet eventually led to the creation of the Internet, an international web of interconnected government, education, and business computer networks that has been called "the largest machine ever constructed." Using appropriate software, a computer terminal or personal computer can send and receive data via an Internet protocol packet (or an electronic envelope with an address). Communications programs on the intervening networks "read" the addresses on packets moving through the Internet and forward the packets toward their destinations.

Cerfing the Internet

In 2004, the Association for Computing Machinery bestowed its A. M. Turing Award—considered the Nobel Prize of computer science—to two men who were largely responsible for the development of the Internet: Vinton G. Cerf and Robert E. Kahn, for "the design and implementation of the Internet's basic communications protocols, TCP/IP [transmission-control protocol and Internet protocol], and for inspired leadership in networking." It was their development of a format for transferring information among diverse computers and computer programs that made the Internet possible.

Cerf, known as the father of the Internet, has had a broad career, from teaching electronics at the university level to working for WorldCom and MCI. On September 8, 2005, it was announced that he had joined the seven-year-old company Google, which had created the most popular search engine on the Internet. Characterizing the decision as a move to his "dream job," Cerf said he planned to work on new applications for Google's information infrastructure: "While it presents itself as a Web interface to most people, Google could just as well present itself as a programmable interface, which means that you can start writing software that gets information through the eyes, so to speak, of Google." Cerf's interests include grid computing, peer-to-peer interactions, and mobile communications using "geographically indexed databases."

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Cerf has not limited himself to planet Earth, however: He has an ongoing project with NASA's Jet Propulsion Laboratory to create an "interplanetary internet" that would allow computer systems on old and new spacecraft to access each other's data. A self-described "62 going on 12," Cerf enjoys working with people half his age: They have a can-do attitude, he says, because they "don't know you can't do that, so they go off and do it."

Source: Quotations of Cerf from an interview with Kevin Wolf, Associated Press, accessed on www.MSNBC.com, and inverview with Antone Gonsalves for the online journal *ITNews.com*, www.itnews.com.au. Both accessed September, 2005.

IMPACT

From approximately one thousand networks in the mid-1980's, the Internet grew to an estimated thirty thousand connected networks by 1994, with an estimated 25 million users accessing it regularly. Around that time, with personal computers well established in both homes and offices, the use of the Internet and e-mail started to expand exponentially as universities, businesses, and members of the general public alike began to use e-mail and the World Wide Web for daily communications and research.

Access to the Internet is made through modems attached to computers that connect to local area networks (LANs), usually by subscribing to Internet service providers (ISPs). These services make e-mail and access to the World Wide Web available. Users are able to access online encyclopedias and magazines, electronic discussion groups and bulletin boards, blogs, online "e-books," paid subscription services (such as reference databases available through libraries for their patrons), and many other sources of information and communication, on nearly every specialized interest area imaginable. Many universities converted large libraries to electronic form for Internet distribution. Publishers began to market their works in electronic form and to create new works, or integrated databases, for sale by subscription. The Internet revolutionized these and many other industries and created entirely new specializations and academic disciplines under the head of "information science." Numerous corporations and small businesses soon began to market their products and services over the Internet.

Problems became apparent with the commercial use of the new medium, however, as the protection of copyrighted material proved to be difficult; data and other text available on the system can be "downloaded," or electronically copied. Issues of privacy and identity theft necessitated protections from unauthorized use via the Internet. Therefore, most companies, hospitals, financial institutions, and individuals had to erect virtual "firewalls" to screen incoming communications and keep antivirus and antispyware programs up to date to maintain the privacy of the information stored on their computer drives. By the late 1990's, the Internet also contained numerous information sites to improve public access to the institutions of government.

Today, Internet users can be found from developed nations to the most remote villages as telecommunications lines are improved and international access has continued to expand. The Internet, even more than space exploration, has reinforced the notion of Earth as a "global village."

See also Artificial Intelligence; Personal Computers.

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—*Daniel G. Graetzer, updated by Christina J. Moose*

IONOSPHERE

THE SCIENCE: Arthur Edwin Kennelly and Oliver Heaviside independently proposed the existence of an electrified layer in the upper atmosphere that would reflect radio waves around the curved surface of the Earth.

THE SCIENTISTS:

Arthur Edwin Kennelly (1861-1939), British American electrical engineer and Harvard professor
Oliver Heaviside (1850-1925), English physicist and electrical engineer
Balfour Stewart (1828-1887), Scottish physicist
Guglielmo Marconi (1874-1937), Italian electrical engineer
Sir Edward Victor Appleton (1892-1965), English physicist who discovered the ionosphere
Heinrich Hertz (1857-1894), German physicist

HOW DO RADIO WAVES BEND?

On December 12, 1901, only thirteen years after Heinrich Hertz had discovered radio waves, Guglielmo Marconi succeeded in transmitting radio signals from Cornwall, England, to Newfoundland, Canada. This historic event was difficult to explain, since it was known that radio signals consisted of electromagnetic waves like light, which travel in nearly straight lines. Thus, there was considerable discussion among scientists as to how Marconi's signals could travel around the curved surface of the Atlantic Ocean. Several scientists tried to show that electromagnetic waves of sufficiently long wavelength could bend around the Earth's curvature by diffraction (the small tendency of waves to spread around obstacles). Calculations showed, however, that diffraction theories were not enough to explain Marconi's results.

The correct explanation was suggested almost simultaneously in 1902 by Arthur Edwin Kennelly in the United States and Oliver Heaviside in England. They independently proposed the existence of a layer in the upper atmosphere that could conduct electricity and reflect radio waves back to Earth. Successive reflections between this conducting layer and the surface of the Earth could guide the waves around the Earth's curvature. Heaviside also suggested that the conductivity of this region might result from the presence of electrically charged particles, called ions, in the upper atmosphere caused by solar radiation. This layer would later be labeled the "ionosphere."

Atmospheric "Tides"

The idea of such an electrically charged conducting shell in the upper atmosphere had already been suggested by Balfour Stewart twenty years earlier in 1882. In his study of terrestrial magnetism, Stewart had proposed that electrical currents flowing high in the atmosphere could explain the small daily changes in the Earth's magnetic field. Such variations would be caused by the tidal movements in the surrounding "sea of air," which were caused by solar and gravitational influences. This explanation of fluctuations in the Earth's magnetism, combined with many peculiar features of shortwave radio, seemed to confirm the existence of the Kennelly-Heaviside layer, but these phenomena provided only indirect evidence.

Measuring the Ionosphere

The first direct evidence for the existence of the ionosphere was obtained by Sir Edward Victor Appleton, with the assistance of Miles A. F. Barnett, in 1924. At the University of Cambridge, Appleton had studied radio signals from the new British Broadcasting Company (BBC) station in London and had noticed the typical variations in their strength. When he took up a new position at the University of London in 1924, Appleton arranged to use the new transmitter at Bournemouth after midnight, with receiving apparatus located at Oxford University. By varying the transmitter frequency, he hoped to detect any changes in signal strength that resulted when ground waves and waves reflected from the ionosphere (assuming they existed) interfered with one another.

On December 11, 1924, Appleton and Barnett observed the regular fading in and out of the signal as the frequency of the transmitter was slowly

APPLETON'S ANATOMY OF THE IONOSPHERE

In the winter of 1926, Sir Edward Appleton found that before dawn the ionization of the Heaviside layer (E layer) was reduced sufficiently by recombination of electrons and ions to allow penetration by radio waves. Reflection was still observed from a higher layer, however, where the air was too thin for efficient recombination, and the lower boundary of the Appleton layer (F layer) was measured at about 230 kilometers above Earth. A solar eclipse in 1927 made it possible to observe that the height of the Heaviside layer changed when the eclipse began, showing that ionization was caused by solar radiation.

The pulse, or radar, technique (introduced in the United States by Merle Tuve and Gregory Breit) was also developed at this time for measuring the ionosphere. In this method, a transmitted radio pulse resulted in two received pulses, one from the ground wave and one from the reflected wave, both of which could be recorded and compared. The technique led to the discovery of the splitting of echoes, a result of the influence of Earth's magnetic field on the ionosphere, which separates a radio wave into two parts by double refraction—the bending of waves into two different components as they pass from one medium to another.

In developing his "magneto-ionic" theory to explain this result, Appleton showed that free electrons rather that ions caused the reflection of radio waves. This theory, later called the "Appleton-Hartree equation," showed that the electron density and the magnetic field at any layer in the ionosphere can be determined by measuring the critical frequency for penetrating that layer. Systematic experiments on the variation of electron densities in the ionosphere were begun in 1931, and it was found that E-layer densities increased as the Sun was rising and decreased after noon. Ionization remained low at night, except for sporadic increases possibly caused by meteoric dust. A weak region of ionization was discovered below the E layer and designated as the D layer.

In 1932, Appleton organized a scientific expedition to study the ionosphere in northern Norway as part of an international effort to study the polar region. There, he recorded the first example of a polar radio blackout caused by charged particles projected into the atmosphere from the Sun. By World War II, his methods were being used in more than fifty stations around the world to monitor ionospheric conditions. For his work on the ionosphere, Appleton won the 1947 Nobel Prize in Physics.

increased. From the data they collected, they calculated that the reflection that they had discovered was from a height of about 100 kilometers. This confirmation of the Kennelly-Heaviside prediction was published in 1925 in *Nature* under the title "Local Reflection of Wireless Waves from the Upper Atmosphere."

In 1926, Appleton found that the ionization of the Heaviside layer (E layer) was sufficiently reduced before dawn by recombination of electrons with positive ions to allow penetration by radio waves. Reflection, however, was still observed as originating from a higher layer where the air was too thin for efficient recombination. The height of that layer, now called the Appleton layer (F layer), was measured at about 230 kilometers above the Earth. This result was published in *Nature* in 1927 under the title "The Existence of More than One Ionized Layer in the Upper Atmosphere." Moreover, observations during a solar eclipse in 1927 showed that the height of the Heaviside layer changed, revealing that ionization was really caused by solar radiation, as suggested by Heaviside.

Impact

In 1931, systematic experiments were begun to determine the variation of electron densities in the ionosphere, revealing an increase in ionization as the Sun was rising and low ionization at night, except for sporadic increases possibly caused by meteoric activity. Noon ionization was found to increase as the sunspot maximum of 1937 was approached, suggesting a correlation between sunspots and increases in the ultraviolet radiation that ionizes the upper layers of the atmosphere. This made it possible to measure the ultraviolet radiation from the Sun even though little of it reaches the ground. During the sunspot maximum of 1957-1958, the International Geophysical Year was established to study geophysical phenomena on a worldwide scale, including their relation to ionospheric variations. Thus, study of the ionosphere has contributed to developments in other sciences, such as astronomy, meteorology, and geophysics.

The early development of radar was closely associated with the studies of the ionosphere. The most powerful radar systems use the over-the-horizon technique of reflecting radar signals from the ionosphere to cover distances up to about 3,000 kilometers, about ten times farther than conventional radar. Over-the-horizon radar systems depend on computers to chart the constantly changing intensity and thickness of the ionosphere and to determine where conditions are best and which frequencies are needed for maximum performance. Thus, the ionosphere has become an indispensable tool for both communications and national security.

See also Atmospheric Circulation; Atmospheric Pressure; Chlorofluorocarbons; Global Warming; Ozone Hole; Stratosphere and Troposphere.

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—*Joseph L. Spradley*

Isotopes

The Science: J. J. Thomson's experiments proved that atoms of a pure chemical substance did not necessarily have identical atomic weights.

The Scientists:

Sir J(oseph) J(ohn) Thomson (1856-1940), British physicist
Frederick Soddy (1877-1956), British chemist
Eugen Goldstein (1850-1930), German physicist

The Puzzle of Radioactivity

Early in the nineteenth century, the English chemist John Dalton (1766-1844) proposed what would become the modern theory of the atom. Dalton believed that if he were able to keep on dividing a piece of a pure chemical substance (for example, an element such as aluminum), he would finally arrive at its smallest part, an atom, which would be incapable of further division. All atoms of the same chemical substance were thought to be exactly alike in size, shape, and weight.

Following the discovery of natural radioactivity in the late 1890's, much effort went into the investigation of several families of radioactive elements. Radioactivity involves the steady, spontaneous emission of either electrically charged particles (called alpha and beta particles) or penetrating radiation (gamma rays) by certain unstable elements. Thorium, for example, was observed to decay by means of a series of such emissions, transforming into a whole chain of different but related "daughter elements," each of which decayed and became a chemically different substance, until the stable element lead was produced.

By the early twentieth century, scientists using the techniques of analytic chemistry had become skilled in separating mixtures of elements. In this context, it came as a surprise when chemist Frederick Soddy discovered that some of the atoms produced in the radioactive series, although chemically identical, seemed to have different atomic weights. Thus was born the idea of the "isotope." Although it was Soddy who coined the word in 1913, it was the crucial work of the physicist J. J. Thomson that proved the existence of isotopes and provided a new method of chemical analysis.

Negative Rays: The Electron

At the time of Thomson's pioneering work, the structure of the atom itself was still unclear. Within a few years, however, the work of Ernest Rutherford (1871-1937) and his coworkers at Manchester University in England would demonstrate the modern concept of the atom: a miniature solar system in which most of the mass was concentrated in a tiny core of positively charged particles, the nucleus, which was surrounded by a group of negative particles called electrons. The atom as a whole was electrically neutral.

The electron itself had been discovered by Thomson about ten years before his work on isotopes. In that earlier work, he passed electricity through a gas contained in a glass tube at very low pressure. A battery was connected to two metal plates, or electrodes, that were sealed in the walls of the tube. The electrode on the positive battery terminal was called the anode; the other, the cathode. When most of the air was removed from the tube, an eerie blue glow would be sent out by the gas remaining in the tube, and electricity would begin to flow. At still lower pressures, the glow disappeared completely, and a strange greenish light appeared in the glass at the end of the tube opposite the cathode.

Experiments of this kind showed that any obstacle placed between the electrodes would cast a sharp shadow on the glass wall. It seemed that something was streaming from the cathode to the anode. Thomson subsequently concluded that "cathode rays" consisted of electrons (which he called "corpuscles") and had caused the effect that he had observed. He was able to measure the amount of electrical charge that the electrons carried for each unit of their weight, or mass. This characteristic factor is known as a particle's charge-to-mass ratio. In 1906, Thomson was awarded the Nobel Prize in Physics for his discovery of the electron.

J. J. Thomson on Ionization

In 1913 J. J. Thomson summarized his investigations into positive electrical discharges and the discovery of chemical isotopes.

The occurrence of the multiple charge does not seem to be connected with the valency or other chemical property of the atom. . . . Elements as different in their chemical properties as carbon, nitrogen, oxygen, chlorine, helium, neon, a new gas whose atomic weight is 22, argon, krypton, mercury, all give multiply charged atoms. The fact that these multiple charges so frequently occur on atoms of the inert gases proves, I think, that they are not produced by any process of chemical combination.

All the results [of my experiments] point to the conclusion that the occurrence and magnitude of the multiple charge is connected with the mass of the atom rather than with its valency or chemical properties. We find, for example, that the atom of mercury, the heaviest atom I have tested, can have as many as 8 charges, krypton can have as many as 5, argon 3, neon 2, and so on. There is evidence that when these multiple charges occur the process of ionisation is generally such that the atom starts either with one charge or with the maximum number, that in the ionisation of mercury vapour, for example, the mercury atom begins either with 1 charge or with 8, and that the particles which produce the parabola corresponding to 5 charges, for example, started with 8 and lost 3 of them on its way through the tube in the cathode. . . .

Image Not Available

Source: Sir Joseph John Thomson, "Rays of Positive Electricity." *Proceedings of the Royal Society A* 89 (1913): 1-20. Excerpted in Henry A. Boorse and Lloyd Motz, *The World of the Atom*, Vol. 1 (New York: Basic Books, 1966).

Positive Rays: More Complex

In 1886, Eugen Goldstein, a German physicist working in Berlin, had shown that if the cathode in the tube were filled with holes, a second kind of ray—this time electrically positive—could also be observed flowing through the tube. These rays, however, were headed in the opposite direction, toward the negative cathode, and as they passed through the holes, they created brilliant streams of light in the gas.

Although the cathode rays themselves consisted of electrons, the positive rays seemed to be more complex. A standard technique for exploring the nature of a stream of charged particles was to shoot them through the two poles of a magnet. Electrically charged moving particles were known to have their paths bent as they moved through a magnetic field, and the amount of bending could be shown to depend on their charge-to-mass ratio and speeds: The tracks of heavier particles would be bent less than those of lighter ones, and the tracks of faster particles would be bent less than those of slower ones. Charged particles, however, can also be pushed by electric fields. In his painstaking experiments, using a clever combination of the two kinds of fields, magnetic and electric, Thomson found that he could actually separate and identify the charged particles that made up the positive rays.

Thomson believed that the electrons making up the cathode ray were forced into the tube by repulsion from the negative cathode. Apparently, the positive particles were then formed in the gas by collision with the cathode rays. As an atom lost an electron, it became a positive particle called an "ion"—an atom minus one of its electrons. By examining the records of the tracks that those positive rays made on impact with a photographic film, Thomson was able to determine the weights of the positive particles. For example, when a tiny amount of the rare gas neon was in the tube, two quite different atomic weights of neon showed up. One had a weight of 20 units; the other, 22 units. These were the two isotopes of the element neon.

Impact

Thomson's work was a crucial step in the creation of the modern theory of the atom. Although his own ideas about how positive and negative charges are arranged inside an atom proved incorrect, his work paved the way for Rutherford's dynamic model, which soon became widely accepted.

In the Rutherford model, there are equal numbers of positive particles (protons) in the nucleus, and they are balanced by an equal number of negative electrons orbiting the nucleus. The extremely light electrons determine all an element's chemical properties. Hence, isotopes of different atomic weights must have nuclei of different weights. According to Rutherford's model, each isotope's nuclei had to have exactly the same number of the heavy, positive protons, so it seemed that a third kind of particle—heavy but electrically neutral—might also be inside the nucleus. Twenty years later, a third particle, called the neutron, was discovered and identified. Thus, isotopes were finally understood as atoms of an element that have a total number of neutrons inside their nuclei that is different from the total number of neutrons in the nuclei of other standard atoms of that element.

In many practical applications, isotopes of certain elements are used for a variety of purposes. Archaeologists, for example, make use of two of carbon's four known isotopes to determine the ages of objects that may be many thousands of years old. Radioactive isotopes are used as chemical tracers within the human body for medical diagnosis. Also, the possibility of the fusion of pairs of the three isotopes of the lightest element, hydrogen, offers hope for the creation of nonpolluting sources of energy.

See also Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Definite Proportions Law; Electrons; Neutrons; Oxygen; Periodic Table of Elements; Plutonium; Radioactive Elements; Radiometric Dating; Spectroscopy; X-Ray Fluorescence.

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—*Victor W. Chen*

JUPITER'S GREAT RED SPOT

THE SCIENCE: Gian Domenico Cassini, using an improved telescope, observed a large feature, now called the Great Red Spot, in the southern hemisphere of Jupiter. He used the motion of this feature around the planet to measure the rotational rate of Jupiter to a high degree of accuracy.

THE SCIENTISTS:

Gian Domenico Cassini (1625-1712), Italian astronomer who is credited with discovering the Great Red Spot

Robert Hooke (1635-1703), English physicist who first observed a feature in Jupiter's southern hemisphere that may have been the Great Red Spot

Giuseppe Campani (1635-1715), Italian lens grinder and telescope maker who built the long-focal-length telescope used by Cassini

EARLY SIGHTINGS

The Great Red Spot on Jupiter has puzzled astronomers ever since it was first seen in 1665. The development of the telescope and improvements in the resolution of telescopes made it possible to see the spot by the middle of the seventeenth century. The size and the color of the spot have varied significantly since it was first observed. The English physicist Robert Hooke first reported seeing a large oval-shaped feature in the southern hemisphere of Jupiter in 1664. The oval seen by Hooke is believed to have been the spot, although Hooke did not mention its color.

Credit for the discovery of the Great Red Spot is generally given to the Italian astronomer Gian Domenico Cassini, who observed it in 1665. At that time, Cassini was a professor of mathematics and astronomy at the University of Bologna, Italy. He had seen spots on Jupiter beginning in 1664, but he quickly realized that these spots were actually the shadows of Jupiter's largest moons (which Galileo had observed at the beginning of the century). Then Cassini observed an "exceptional" spot," which he called the "big permanent spot."

Cassini's many astronomical discoveries were possible because he was able to observe the sky with new, powerful telescopes made by Giuseppe Campani of Rome. Campani and his brother Matteo Campani-Alimensis were experts in grinding and polishing lenses, especially lenses with very long focal length and small curvatures. Because of their small curvatures, these lenses did not suffer from the same optical problems that lenses with sharper curvatures exhibited; thus they provided clearer views of objects in the sky. Campani's telescopes employed these long-focal-length lenses to study the planets Jupiter, Saturn, Mars, and Venus. Beginning in 1664, Cassini made many important discoveries, which were possible only because of the great magnification and image clarity of Campani's new telescope.

Anatomy of the Spot

The spot is located in Jupiter's southern hemisphere, about 22° south of the planet's equator and has been continuously present since the time it was discovered by Cassini. Jupiter is a gas planet, composed mainly of hydrogen and helium. What appears to be Jupiter's surface, when viewed from the Earth, is actually a layer of clouds. Therefore, the Great Red Spot is not actually a spot on the surface of Jupiter but, rather, a storm high in Jupiter's atmosphere. There are many other colored bands and spots visible in these high clouds near the top of Jupiter's atmosphere. The Great Red Spot is simply the largest and most easily visible of these features.

The spot is believed to be a giant, hurricane-like storm, caused by interactions between high and low temperatures and pressures, as are hurricanes on Earth. The top of the clouds in the spot extend about 5 miles higher than nearby clouds, and they are cooler. On Earth, hurricanes are much smaller in size than the spot, and they last for only a few days. In addition, hurricanes on Earth are "cyclonic," that is, they are low-pressure systems. The spot is "anticyclonic," that is, it is a high-pressure system. On Earth, hurricanes weaken considerably when they pass over land, so some scientists speculate that the spot persists because it does not pass over land; on Jupiter, there is no land over which to pass. Other scientists suggest that Jupiter's internal heat source continues to provide energy to this giant storm, allowing it to persist for centuries.

The spot, an oval measuring about 17,000 miles long and 9,000 miles wide, is so large that it could contain three Earths. Its size and color vary from year to year. The spot rotates counterclockwise, with a period of six days. Similar structures have been seen in the atmospheres of Saturn and Neptune.

Cassini's Measurements

Once Cassini recognized that the spot traveled around the planet as Jupiter rotated, he knew he could measure how long it took for the spot to travel completely around the planet and thus determine the planet's period of rotation on its axis. The value he obtained for Jupiter's rotation period was 9 hours and 56 minutes, results he published in 1665. Cassini's value is within a few minutes of the best value obtainable with modern instruments.

Cassini continued to observe Jupiter throughout his career. In about 1690, he was the first person to report that Jupiter's atmosphere displayed "differential rotation," the motion of some features around the planet at

GIAN DOMENICO CASSINI, PLANETARY EXPLORER

In July, 1664, a professor of astronomy at the University of Bologna, Gian Domenico Cassini, made his first major observation: Jupiter was not a perfect sphere but instead was flattened at its poles. Over the next few years he measured Jupiter's rotational period, observed its moons, and discovered discrepancies in his own measurements that, at first, he attributed to light having a finite speed. (However, he later appears to have rejected his own idea, and in 1676 Danish astronomer Ole Rømer would use Cassini's measurements to calculate the speed of light.)

In 1666, Cassini observed surface features on Mars, including Syrtis Major. Again, he measured the planet's rotational period using these features and produced a value of 24 hours and 40 minutes—within 3 minutes of the period now accepted. He also attempted to determine the rotational period of Venus, which he calculated as 23 hours, 20 minutes. What Cassini observed to produce this conclusion is unclear; Venus is entirely covered by bright clouds, and its rotational period (about 243 days) became clear only with the advent of radar.


(Library of Congress)

By now Cassini's measurements had made him famous throughout Europe, and he came to the attention of Jean-Bapiste Colbert, the French minister of finance. At Colbert's suggestion, King Louis XIV invited Cassini to head the new Paris observatory in 1669. In Paris, Cassini discovered two moons of Saturn, Iapetus and Rhea. In 1675, he recognized that Saturn's ring was divided, separated by a dark gap now called the Cassini Division. In 1677, Cassini demonstrated that Saturn was flattened at its poles, and in 1684 he discovered two more moons, Dione and Thetys. In 1705, he correctly suggested that Saturn's ring might not be a solid disk but rather a swarm of small objects orbiting the planet. Cassini also observed several comets between 1672 and 1707, as well as Jupiter's Great Red Spot.

During his years at the Paris observatory, Cassini organized a renowned group of astronomers—including Christiaan Huygens, Ole Rømer, and others—known as the Paris School. Trained in engineering, he published several works on flood control, served as inspector of water and waterways, and became superintendent of the Fort Urban fortifications. By 1711 he was blind, and he died in Paris on September 14, 1712. His son Jacques (1677-1756) became head of the Paris observatory, and his grandson César-François Cassini de Thury (1714-1784) and great-grandson Jacques-Dominique de Cassini (1748-1845) also became noted astronomers.

slightly different rates than others. Cassini may also have seen the effects of a comet impacting Jupiter. Between December 5 and December 23, 1690, Cassini observed a feature that appeared in the planet's atmosphere. That feature is similar to features observed in 1994, when more than twenty fragments of the comet Shoemaker-Levy 9 hit the planet. Japanese astronomers Isshi Tabe and Junichi Watanabe interpreted Cassini's drawings to conclude that he observed the effects of a similar cometary impact in 1690.

Impact

Cassini's discovery of the Great Red Spot allowed him to develop techniques to obtain precise measurements of the rotation rates of Jupiter, Saturn, and Mars by observing the time it takes for a feature to move completely around the planet. These techniques are still employed by contemporary astronomers to measure rotation rates of planets, moons, and asteroids. In recognition of Cassini's studies of gas giant planets, the National Aeronautics and Space Administration (NASA) named its Saturn orbiter the Cassini spacecraft, which was launched in October, 1997.

In 1878, Jupiter's Great Red Spot was so named because observers around the world noticed that its color had changed to a very intense red. Scientists believe the reddish color results from chemical compounds containing sulfur and phosphorus, but the reason the colors keep changing is not understood. The spot has persisted for more than three hundred years, providing evidence for how long storms can last in the atmosphere of Jupiter and therefore a greater understanding of Jupiter as a planet. The survival of a single storm for such a long time has also prompted planetary scientists to rethink their ideas about how storms develop, evolve, and survive, since their persistence on gas giant planets clearly is much different from storms on rocky planets.

See also Galileo Probe; Voyager Missions; Weather Fronts.

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—*George J. Flynn*

KELVIN TEMPERATURE SCALE

THE SCIENCE: An international conference established a standard scale of temperature values for worldwide use.

THE SCIENTISTS:
William Thomson, Lord Kelvin (1824-1907), British physicist
Anders Celsius (1701-1744), Swedish astronomer
Sir Humphry Davy (1778-1829), British chemist
Thomas Johann Seebeck (1770-1831), German physicist
Max Planck (1858-1947), German physicist

TEMPERATURE SCALES

Galileo Galilei (1564-1642) invented the first crude “thermoscope” for measuring temperature, and the familiar liquid-in-glass thermometer was probably invented by Ferdinand II, Grand Duke of Tuscany, in about 1654. By 1714, Daniel Gabriel Fahrenheit was manufacturing mercury-in-glass thermometers and had established a temperature scale. He set 100° at what he thought was the normal temperature of the human body and 0° at the lowest temperature that could be obtained in a mixture of salt and ice. On this scale, which is still used in the United States, water boils at 212° and freezes at 32°.

In 1741, Anders Celsius proposed a scale that was based on the properties of water. On this scale, water’s boiling temperature was 0° and its freezing temperature was 100°. This made 1 degree Celsius almost twice as large as 1 degree Fahrenheit. Shortly after the death of Celsius in 1744, the temperatures of the boiling point and the freezing point of water were reversed. The scale was known as the centigrade scale until 1948, when it became known as the Celsius scale. This scale is widely used because it is part of the well-known and widespread metric system.

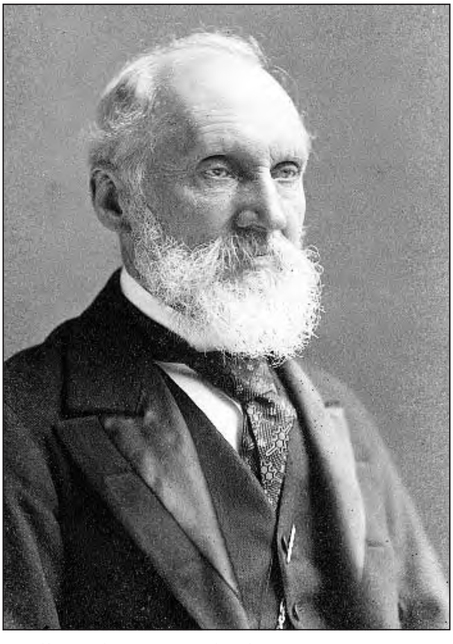
Temperature measurement is actually the measurement of the average motion of the molecules in matter. For this reason, during the nineteenth century, Lord Kelvin proposed a scale on which the zero point would be the coldest possible temperature. At the zero point, the molecules in matter would not move at all—a condition known as absolute zero. Therefore, an ideal theoretical gas would have no volume or pressure at the zero point. One Kelvin (the word "degree" is not used in this system) is the same as 1 degree Celsius. Water freezes at 273.15 Kelvins and boils at 373.15 Kelvins.

International Standards

The international use of temperature scales requires precise agreement on units of measurement and the ability to produce instruments that give the same readings under the same conditions. Also needed are "landmark values," or reference points that can be observed in nature, and methods and instruments must be specified.

Based on the fact that any property of matter that changes with temperature can be used to develop a thermometer, three new instruments were developed that made it possible to achieve greater accuracy and range in international standards.

First, in 1821, Sir Humphry Davy discovered that the electrical resistance of a metal changes with temperature. By the end of the nineteenth century, scientists were able to develop a very reliable platinum resistance thermometer that was to play an important international role. Second, in 1822, the German physicist Thomas Johann Seebeck discovered that electric current flows when two wires made of different metals are joined at both ends if the two junctions (the points at which the wires touch) are at different temperatures. Thermometers based on this principle, which are called thermocouples, are particularly valuable for measuring very high temperatures. Third, at the beginning of the twentieth century Max Planck, another German physicist, determined that objects at still higher tempera-


William Thomson, Lord Kelvin. (Library of Congress)

The International Practical Temperature Scale: Primary Reference Points

Kelvin	*Celsius*	*Reference Point*
13.81 K	– 259.34 C	Triple point of hydrogen*
17.042 K	– 256.108 C	Liquid and gaseous states of hydrogen are in equilibrium at a given pressure
20.28 K	– 252.87 C	Hydrogen boils
27.102 K	– 246.048 C	Neon boils
54.361 K	– 218.789 C	Triple point of oxygen
90.188 K	– 182.962 C	Oxygen boils
273.16 K	0.01 C	Triple point of water
373.15 K	100 C	Water boils
692.73 K	419.58 C	Zinc freezes
1,235.08 K	961.93 C	Silver freezes
1,337.58 K	1,064.43 C	Gold freezes

*The "triple point" refers to the temperature at which a chemical element exists simultaneously in the gaseous, liquid, and solid states.

tures could be measured by means of the radiation that they emit. The "optical pyrometer" was soon built for this purpose.

These three tools, however, had to be calibrated. In 1927, all countries that belonged to the International Bureau of Weights and Measures adopted the International Temperature Scale. Because of improvements in techniques, the scale was revised in 1948, 1960, and 1968. The International Practical Temperature Scale of 1968 (IPTS-68) used the Kelvin, along with eleven fixed primary reference points. In addition, IPTS-68 has twenty-nine secondary reference points listed between 13.956 Kelvins and 3,660 Kelvins. The most fundamental reference point is the setting of the triple point of water at 273.16 Kelvins, which is based on the belief that absolute zero is 0 Kelvins, or –273.15° Celsius.

IPTS-68 also requires that particular instruments be calibrated to the reference points. The platinum resistance thermometer is used for temperatures from 13.81 Kelvins to 903.89 Kelvins (a secondary reference point based on the melting point of antimony). From 903.89 Kelvins to 1,337.58 Kelvins, a thermocouple using platinum and an alloy of platinum is used. At temperatures higher than 1,337.58 Kelvins, the optical pyrometer is used. In 1978, the provisional scale EPT-76 was added to cover the range between 0.5 Kelvin and 30 Kelvins. The next revision of IPTS-68 may incorporate EPT-76 and possibly extend the scale even closer to 0.0 Kelvins.

IMPACT

Precise measurement is fundamental to science, and scientific and technical progress depends on precision. Temperature is a primary property of nature, as are mass, length, and time. The measurement of any of these properties must be dependable and easily reproduced in order to be useful.

IPTS-68 helps scientists to study temperatures that are far beyond normal experience. For example, low-temperature superconducting materials are being explored, and without IPTS-68, meaningful results would be difficult to obtain. Nevertheless, IPTS-68 is not final, and its methods do include assumptions. For example, it is possible that the size of the Kelvin is not exactly the same in all parts of the scale. Attempts to determine temperatures more accurately will continue, and modifications will be made in the future.

See also Celsius Temperature Scale; Fahrenheit Temperature Scale; Liquid Helium; Superconductivity; Thermodynamics: Third Law.

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—*Paul R. Boehlke*

KEPLER'S LAWS OF PLANETARY MOTION

THE SCIENCE: Johannes Kepler, using the extremely accurate astronomical data inherited from Tycho Brahe, and over years of diligent persistence, single-handedly derived the three laws of planetary motion. Without these laws, Sir Isaac Newton might not have been able to form his law of universal gravitation.

THE SCIENTISTS:

Johannes Kepler (1571-1630), German astronomer who derived the three laws of planetary motion

Tycho Brahe (1546-1601), Danish astronomer who brought mathematical precision to observational astronomy

Sir Isaac Newton (1642-1727), English physicist and mathematician who used Kepler's third law to deduce the universal law of gravitation

Nicolaus Copernicus (1473-1543), advocate of the heliocentric (Sun-centered) universe, a model Kepler championed

HELIOCENTRISM

The first serious challenge to Ptolemy's Earth-centered universe, which had stood for fourteen hundred years, was Nicolaus Copernicus's Sun-centered (heliocentric) model, published in 1543 as *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*, 1939; better known as *De revolutionibus*). Unfortunately, because Copernicus, like the Greeks, assumed that the planets moved in circular (not elliptical) orbits, his theory was inaccurate and offered no practical improvement on the ancient model. Johannes Kepler, by sheer dogged persistence over many years, derived the correct mathematical form of planetary orbits—his first law—as well as two additional laws of planetary motion.

Tycho Brahe, the first person since the Greeks to improve astronomy, devoted his life to the patient observation of planetary motion, measuring this motion with incredible accuracy years before the invention of the telescope. Kepler assisted Tycho during Tycho's last two years of life, acquiring his voluminous collection of data upon Tycho's death in 1601. Kepler had long been convinced of the correctness of the Copernican theory, but he knew that it was seriously flawed. He therefore turned his considerable mathematical skills to solving the problem of planetary orbits. To Kepler, this was a religious quest; the key to God's mind was harmony and simplicity manifested in geometric order. To solve the mysteries of the solar system was to understand the grand secret of the universe.

Kepler assumed Tycho's post of imperial mathematician to Emperor Rudolf II of Bohemia in 1601, a position he occupied until Rudolf's death in 1612. Although he had to attend to royal astrological duties, the position gave him status, a salary, and time to pursue his scientific interests. During this most fruitful period of his professional life, he single-handedly founded scientific astronomy and invented instrumental optics.

THE IMPERFECT CIRCLE

Kepler began the astronomical analysis of planetary orbits by attempting to meld Tycho's data on the orbit of Mars into a Copernican system of simple, uniform circular motion about the Sun. Over the next four years, however, Kepler failed repeatedly; Tycho's data placed the orbit eight minutes of arc outside the predicted Copernican orbit, an error exceeding the accuracy of the measurements by at least a factor of four. Not willing to overlook this difference, Kepler had to assume that the Copernican scheme was seriously flawed. To rectify it he had to abandon the one assumption Copernicus had lifted directly from the ancient Greeks: that the planets moved in circular paths (or combinations of circles) at uniform speeds. By trial and error, he discovered that the planetary orbits corresponded to a simple geometrical figure known to mathematicians since the third century B.C.E. as the ellipse.

LAWS OF PLANETARY MOTION

Kepler's first law of planetary orbits, building on this ancient knowledge, states that all planets move in elliptical paths, with the Sun at one of the foci of each ellipse. (Mathematically, an ellipse is a curve for which the

KEPLER'S LAWS OF PLANETARY MOTION

Johannes Kepler's three laws of motion, articulated in the first years of the seventeenth century, laid the foundation for Sir Isaac Newton's law of universal gravitation.

FIRST LAW: A planet orbits the Sun in an ellipse, with the Sun at one of the two foci.

SECOND LAW: The line joining the planet to the Sun sweeps out equal areas in equal times as the planet travels around the ellipse.

THIRD LAW: The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semimajor axes. That is, the time it takes a planet to complete its orbit is proportional to the cube of its average distance from the Sun. The farther from the Sun an object is, the more slowly it moves.

Johannes Kepler. (Library of Congress)

sums of the distances of any point on the curve from two internal fixed points, the foci, are equal to the sums of distances from the foci to any other point on the curve.)

This law by itself was incomplete because it provided absolutely no information about how the speed of a planet in its orbit was related to its orbital position. If such a relationship could be found, the features of any planet's motion could be elegantly and succinctly summarized. Although Kepler had no guarantee that such a relationship even existed or could be found, such was his faith in the order of the universe that he proceeded on the basis that it lay hidden in Tycho's voluminous data. By sheer persistence and ingenuity, Kepler revealed another simple law, to be called the second law of planetary motion: During any given time interval, the imaginary line connecting a planet and the Sun sweeps out the same area anywhere along the elliptical path. As a result of this law, it followed that the distance from the Sun to a planetary position multiplied by the speed at that point is equal to a constant, thus giving Kepler his simple relationship.

Kepler's laws established the possibility of accurate astronomical prediction without resorting to the multiplicity of geometric artifices employed by previous systems that posited circular orbits. Kepler labored for several years on a book detailing these laws, readying it for publication in 1606. Three more years were required to find a publisher and to raise the money to pay the printing costs, an expenditure he had to assume since no wealthy patron offered support. Printing began in 1608, and the book was released the following summer as *Astronomia nova* (1609; *New Astronomy*, 1992).

Kepler's first and second laws of planetary motion were discovered by a bizarre combination of blundering intuition and an astute alertness for hidden clues. The laws were phenomenally successful at predicting planetary positions, but Kepler remained dissatisfied because no overall pattern connecting the orbits of different planets existed. Although there was no good reason that the motions of unrelated planets should be connected, Kepler, who was obsessed with the conviction that nature was simple and harmonious, believed a relationship did exist. Consequently, he spent a decade relentlessly pursuing this quest despite the many personal misfortunes that plagued the latter part of his life. (After Rudolf II died, Kepler lost his position at court and was forced to accept a lesser position in Austria.)

After years of unceasing toil, he found that there was indeed a pattern connecting the orbits of different planets: the third law of planetary motion. This law states that the square of the period of revolution of a planet about the Sun is proportional to the cube of the mean radius of the planetary orbit. Against the backdrop of European turmoil (as the Thirty Years' War was beginning) as well as personal tragedy (his wife had died, his patron Rudolf II was overthrown, his mother was tried as a witch, and Kepler himself fell into poverty), Kepler published *Harmonices mundi* (1619; *The Harmony of the World*, 1997). The irony was unintended.

Impact

Not only are Kepler's three laws the foundation upon which modern astrophysics was constructed, but the intervening centuries verified their accuracy for all types of orbits, including those followed by charged particles moving under the action of electrical forces. Kepler never realized the true significance of his laws, because without differential calculus (invented by Isaac Newton), the three laws show no apparent connection to each other.

The connection was revealed eighty years later when Newton proved that an elliptical orbit was one of the logical consequences of his laws of motion and gravitation. The objective importance of Kepler's third law to Newton is inestimable, as it provided the final clue for Newton to deduce and verify his law of universal gravitation.

Although Kepler is honored for his work in astronomy, a subtle and perhaps even more important contribution was his innovative attitude toward astronomy, an attitude destined to have profound effects on the future of the physical sciences. This was a shift from attempting to fit the universe to preconceived geometrical models to a new emphasis on the mathematical relationships underlying the observations. His successful attempt to formulate physical laws in mathematical form, based on precise quantitative data, established the equation as the prototypical essence of physical law.

See also Brahe's Supernova; Calculus; Gravitation: Newton; Heliocentric Universe; Mössbauer Effect; Pendulum.

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—*George R. Plitnik*

KINETIC THEORY OF GASES

THE SCIENCE: Daniel Bernoulli developed the first systematic theory to explain the behavior of gases in terms of their kinetic (or motion-related) properties. Using a mathematical approach, he established a formal relationship between, on one hand, the many tiny collisions between individual gas molecules and the walls of a container and, on the other hand, the overall pressure exerted on the container by the gas taken as a whole.

THE SCIENTISTS:
Daniel Bernoulli (1700-1782), Swiss mathematician and scientist
Robert Boyle (1627-1691), Irish chemist
James Clerk Maxwell (1831-1879), Scottish physicist
Johannes Diderik van der Waals (1837-1923), Dutch physicist

BOYLE'S LAW

By the seventeenth century, scientists had noted that gases had unusual properties that they could not explain. In particular, gases were fluids in the sense that they could flow and fill a volume having an irregular shape, but they could also exert a force on the walls of a closed container. This latter property of gases was easily demonstrated placing a gas in a container that was capped by a piston and noting that the piston was supported by the gas.

The Irish chemist Robert Boyle took the first step in developing a theory to explain some of the properties of a gas. Boyle was a careful experimentalist, and he studied the behavior of a gas held in a container topped by a piston. He kept the container and the gas at a constant temperature and measured the gas's volume and pressure, that is, the force exerted on the piston divided by the area of the piston. In 1660, Boyle published the results of a series of measurements of the pressure and volume of a gas that was held at a constant temperature. These results demonstrated that the volume of a gas is inversely proportional to the pressure it exerts, a result now known as Boyle's law.

Prior to Boyle's measurements, physicists had studied the mechanical properties of springs. It was well established that the force required to compress a spring increased linearly as the spring got shorter. Boyle suggested that the length of a spring was analogous to the volume of a gas inside a container, and the force exerted by the spring was analogous to the force exerted by the gas against the container. Thus, Boyle suggested, gases were in some sense springs that, when they were compressed or distorted, exerted a force proportional to their degree of compression.

Boyle was also aware that that the volume of a gas increases when the gas is heated. However, he was not able to determine a mathematical relationship between a gas's temperature and its volume, because there was no well-established temperature scale in Boyle's era. It was the development of accurate and reproducible thermometers by the German scientist Daniel Gabriel Fahrenheit, who invented the mercury thermometer in 1714, that allowed the relationship between temperature and volume to be precisely determined.

MOLECULES IN MOTION

Working from Boyle's law as a starting point, the Dutch-born Swiss mathematician and physicist Daniel Bernoulli attempted to determine the physical cause of which the law was an effect. Bernoulli, who was teaching in St. Petersburg, Russia, at the time, became the first scientist to understand air pressure in terms of the behavior of the individual molecules making up the air. Unlike Boyle, who took a careful series of measurements, Bernoulli took a theoretical approach to explaining the pressure ex-

Daniel Bernoulli. (Library of Congress)

erted by a gas. He considered a cylinder that was oriented vertically, was sealed at the bottom, and had a piston at the top. The piston, which was free to move up and down but which would not allow gas to escape, had a weight on top of it. The piston and weight were supported by the pressure of the gas inside the cylinder.

Bernoulli proposed that a gas was composed of individual objects, which we now call molecules, that move very rapidly, colliding with the surface of the piston. When they hit the piston, the molecules are reflected back in the opposite direction. Each collision exerts a minute force on the piston. The macroscopic pressure exerted by the gas on the piston represents the sum of the force of all these minute collisions. Thus, the gas behaves as a fluid, expanding to occupy more volume as the piston is moved upward, increasing the available volume of the container. However, if the speed of the molecules remains constant, then as the volume of the container increases, the time required for an individual gas molecule to move across the container and strike the piston also increases. There are therefore fewer collisions in any given time interval, and the pressure exerted on the piston decreases proportionally. Bernoulli's model, published as a chapter in his *Hydrodynamica* (1738; *Hydrodynamics*, 1968) is called a "kinetic theory," because the macroscopic properties of the gas depend on molecular motion.

Bernoulli's kinetic theory was not widely accepted at the time. Most scientists believed that the molecules in a gas stayed more or less in place, repelling each other from a distance by the action of some unknown force. The British physicist Sir Isaac Newton had shown that the inverse relationship between pressure and volume of a gas could follow simply from an inverse square law of repulsion between the gas molecules. Thus, in Bernoulli's era, the accepted model was that gas molecules were essentially fixed in position. This, too, may have been a function of the relative dearth of rigorous temperature-related experimentation, as the intimate relationship between temperature and kinetic energy was entirely unknown.

One weakness in Bernoulli's kinetic theory was that the speeds of the individual molecules in a gas could not be measured; thus, the pressure each molecule exerted on a piston could not be calculated. Bernoulli understood that it was not necessary to determine the speed of each molecule. The

A Father-Son Rivalry

In 1700, Daniel Bernoulli was born to a long line of mathematicians, physicians, and scientists. His father, Johann, was an expert in Leibnizian calculus. In 1705, Daniel's uncle Jakob died and Johann assumed his brother's vacant chair of mathematics at the University of Basel. Johann became involved in the priority disputes between Sir Isaac Newton and Gottfried Wilhelm Leibniz over the invention of calculus and demonstrated the superiority of Leibniz's notation in the solution of particular problems. After 1705, Johann worked primarily on theoretical and applied mechanics.

In the meantime, Daniel obtained his master's degree in 1716 and was taught mathematics by his father and his elder brother Nikolaus II. Attempts to place him as a commercial apprentice failed, and he studied medicine at several different universities, at last settling in Basel with a doctorate in 1721, his thesis concerning respiration. His first attempts to obtain a university post failed, but his *Exercitationes quaedam mathematicae* (1724; mathematical exercises) landed him a post at the St. Petersburg Academy. Daniel Bernoulli obtained a position in the St. Petersburg Academy in 1725 and remained there until 1733. In 1727, Leonhard Euler joined him. His most productive years were spent in St. Petersburg. He wrote an original treatise on probability, a work on oscillations, and a draft of his most famous work, *Hydrodynamica* (1738; *Hydrodynamics by Daniel Bernoulli*, 1968), in which he expounds his kinetic theory. He returned to Basel to lecture in medicine but continued to publish in the areas that interested him most—mathematics and mechanics. His father, Johann, tried to establish priority for the founding of the field of hydrodynamics by plagiarizing his son's original work and predating the publication. This is only the worst of many examples of the antagonism that Johann felt toward his son.

In 1743, Daniel began lecturing on physiology, which was more to his liking than medicine, and was offered the chair of physics in 1750. He lectured on physics until 1776, when he retired. His most important contributions center on his work in rational mechanics. He returned to probability theory in 1760 with his famous work on the effectiveness of the smallpox vaccine, arguing that the vaccine could extend the average lifespan by three years. He published a few more minor works on probability theory through 1776. Throughout his career, he won numerous prizes for astronomy, magnetism, navigation, and ship design. He died in Basel in 1782.

macroscopic pressure could be determined simply by knowing the average speed of the molecules, the mass of the molecules, and the rate of collision. Bernoulli, however, was not able to determine the relationship of the speed of a gas molecule to its temperature, which, like pressure and volume, was a measurable macroscopic property.

Maxwell and van der Waals

It was not until the 1850's that the link posited by Bernoulli between the properties of the individual molecules making up a gas and the macroscopic behavior of the gas gained widespread acceptance in the scientific community. In 1859, the Scottish physicist James Maxwell attacked the problem. Maxwell adopted Bernoulli's model of gas molecules as perfectly "elastic particles" (that is, particles that obey Newton's laws of motion but that lose no energy when they collide with each other or with other objects). Maxwell quickly recognized that even a small container of gas held far too many molecules to permit him completely to analyze this system using Newton's laws. However, Maxwell also realized that he simply needed to understand in principle how the microscopic picture of molecules in motion was connected with gases' macroscopic properties, which represented averages over extremely large numbers of molecules. Using a statistical approach, Maxwell was able to find the "velocity distribution function," that is, a function to determine the number of gas molecules that have a given velocity for gases at a fixed temperature.

The modern understanding of the behavior of gases was developed by Johannes Diderik van der Waals, who related pressure, volume, and temperature in an equation that extended the results obtained by Bernoulli to include the finite size of gas molecules and the small attractive force between the molecules, now called the van der Waals force. Van der Waals was awarded Nobel Prize in Physics in 1910 for this work.

Impact

Once Bernoulli's kinetic theory of gases gained widespread acceptance, it had a major impact on how theoretical physicists attempted to understand the large-scale physical properties of objects. Bernoulli's work introduced several new ideas to the world of physics. In developing the first kinetic theory of gases, he proposed that the macroscopic properties of objects can be explained by the motion and behavior of the particles that make up those objects.

Thus, Bernoulli showed that by considering the behavior of the atomic and molecular constituents of matter, the large-scale physical properties of matter can be understood. This concept was important in many areas of physics, for example to the subsequent understanding of conduction of electricity, heat, and sound through matter. Bernoulli, moreover, expressed the results of his theory in terms of statistics. Statistics would arise as a science in its own right in the nineteenth century, and the use of statistical formulations in the physical sciences would become more acceptable thereafter. Statistical physics would become particularly important with the development in the twentieth century of quantum mechanics, a field of physics in which all the properties of the particles that make up an object are expressed in probabilistic terms.

See also Atmospheric Pressure; Atomic Theory of Matter; Boyle's Law; Thermodynamics: First and Second Laws; Thermodynamics: Third Law.

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—*George J. Flynn*

LAMARCKIAN EVOLUTION

THE SCIENCE: In *Zoological Philosophy*, Lamarck proposed a pre-Darwinian theory of organic evolution or transmutation of species and explained it by the twofold mechanism of natural progress and the inheritance of acquired characteristics.

THE SCIENTISTS:

Jean-Baptiste Lamarck (1744-1829), naturalist who proposed that evolutionary change takes place by the use and disuse of organs

Edward Drinker Cope (1840-1897), American paleontologist

Georges Cuvier (1769-1832), French naturalist, famous comparative anatomist, and paleontologist

Georges Louis Leclerc, Comte de Buffon (1707-1788), French naturalist and encyclopedist of natural history
Carolus Linnaeus (1707-1778), Swedish taxnomist
Erasmus Darwin (1731-1802), English physician and grandfather of Charles Darwin
Jean-Baptiste Bory de Saint-Vincent (1778-1846), French botanist
Charles Darwin (1809-1882), English naturalist

Species: Mutable or Immutable?

During the eighteenth century, a number of naturalists, including the great taxonomist Carolus Linnaeus and the comte de Buffon in later life, questioned the doctrine of the immutability of species. According to the common understanding, new forms resulted from either hybridization or degeneration of type. The idea of unlimited change found expression in the works of philosophe Pierre-Louis Moreau de Maupertuis and in several other philosophers, including J. B. Robinet and Charles Bonnet. The latter theories, however, did not find many adherents and were not grounded in the systematic study of organic beings. Before 1800, Lamarck himself accepted the immutability of species, although his attempts to discover a natural classification of plants in his first book, published in 1779, became important when he later conceived of the evolutionary process. During the 1790's he worked on the classification of invertebrates, which had all been lumped together into one group. He also did research on physico-chemico problems and attempted to persuade his contemporaries that his chemistry was superior to the new chemistry of Antoine-Laurent Lavoisier (it was not, and Lavoisier became the father of modern chemistry).

Before he published *Philosophie zoologique* (1809; *Zoological Philosophy*, 1914), Lamarck published other works in which he worked out the principles of organic change. The main lines of these principles included spontaneous generation at the lowest levels of both the plant and animal kingdoms, the natural production of increasingly complex organisms from simpler ones, and the influence of the environment that altered the natural progress toward ever-increasing complexity.

Two issues led Lamarck to the idea of species mutability. First was his rejection of the extinction of species, a phenomenon that had been suspected but not convincingly demonstrated until the 1790's. As an adherent of geological uniformitarianism—the idea that geological changes were slow and steady—he rejected the explanation proposed by Georges Cuvier and others that geological catastrophes had erased entire species. Lamarck asserted that the forms no longer in existence had changed into present forms.

Second, he devised a theory of spontaneous generation to account for the origin of the simplest living forms. The causes of spontaneous generation were entirely physical; subtle fluids, of which heat, light, and electricity were examples, occasioned the organization of inorganic matter and excited the process of life. His experience in classification supported his idea that nature progressed from simple to complex in the production of living beings. Lamarck's theory of evolution rested on a phylogenetic (historical) interpretation of the gradation of organic beings. Although individuals could not be placed in a linear manner on the scale, the large groups could.

The March of Progress

The fact of organic transformation required a cause. During the eighteenth century the idea of the "march of human history"—that is, the notion that species naturally evolved toward more refined, better forms—was predominant. Along similar lines, Lamarck proposed two quite different causes for organic diversity. The first and more important cause was the tendency of nature to cause an increase in complexity of organization of animals. The second cause was the influence of the environment upon heredity. In chapter 7 of *Zoological Philosophy*, Lamarck elucidated the two laws of inheritance: first, continuous use strengthens an organ and continuous disuse weakens it until it ultimately disappears; second, through long-term environmental influences, organisms developed needs that occasion inherited changes in organs through use or disuse. These laws formed his so-called principle of the inheritance of acquired characteristics.

Lamarck was inconsistent in his assertions concerning the necessity of both causes. In some places he argued that evolution occurred even in the absence of environmental effects; in others, having noted that when species reproduce in an unchanging environment they do not change, he seemed to deny the inevitability of progress. Lamarck provided three pages of speculations concerning how structures might change. For example, he asserted that the membranes between the toes of a bird stretched until the webbed foot formed in waterfowl. The horns and antlers of male ruminants formed in response to the excess flow of inner fluids stirred up by fits of anger.

Lamarck's *Zoological Philosophy*

Lamarck worked out these views in *Zoological Philosophy*. In part 1, he presented his views on the natural classification of animals and the fact

LAMARCK ON INHERITED TRAITS

In his Zoological Philosophy, *Jean-Baptiste Lamarck made his case for the heritability of traits.*

Circumstances have an influence on the form and the organic structure of animals. What this means is that by undergoing significant change, the circumstances proportionally alter, over time, both the form and the organic structure itself. . . .

Thus, efforts made in any direction whatever . . . enlarge these parts and make them acquire dimensions and a shape which they would never have attained if these efforts had not become the habitual action of the animals which carried them out. Observations undertaken on all the known animals provide examples of this everywhere.

Is it possible that there is a more striking one than the kangaroo? . . . 1. Its front limbs . . . have remained thin, very small, and almost without force. 2. The back limbs . . . have, by contrast, undergone a considerable development and have become very large and very powerful. 3. Finally, the tail . . . has acquired at its base an extremely remarkable thickness and power. . . .

Conclusion Accepted Up Until Today: Nature (or its author), in creating the animals, anticipated all the possible sorts of circumstances in which they would have to live and gave to each species a fixed organic structure, as well as a determined and invariable form for its parts, which forces each species to live in those places and climates where it is located and to maintain there the habits which we know it has.


(Library of Congress)

My Personal Conclusion: Nature, by producing in succession all the animal species and beginning with the most imperfect or the simplest, gradually made the organic structure more complicated; as these animals generally spread out into all the habitable regions of the world, from the influence of the circumstances which each species encountered, it acquired the habits which we know in it and the modifications in its parts which observation reveals to us in that species. . . .

Could there be in natural history a more important conclusion, one to which we ought to give more attention, than the one I have just revealed?

Source: Jean-Baptiste Lamarck, *Zoological Philosophy*, chapter 7. Translanted by Ian Johnston, Malaspina University-College, Nanaimo, B.C., Canada, April, 2000. Available at http://www.mala.bc.ca/~johnstoi/LAMARCK/lamarckF.htm. Accessed September, 2005.

that classification reveals increasing complexity, which is interrupted by environmental factors leading to the inheritance of acquired characteristics. Part 2 detailed Lamarck's materialistic definition of life and his views on spontaneous generation. Part 3 encompassed his views on the nature of the nervous system, again explained in terms of physical causes.

One of the functions of the nervous system was to create unconscious needs or instincts, the actions of which could change habits and lead to deviations from the progressive plan of nature. This action was not universal in all species. Lamarck believed that the most important features of animals were the nervous, respiratory, and circulatory systems, in that order. On the linear scale of organisms, descending down from the top position, occupied by humans, to the lowest, the infusoria, one could observe the simplification and finally the disappearance of these systems. In species with little-developed nervous systems in particular (and in plants), habits formed from the direct influence of the external fluids upon the internal organization, while in more advanced organisms, the nonconscious "internal sentiment" mediated the influence of the external fluids.

Cuvier's Attacks

Lamarck's ideas gathered a few adherents. However, even before the publication of *Zoological Philosophy*, Georges Cuvier, the most important comparative anatomist and paleontologist in France at the time, attacked Lamarck's system. He rejected Lamarck's geological uniformitarianism and organic tranformationism and interpreted geological history as a series of alternations of catastrophes that caused extinction and creation of new species. Furthermore, he believed in a very tight or rigid organization of the organism, in which all structures worked together to perform the functions necessary to life. Any change in structure beyond the normal bounds would result in death. When *Zoological Philosophy* appeared, the general public as well as the scientific community largely ignored it.

Impact

It is interesting to note that in the 1790's Erasmus Darwin, the grandfather of Charles Darwin, published a theory of organic transmutation, in which he also argued for natural progression and presented a view similar to Lamarck's on the inheritance of acquired characteristics. Lamarck himself, however, viewed the latter mechanism as secondary, and the overemphasis on its importance stemmed from Cuvier's ridicule of Lamarck's bird examples and his focus on it in his obituary of Lamarck. During the

1820's several minor figures and a more important one, Jean-Baptiste Bory de Saint-Vincent, attempted to gain adherents for Lamarck's views. While their views sometimes bore little resemblance to Lamarck's actual works, the idea of organic transformation remained alive. Lamarck's idea that evolution did occur, moreover, may have prepared the way for the acceptance of Charles Darwin's theory, especially in Italy. Lamarckianism also had adherents outside the realm of biology. It influenced the social evolution theories of Herbert Spencer, for example, and had a number of proponents, such as the neo-Lamarckian American paleontologist Edward Drinker Cope, who liked the idea that organisms themselves drove their own destiny.

Charles Darwin himself was well aware of Lamarck's work. His conception of evolution, however, differed greatly from the earlier one. Unlike Lamarck, Darwin did not consider evolution to be progressive. Moreover, Darwin's mechanism for evolutionary change, natural selection, bore no resemblance to the inheritance of acquired characteristics. However, in the absence of an understanding of genetics, Darwin did speculate that the use and disuse of anatomical parts and the influence of habits of life and the environment might cause variations in individuals, variations on which natural selection operated.

See also Evolution; Fossils; Human Evolution.

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—*Kristen L. Zacharias*

LANGEBAAN FOOTPRINTS

THE SCIENCE: In 1997, scientists discovered ancient fossil footprints left by a woman who walked on the shores of a South African lagoon, Langebaan, approximately 117,000 years ago. These footprints were made by one of the earliest members of the human race.

THE SCIENTISTS:
David Roberts, geologist, Council for Geoscience, Bellville, South Africa
Lee R. Berger (b. 1965), paleoanthropologist, University of Witwatersrand, Johannesburg, South Africa
Stephan Woodborne, archaeologist, Council on Scientific and Industrial Research, South Africa

FOOTPRINTS IN THE SAND

About 117,000 years ago, a human being walked in the sand beside the shores of Langebaan Lagoon, located on the western seacoast of South Africa about 60 miles (97 kilometers) north of Cape Town. The sand was wet and soft because of a recent rainstorm, and as the the individual walked, her feet created a right-left-right pattern of footprints on the sand dune. By comparing the size and shape of these footprints with those of modern South African native peoples, scientists estimated that the ancient walker stood between 5 feet and 5 feet, 4 inches (156-160 centimeters) tall and was probably a woman. She was walking from the sea toward the lagoon, perhaps hunting for mussels or looking for what the storm had washed up.

Through a rare geological process, some of the footprints were fossilized. Many layers of sand were blown by the wind, covering the footprints and preserving their shape. Over a long period of time, shell fragments in the sand were dissolved by water, releasing calcium carbonate and turning the sand into hard, cementlike rock. Many thousands of years later, erosion caused this rock to break apart and once again expose three footprints to the open air.

DISCOVERY AND PRESERVATION EFFORTS

In 1997, the fossilized footprints were discovered by David Roberts, a geologist with the Council for Geoscience in Bellville, South Africa, who was exploring nearby rock formations. Roberts noticed that there were many small pieces of rock that looked as if they had been chipped out by ancient humans while they were making stone tools or weapons. He also saw fossilized animal tracks and began looking to see if any human fossil tracks might be found in the rock slabs on the shore. On August 14, 1997, he reported that he had found three ancient human footprints that were surprisingly well preserved. The prints are 8.5 inches (21.5 centimeters) long, and one of them gave a very clear imprint of the complete human foot (the big toe, ball, arch, and heel). Another footprint was less clearly marked, and only part of the third footprint remained.

Although scientists could not date the footprints themselves, the rock surrounding the prints underwent a series of tests by Stephan Woodborne, a South African archaeologist with the Council on Scientific and Industrial Research. Woodborne estimated that the fossils were about 117,000 years old. The footprints are very fragile, and in June, 1998, a resin cast was made to preserve a permanent copy of them. The footprints themselves were then removed and later placed on display at the South African Museum in Cape Town.

Roberts worked with Lee Berger, a paleoanthropologist at the University of Witwatersrand in Johannesburg, South Africa, to study the footprints further. Paleoanthropology involves the study of how humans lived many thousands of years ago, based on the fossils and objects that ancient people have left behind. Berger theorized about how the woman who left the footprints might have lived.

People living in South Africa 100,000 years ago did not hunt or fish in complex ways but moved around from spot to spot gathering fruit and scavenging for small animals and shellfish from the ocean's edge. They used stone tools but did not have bows and arrows. In the rock lying underneath the fossils, Roberts discovered Stone Age tools that he believed were made by the people who left the footprints. These included blades for scraping and cutting, a spear point, and a large stone core from which other tools were chipped. The woman's people would have lived in caves in small family groups, and they knew how to make fire. Although they did not create art, they would have had rituals that involved dancing and painting their bodies with ocher pigments. Clothing would have been made from animal skins, but no jewelry would have been worn. Scientists do not know if these people were able to speak.

Impact

The significance of the fossil footprints lies partly in their age and partly in how rare they are. Only a few sets of fossil footprints have ever been found in Africa. Even more important, the Langebaan footprints date from the point in history when modern humans were evolving—the period that saw the emergence of *Homo sapiens*, the modern human species. Scientist have discovered very few fossil remains of modern humans from this time period. In contrast, thousands of fossils have been found from much earlier periods of human history (before 2 million years ago).

Berger has suggested that the footprints might be those of "Eve," an individual female living in South Africa between 100,000 and 300,000 years ago from whom scientists believe that all modern humans are descended. Berger believes that the southern tip of Africa was an ideal place for new species of humans to evolve, because it is isolated from the rest of the continent by geographical barriers (mountains and deserts). This isolation would have allowed the ancient ancestors of modern humans to evolve and change separately from other human species in the world, until *Homo sapiens* finally emerged.

Berger's theory has not been accepted by other scientists, however. Based on DNA (deoxyribonucleic acid) evidence, paleoanthropologists agree that a common female ancestor existed, but there is no way of knowing whether she was the woman who left the Langebaan footprints. The footprints, moreover, do not help scientists understand in detail how ancient humans lived or how they looked. They are of interest simply because they look much like human tracks that might have been left on a shoreline only hours ago, although they were made by a human ancestor who lived more than sixty thousand human generations ago.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Helen Salmon*

Lascaux Cave Paintings

The Science: The discovery of cave paintings at Lascaux helped archaeologists to explain how prehistoric art evolved and how early it began.

THE SCIENTISTS:

Henri-Édouard-Prosper Breuil (1877-1961), French archaeologist
Marcel Ravidat, the seventeen-year-old youth who was the first to enter the cave
Jacques Marsal,
Georges Agnel, and
Simon Coencas, the other boys who discovered the cave

A MYSTERIOUS CAVE

On September 12, 1940, shortly after the beginning of World War II in Europe, three local boys and two refugees from the German-occupied region of France were roaming through a field in southwestern France when they heard the faint sound of barking. Their dog had fallen into a small hole at the base of a fallen tree. One of the local youths, Ravidat, went in after it and slid about twenty feet to a sandy floor. Striking matches to light a large underground hall measuring approximately sixty by thirty feet, he became the first person in fifteen thousand years to see the remarkable multicolored cave paintings of Lascaux (named for the ruins of a place called Château Lascaux that was on the same property as the cave).

Although they had no way of knowing it, what the five boys had discovered looked much like the famous Altamira paintings found in northern Spain seventy years before. The Lascaux cavern walls were covered with paintings of wild beasts: horses and stags, oxlike creatures with strange long bodies, and bulls with strange spotted patterns covering parts of their bodies. Scattered among the animals in this prehistoric scene was a series of checkerboard symbols and leaflike designs. One of the youths, Estréguil, made quick sketches of the paintings.

The boys brought news of their discovery to their schoolmaster, who passed on the news to experienced archaeologists. One of these was Abbé Bouyssonie, the archaeologist who had discovered the famous Neanderthal man skeleton in 1908. Henri-Édouard-Prosper Breuil was another expert for whom this discovery was especially important. Breuil was interested in devising a general theory of how prehistoric art had evolved. The cave paintings at Lascaux looked as if they might contain a key.

Breuil and the other archaeologists explored the cave more fully, finding eighty paintings on their first try, both in the main hall and in a side cave. Most of the paintings were found on blocks of stone that had fallen from the cavern ceiling. Although it would take some time before any real theory could be developed, Breuil sent an article about the find to the distinguished English scientific journal *Nature*.

Image Not Available

The Paintings

The paintings ranged from about a foot to more than fifteen feet in length. Many techniques had clearly been used for artistic effect, and many paintings had been touched up since the time they were first made. One of the most useful paintings for suggesting how people lived during that time showed a man lying beside his hunting tools—a javelin and a throwing stick. Looking at a bison that had been gored by his spear, the hunter seemed to be fatally wounded. Also notable was the outline of a child's hand and forearm, perhaps a "signature" for the group of artists. Strangely, among all the paintings in the cavern, this was the only reminder of the community of artists.

Most of the paintings were of many different animals, but some seemed to be telling practical stories. One of these showed a number of horses, some upside down, showing how primitive hunters had driven such animals off cliffs. This painting was later called *Falling Horses*. Other paintings were too strange to be readily interpreted. One of these came to be known as *The Apocalyptic Beast*. The beast did not look like any animal known to archaeologists, although it may have been an ox or a prehistoric rhinoceros. The body was massive and sagging, as if in a late stage of pregnancy, but the head was much too small for the rest of it. It was spotted with oval-shaped rings and had "horns" that looked like straight sticks and were covered with tufts. Perhaps the most important discovery regarding the

Lascaux cavern was suggested by Breuil as soon as he saw it. Based on paintings he had studied in the nearby museum of prehistoric cultures at Les Eyzies, he was sure that the Lascaux paintings were older than the Magdalenian archaeological period (15,000-10,000 B.C.E.). Breuil and other archaeologists came to believe that prehistoric art had first developed in an earlier age, which he called Perigordian.

IMPACT

Although archaeologists had studied prehistoric artifacts throughout Western Europe since the first half of the nineteenth century, the discovery in 1868 of cave paintings at Altamira had offered the first evidence that prehistoric humans had practiced painting.

The paintings at Altamira, like the ones at Lascaux, were very colorful and were mostly of bison and other animals. There were also some designs—such as checkers, squares, and dots—as well as some engraved (not painted) "semihuman" figures. Some archaeologists have suggested that these pictures may show early rituals.

Archaeologists' greatest disappointment about the paintings at Altamira had been that there was no way to date the paintings in order. Generally, they agreed that prehistoric art had first appeared in the Aurignacian period (about 25,000 to 15,000 B.C.E.), but they were unable to tell when the paintings first began to be as sophisticated as those found at Altamira. Breuil's work at Lascaux, based on his earlier work at many different sites, helped to show that complex painting techniques had developed much earlier than anyone had thought.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lucy; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Byron D. Cannon*

LASERS

THE SCIENCE: Taking its name from the acronym for "light amplification by the stimulated emission of radiation," a laser is a beam of electromagnetic radiation that is monochromatic, highly directional, and coherent. Lasers have found multiple applications in electronics, medicine, and other fields.

THE SCIENTISTS:

Theodore Harold Maiman (b. 1927), American physicist
Charles Hard Townes (b. 1915), American physicist
Arthur L. Schawlow (1921-1999), American physicist
Mary Spaeth (b. 1938), the American inventor of the tunable laser

COHERENT LIGHT

Laser beams differ from other forms of electromagnetic radiation in consisting of a single wavelength, being highly directional, and having waves whose crests and troughs are aligned. A laser beam launched from Earth has produced a spot a few kilometers wide on the Moon, nearly 400,000 kilometers away. Ordinary light would have spread much more and produced a spot several times wider than the Moon. Laser light can also be concentrated so as to yield an enormous intensity of energy, more than that of the surface of the Sun, an impossibility with ordinary light.

In order to appreciate the difference between laser light and ordinary light, one must examine how light of any kind is produced. An ordinary lightbulb contains atoms of gas. For the bulb to light up, these atoms must be excited to a state of energy higher than their normal, or ground, state.

This is accomplished by sending a current of electricity through the bulb; the current jolts the atoms into the higher-energy state. This excited state is unstable, however, and the atoms will spontaneously return to their ground state by ridding themselves of excess energy.

As these atoms emit energy, light is produced. The light emitted by a lamp full of atoms is disorganized and emitted in all directions randomly. This type of light, common to all ordinary sources, from fluorescent lamps to the Sun, is called "incoherent light."

Laser light is different. The excited atoms in a laser emit their excess energy in a unified, controlled manner. The atoms remain in the excited state until there are a great many excited atoms. Then, they are stimulated to emit energy, not independently, but in an organized fashion, with all their light waves traveling in the same direction, crests and troughs perfectly aligned. This type of light is called "coherent light."

Theory to Reality

In 1958, Charles Hard Townes of Columbia University, together with Arthur L. Schawlow, explored the requirements of the laser in a theoretical paper. In the Soviet Union, F. A. Butayeva and V. A. Fabrikant had amplified light in 1957 using mercury; however, their work was not published for two years and was not published in a scientific journal. The work of the Soviet scientists, therefore, received virtually no attention in the Western world.

In 1960, Theodore Harold Maiman constructed the first laser in the United States using a single crystal of synthetic pink ruby, shaped into a cylindrical rod about 4 centimeters long and 0.5 centimeter across. The ends, polished flat and made parallel to within about a millionth of a centimeter, were coated with silver to make them mirrors.

It is a property of stimulated emission that stimulated light waves will be aligned exactly (crest to crest, trough to trough, and with respect to direction) with the radiation that does the stimulating. From the group of excited atoms, one atom returns to its ground state, emitting light. That light hits one of the other exited atoms and stimulates it to fall to its ground state and emit light. The two light waves are exactly in step. The light from these two atoms hits other excited atoms, which respond in the same way, "amplifying" the total sum of light.

If the first atom emits light in a direction parallel to the length of the crystal cylinder, the mirrors at both ends bounce the light waves back and forth, stimulating more light and steadily building up an increasing intensity of light. The mirror at one end of the cylinder is constructed to let through a fraction of the light, enabling the light to emerge as a straight, intense, narrow beam.

IMPACT

When the laser was introduced, it was an immediate sensation. In the eighteen months following Maiman's announcement that he had succeeded in producing a working laser, about four hundred companies and

BEFORE THE LASER: THE MASER

Charles H. Townes is internationally known for his invention of the maser and for his research in the field of microwave physics. From 1941 to 1947, he was employed at the Bell Telephone Laboratories, where he worked extensively in designing radar bombing systems. This project was followed by a period of radar research, which turned Townes's attention to the field of microwave spectroscopy. From 1948 to 1961, he was a professor at Columbia University, where he continued his work in microwave physics and served as the executive director of the Columbia Radiation Laboratory and the chairman of the physics department. He also became interested in astronomy, conducting research in both the infrared and the radio portions of the electromagnetic spectrum.

In 1951, Townes conceived the idea for the maser, which stands for "microwave amplification by stimulated emission of radiation." According to Townes, he was sitting on a park bench, admiring some azalea bushes, when it occurred to him that molecules and atoms are "nature's original broadcasters" because of their natural oscillations between energy levels. Seeking to produce shorter microwaves, he pondered the possibility of using controlled molecular or atomic activity. His idea proved correct, and the word "maser" was coined. Townes's first maser used ammonia gas as the active material. In 1958, Townes and Arthur L. Schawlow showed theoretically that masers could be made to operate in the optical and infrared region. The optical laser, which resulted from this work, allowed some of the most exciting uses of the fundamental maser idea.

Both masers and lasers became important tools in basic science and communications research. Townes employed the maser as an atomic clock to verify precisely the famous Michelson-Morley experiment, which demonstrated that the speed of light is constant. He also did extensive research with masers in radio astronomy. Masers could work as extremely sensitive receivers for short radio waves. They were of great importance in radio astronomy and would be used in space research programs to record radio signals from satellites.

several government agencies embarked on work involving lasers. Activity centered on improving lasers, as well as on exploring their applications. At the same time, there was equal activity in publicizing the near-miraculous promise of the device, in applications covering the spectrum from "death" rays to sight-saving operations. A popular film in the James Bond series, *Goldfinger* (1964), showed the hero under threat of being sliced in half by a laser beam—an impossibility at the time the film was made because of the low power-output of the early lasers.

In the first decade after Maiman's laser, there was some disappointment. Successful use of lasers was limited to certain areas of medicine, such as repairing detached retinas, and to scientific applications, particularly in connection with standards: The speed of light was measured with great accuracy, as was the distance to the Moon. By 1990, partly because of advances in other fields, essentially all the laser's promise had been fulfilled, including the death ray and James Bond's slicer. Yet the laser continued to find its place in technologies not envisioned at the time of the first laser. For example, lasers are now used in computer printers, in compact disc players, and even in arterial surgery.

See also Cosmic Microwave Background Radiation; Liquid Helium; Medieval Physics; Mössbauer Effect; Neutrons; Nuclear Fission; Oil-Drop Experiment; Optics; Pendulum; Plutonium; Quantized Hall Effect; Quantum Mechanics; Quarks; Schrödinger's Wave Equation; Spectroscopy; Speed of Light; Superconductivity; Superconductivity at High Temperatures; Thermodynamics: First and Second Laws; Thermodynamics: Third Law; Wave-Particle Duality of Light; Weather Fronts; X Radiation; X-Ray Crystallography; X-Ray Fluorescence.

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—*Grace Marmor Spruch*

LIGHTNING

THE SCIENCE: By drawing lightning from storm clouds, Franklin's dangerous kite experiment conclusively demonstrated that this natural phenomenon was a form of electricity. The experiment also offered further proof of his single-substance theory of electricity and showed that this fluid-like static energy could be passed from one object to another.

THE SCIENTISTS:

Benjamin Franklin (1706-1790), American statesman, publisher, author, and scientist

William Franklin (1730/1731-1813), Benjamin Franklin's son and last royal governor of New Jersey

LIGHTNING AND LIGHTNING RODS

Benjamin Franklin's kite experiment started with two related questions: What is the nature of electricity? and Is lightning a form of electricity? Franklin indicated in his autobiography that prior to this investigation his interest in electricity had been inspired by Adam Spencer. Spencer had lectured on the subject in Boston in 1744 and then later, at Franklin's invitation, in Philadelphia.

Soon afterward, Franklin attempted various electrical tests, which he frequently reported in letters to his English friend Peter Collinson. Collinson read this correspondence at meetings of the Royal Society and eventually assisted in the London publication of Franklin's letters in *Experiments and Observations on Electricity* (1751-1754). Translated into several languages, this two-volume work established Franklin's reputation within the scientific communities of both Europe and the American colonies.

As early as 1749, Franklin had suspected that lightning was an electrical discharge from storm clouds. In a letter to Peter Collinson he observed that lightning and electricity shared similarities in color, crookedness of motion, and crackling sounds. If lightning is electricity, Franklin wondered, then how did the clouds obtain this electrical static? He conjectured that salt particles found in oceans rub against water to produce an electrical charge on the surface of the ocean. Through evaporation, he further speculated, this charge rises to the clouds, which during certain types of encounters release this charge as lightning.

Franklin observed as well that tall objects, such as steeples, trees, and ship's masts, can trigger the release of electrical energy from clouds. To protect such structures from fires caused by lightning strikes, he recommended 10-foot-long “upright rods of iron made sharp as a needle.” Extended from the peaks of high structures, these devices would preemptively attract “electrical fire” from the clouds. Although his report on the kite experiment in the October 19, 1752, edition of *The Pennsylvania Gazette* states that a test of his lightning-rod theory succeeded in Philadelphia, it remains uncertain whether he personally had conducted such a trial by this date.

The Kite Test

It is virtually certain, however, that with the assistance of his twenty-one-year-old son William in June, 1752, Franklin did indeed conduct a kite test of his theory about the electrical nature of lightning. In a letter to Collinson dated October 19, 1752, as well as in the article published that same month in *The Pennsylvania Gazette*, Franklin reported that during a thunderstorm he flew a kite made of a silk handkerchief stretched across cedarwood crosspieces. It had a tail and a foot of wire extended as an antenna from the top. The lower end of the twine descending from the kite was tied with an insulating silk ribbon, from which an iron key was suspended away from Franklin’s hand by a cotton string. To keep the silk ribbon and the key dry during the storm, Franklin stood inside a doorway while flying the kite. When he passed his other hand over the key, a spark leaped from the key toward his knuckle. This transfer of energy proved that lightning was electrical in nature.

Single-Substance Theory

Franklin’s use of a pointed-tip conductor in the kite experiment also advanced the case for his single-substance theory of electricity. At the time of his kite test, the prevalent European theory held that electricity was composed of two separate opposing fluids, effluence and affluence. The kite experiment refuted this prominent theory by enabling Franklin to measure the charge of the lower part of storm clouds, which he found to be negative in nature. This reading supported his theory that electricity consisted of a single “electoral fluid” that circulates among and through positively and negatively charged materials. Grouping different materials on the basis of their conductivity, Franklin concluded: “A body which is a good conductor of [electrical] fire readily receives it into its substance, and conducts it thro’ the whole to all the parts.”

Franklin on the Philadelphia Experiments

In his autobiography, Benjamin Franklin recalled his experiments with electricity:

(Library of Congress)

In 1746, being at Boston, I met there with a Dr. Spence, who was lately arrived from Scotland, and show'd me some electric experiments. They were imperfectly perform'd, as he was not very expert; but, being on a subject quite new to me, they equally surpris'd and pleased me. Soon after my return to Philadelphia, our library company receiv'd from Mr. P. Collinson, Fellow of the Royal Society of London, a present of a glass tube, with some account of the use of it in making such experiments. I eagerly seized the opportunity of repeating what I had seen at Boston; and, by much practice, acquir'd great readiness in performing those, also, which we had an account of from England, adding a number of new ones. I say much practice, for my house was continually full, for some time, with people who came to see these new wonders. . . .

Oblig'd as we were to Mr. Collinson for his present of the tube, etc., I thought it right he should be inform'd of our success in using it, and wrote him several letters containing accounts of our experiments. He got them read in the Royal Society, where they were not at first thought worth so much notice as to be printed in their Transactions. One paper, which I wrote for Mr. Kinnersley, on the sameness of lightning with electricity, I sent to Dr. Mitchel, an acquaintance of mine, and one of the members also of that society, who wrote me word that it had been read, but was laughed at by the connoisseurs. . . .

What gave [the work] the more sudden and general celebrity, was the success of one of its proposed experiments, made by Messrs. Dalibard and De Lor at Marly, for drawing lightning from the clouds. This engag'd the public attention every where. M. de Lor, who had an apparatus for experimental philosophy, and lectur'd in that branch of science, undertook to repeat what he called the Philadelphia Experiments; and, after they were performed before the king and court, all the curious of Paris flocked to see them. I will not swell this narrative with an account of that capital experiment, nor of the infinite pleasure I receiv'd in the success of a similar one I made soon after with a kite at Philadelphia, as both are to be found in the histories of electricity.

Source: Benjamin Franklin, *The Autobiography of Benjamin Franklin: With Introduction and Notes*. Edited by Charles W. Eliot (New York: P F Collier & Son, 1909).

CONDUCTIVITY

The kite experiment showed, moreover, that the common substance of lightning's "electric fluid" can be passed from one object to another. This principle of conductivity transference so fascinated Franklin that three months after the kite experiment he fashioned an elaborate demonstration utilizing a 9-foot lightning rod that he had attached to the chimney of his home. This rod conveyed electricity through a glass-enclosed wire running down a stairwell to a bell, which was connected by another wire to a second bell. Both bells would ring whenever the lightning rod received an electrical charge. Sometimes so much current passed between the two bells that the entire staircase in Franklin's home lit up brilliantly, as if "with sunshine, so that one might see to pick up a pin." Franklin's wife, legend holds, was not at all pleased by this noisy apparatus—or by her husband's other efforts to convert their home into a laboratory for electrical research.

IMPACT

Franklin's dramatic kite episode became an instant legend. A recurrent subject for paintings and print illustrations over the centuries, the kite test is now a revered part of the world's cultural memory of Franklin. As early as 1767 in *The History and Present State of Electricity*, Joseph Priestley described this episode as a "capital" discovery, "the greatest, perhaps, that has been made in the whole compass of philosophy, since the time of Sir Isaac Newton."

From the standpoint of history of physics, however, the result of Franklin's kite experiment with lightning is not today considered as significant as Priestley thought. Franklin did not know that in France, a month before the Philadelphia kite test, Thomas François d'Aibard had already proved the electrical nature of lightning. This French undertaking, however, was thoroughly indebted to Franklin because it was based on findings he had reported in the first volume of his highly regarded *Experiments and Observations on Electricity Made at Philadelpha in America* (1751). Franklin may have been second in proving that lightning was electricity, but it did not matter. His example in Philadelphia was wonderfully theatrical and proved so appealing to a worldwide audience that others in Europe enthusiastically repeated his experiment.

The kite episode in Philadelphia was, finally, most significant for the evidence it provided in support of two of Franklin's major contributions to the study of physics: his single-substance theory of electricity and his related invention of the pointed-tip lightning rod, still used today. In 1754, two years after Franklin's kite project, the Royal Society in London awarded him the Copley Medal for his electrical research and soon admitted him as a fellow. In spite of initial resistance from the French scientific community, Franklin's reputation for electrical research likewise quickly spread throughout continental Europe.

In America it was the pointed-tip lightning rod on the kite, more than his single-substance theory, that elevated Franklin's fame. Franklin's lightning-rod design, which would become the worldwide standard, was indeed more effective than the European blunt-tipped model. Moreover, its effectiveness when employed to protect buildings from lightning-caused electrical fires was not its only value for Americans. The strategic foot of wire "made sharp as a needle" and extended skyward from the top of the kite's wooden crosspieces became a cultural symbol for eighteenth century Americans. Elated because this colonial device was superior to the European version, Americans proudly celebrated the design of Franklin's lightning rod as a symbol of their new nation's ingenuity and independence.

See also Conductivity; Electric Charge; Electrodynamics; Electromagnetism; Electrons; Magnetism.

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—*William J. Scheick*

LINKED PROBABILITIES

THE SCIENCE: Andrey Markov's formal development of linked probabilities, or Markov chains, provided new computational models for a wide variety of random processes.

THE SCIENTIST:

Andrey Andreyevich Markov (1856-1922), Russian mathematician
Pafnuty Chebyshev (1821-1894), Russian mathematician
A. N. Kolmogorov (1903-1987), Russian mathematician

HISTOGRAMS

Before Pafnuty Chebyshev, Andrey Andreyevich Markov, and A. N. Kolmogorov, a number of oblique working definitions of key statistical properties had been offered, mainly by natural scientists applying statistical methods. These definitions, however, frequently did not coincide or in some cases were even contradictory.

This was also true for basic statistical methods such as the use of histograms in count data analysis. A histogram is constructed by dividing the horizontal axis into segments or classes of a certain data value (such as size, temperature, and the like), which cover the entire range of data values. Over each segment, a rectangle is constructed whose height is proportional to the number of data points in each class segment. This histogram shows the relative class frequencies, which in the limits of smaller subdivisions and larger numbers of samples approaches the underlying probability density distribution for the population.

BERNOULLI'S LAW OF LARGE NUMBERS

A key example of functional, yet vague, statistical concepts awaiting further development was James Bernoulli's so-called law of large numbers. Formally stated, Bernoulli's theorem asserts that frequencies of occurrence for independent chance events must converge eventually in the limit of large numbers of observation to the underlying probability law. In other words, this theorem stated basically that the experimental histogram of samples from a statistical population would match the theoretical probability distribution function more closely, defining a given population as the number of selected samples increases without bound.

Even by the late 1880's, satisfactory proofs under general assumptions had not been found for the large numbers law, nor had its limits of applicability been well determined. This was particularly true for the case of events whose statistical independence or relation was not known or determinable beforehand. Thus, for example, the German statistician Wilhelm Lexis, although arguing for the conceptual modeling of statistical interpretation of natural events on the results of a notional urn drawing, did not believe that evolutionary or otherwise linked or connected series were susceptible to formulation in terms of quantitative probability theory.

As numerous investigators pointed out near the beginning of the twentieth century, in its original (chiefly heuristic) form, the large numbers law gave nothing useful about the precise manner or function form in which statistical averages approach their limit. Many statisticians believed that the law of large numbers is true only for statistically independent events or trials. Nevertheless, without a more rigorous law of large numbers, probability theory would lose its common intuitive foundations and so the issue could not be dismissed simply.

The Central Limit Theorem

In contrast to the German and French schools of statistics, Soviet statisticians (almost exclusively at the University of St. Petersburg) were strongly theoretical in focus, more interested in formal existence and consistency conditions than in applications of statistical laws. It was precisely this group that, from their own perspective, addressed the problems of consistently defining the interpretation and applications scope of the law of large numbers. In 1867, Chebyshev found the first elementary proof of the law of large numbers (LLN) as well as the "central limit theorem" (CLT).

As an advanced graduate student of Chebyshev, Markov in 1884 published a shorter and more perspicious reformulation of Chebyshev's proofs, which began a series of exchanges and further clarifications of the basic concepts underlying, and scope of application, of the large number and central limit theorems to linked, as well as totally independent, events. From a purely theoretical perspective, Markov approached these questions indirectly by considering whether the LLN applied equally to dependent as well as to independent random variables. Then, using the Markov model of (weaked/linked/conditional) dependence to verify the LLN, he examined whether sums of dependent variables satisfy the CLT.

Specifically, in Markov's subsequent work, he focused closely on the theoretical laws governing what is in effect the convergence of empirical histograms to theoretical "probability distributions functions" (pdf's) for a variety of conditions of weak statistical dependency or sample interlinking, as well as independence. The general classes of weakly linked statistical events considered originally by Markov can be considered a generic mathematical model of a random process with only specifically delimited after-effects or with a very short-term memory. This model describes any physical or other system in which the probability of change or transition from one state to another state depends only on the state of the system at the present or immediately preceding time and not on the longer prior history of the process.

Linked Events

A perennial problem by the end of the nineteenth century, related to the issue of independent versus dependent statistical data, was that of estimating the statistical variance of time or space averages of ocean, weather, geologic, or other statistically measured data that could not, strictly speaking, be assumed as totally independent random or unconnected by virtue of their (causal) adjacency.

One of many practical examples of events that both common sense and science describe as linked are meteorologic observations. In 1852, French mathematician Adolphe Quetelet proposed what is probably the first probabilistic model to fit weather observations of consecutive rainy (or cold) and dry (or warm) days. To account for the frequent persistence, or temporal linkedness of rainy (or dry) weather, Quetelet devised for the occasion a simple mathematical formula that explicitly captures an apparently random element but that also exhibits the influence or effect of one or more previous elements on subsequent events. Neither Quetelet nor other largely empirical science-oriented statisticians of the era pursued further the more general possibilities of accounting for linked events or processes.

Markov Extends the Law of Large Numbers

The formal properties, and applications potential, of a general method for describing events with linked probabilities were stumbled upon by Markov at the beginning of the twentieth century. In his 1906 paper, "Extension of the Law of Large Numbers," Markov proved for the first time that both the number of occurrences of a studied event and the sequence of its associated random variables obey the law of large numbers.

Assuming a simple one-link only (first-order chaining) of events, and an unconditional normalized total probability for the event of p, the math order transition probabilities, or probability of a change of binary-determined states between temporally adjacent events, was first derived by Markov to be given by the relation $R_m = p + (1 - p)(p_1 - p_2)^m$. This relation can be interpreted as linking the general conditions under which a system of equations has a unique solution with the specific parameters defining the chaining of events. As stated in his 1907 paper, "Extension of the Limit Theorems of Probability Theory to a Sum of Variables Connected in a Chain," these weakly dependent, or linked, sequences are definable as "numbers connected into a chain in such a manner that, when the value of one of them becomes known, subsequent numbers become independent of the preceding ones."

Likewise, Markov, in publications in 1908 and 1910 to 1912, considered more complex (higher-order) linkings or chainings of events whose probabilities of occurrence depend upon the outcomes of two or more prior trials. In modern probability theory, a sequence is considered to be a Markov chain if the pdf governing its underlying process can be said to have connection, link, or memory extending to one or more prior events. Alternately expressed, in the Markov model, given the present, the future is independent of the past. More generally, random processes having a dependence between successive terms as an intrinsic property of the underlying process are defined as Markov processes.

Examples of Markov Chains

The classical example of a (multiple) Markov chain, as a semiserious test of the efficiency of information-transfer originally given by Markov himself, is that of the written (Soviet) language in Alexander Pushkin's novel *Evgeny Onegin* (1825-1833; *Eugene Onegin*, 1881). Here, letters of the alphabet are subdivided into type states, denoted by 0 if a vowel and 1 if a consonant, so that a page of written text appears as a sequence of the occurrence of 0's and 1's. The vowels and consonants form a first-order Markov chain if, given any string of letters, the probability for the next letter to be a vowel or consonant (0 or 1) is the same as the probability that the next letter will be a vowel or consonant if one knows only the last letter of the entire story.

Although there is no direct evidence that the St. Petersburg school's original work to theoretically validate probability theorems to the case of dependent variables was motivated by prior publications by Lexis or his contemporaries between 1907 and 1911, Markov and a colleague repeatedly referred to several examples and applied problems from their publications. In addition, Markov and his colleagues generally indicated several other examples of physical phenomena exhibiting linked probabilistic behavior. These included the theories of molecular random ("Brownian") motion of Albert Einstein and Paul Langevin, biologic theories of the extinction of genetic families, and the so-called random walk problem. (The random walk, paradigmatic for many probability applications, is defined generically by the motion along a straight line that, at each unit time, can move one unit left or right or not at all, whose probabilities depend only on position.)

Impact

Almost since their discovery, Markov chains have proven to be a powerful method for modeling a wide variety of physical, chemical, and biologic phenomena involving time-dependent/transient and long-run/steady-state behaviors. As early as 1908, A. K. Erlang carried out studies of the steady-state behavior of commercial telephone-exchange traffic (theory of queues), deriving what is now known as the Kolmogorov equations for a finite Markov process. In addition to stock-exchange speculation, and particularly telephone, mail, and road traffic, similar Markov queue models have been applied widely to landing of aircraft and ships, assembly-line component breakdown, scheduling and checkout for clinics and supermarkets, and inventory maintenance.

In the first three decades of the twentieth century, problems of quantitative epidemic spreading and population growth using a second-order Markov model were considered. In addition to the theory of elementary particle collisions and cascades, the theory of statistical mechanics describing the physics of molecules—an important Markov chain application—is the so-called nearest neighbor system, used, for example, as models for crystal lattices and, in chemistry, for treating chemical kinetics and diffusion-controlled reactions.

Following the work of Ludwig von Mises, a number of researchers in operations research combined the methodologies of Markov models and Bayesian decision analysis to facilitate quantitative solution of complex problems in economic and military equipment procurement and deployment.

Thousands of papers have been published on specialized applications of temporal and spatial Markov series. Theoretically, the mathematical methods initiated by Markov were extended later and formalized by Aleksandr Khinchiny, Norbert Wiener, and notably Kolmogorov, establishing probability theory as an identifiable and rigorously founded subdiscipline.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D’Alembert’s Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Gerardo G. Tango*

LIQUID HELIUM

THE SCIENCE: Heike Kamerlingh Onnes transformed helium gas into liquid helium, initiating the study of matter at temperatures approaching the lowest achievable temperature, absolute zero.

THE SCIENTISTS:
Heike Kamerlingh Onnes (1853-1926), Dutch physicist
Sir James Dewar (1842-1923), Scottish chemist and physicist

LIQUEFACTION OF GASES

Perhaps the most familiar example of liquefaction is rain, which is caused by the condensation of water vapor in the air. In the late eighteenth century, Antoine-Laurent Lavoisier predicted that other constituents of air would also liquefy if they became cold enough. Lacking effective cooling techniques, scientists wondered whether all gases could be liquefied. Early researchers tried to liquefy gases by compression, forcing molecules closer together. The Dutch scientist Martinus van Marum liquefied ammonia by compression, but attempts by others to liquefy air at high pressures failed. Studies of gases in the nineteenth century suggested the reason for this failure: A gas will liquefy only if its temperature and pressure are below characteristic critical values. These conditions were not then obtainable for the pressurized air.

One way to cool a gas is to force it to expand quickly. Pursing one's lips and blowing on one's palm illustrates this effect, which is the basis of household refrigerators and air conditioners. In 1877, Louis-Paul Cailletet liquefied oxygen and nitrogen by using more extreme expansion. This produced temperatures below –120° Celsius, at which point the liquids that had been formed quickly evaporated.

In 1883, Polish physicists Zygmunt Florenty von Wróblewski and Karol S. Olszewski improved oxygen liquefaction using a modified Cailletet-type apparatus, in which gas was expanded through a valve into a tube with a closed end that was immersed in liquid ethylene. Reducing the pressure above the ethylene with a vacuum pump caused the ethylene to boil rapidly, cooling to below –130° Celsius. This technique kept the oxygen in a liquefied state.

The Joule-Thomson Process

Several advances paved the way toward achieving lower temperatures. The first was the use of the Joule-Thomson effect, in which a gas cools by expanding through small openings in a porous material. Compressed gas is sent through such an opening, cooling and partially liquefying in the process. The liquid settles in a flask, and the expanded gas is returned to the original container. Along the way, the expanded gas is cooled by a heat exchanger fluid that makes thermal contact with the cold liquid-gas mixture. The process is repeated again and again, enhancing the cooling effect and making it possible to produce large quantities of liquid. Devices of this type were patented independently by William Hampson in England and Carl Paul Gottfried von Linde in Germany in 1895.

Dewar's Research

In the 1890's, Sir James Dewar used this kind of apparatus to liquefy hydrogen, which has a critical temperature of –240° Celsius. He first cooled the hydrogen gas to –205° Celsius by putting it in thermal contact with liquefied air under reduced pressure. In order to store significant quantities of the liquid hydrogen, he invented a double-walled glass container with exceptional insulating qualities.

Dewar evacuated and sealed the space between the walls to minimize

ZERO RESISTANCE

In 1913, Heike Kamerlingh Onnes received the Nobel Prize in Physics for the liquefaction of helium. In the final section of his address before the Nobel Foundation, he described some of the experiments that had led to his 1911 discovery of superconductivity, the complete absence of resistance to the electrical current passing through a conductor.

Experiments carried down to the freezing temperatures of hydrogen had indicated the likelihood of the resistance becoming zero at helium temperatures, provided one had very pure samples of platinum. By measuring the resistance of platinum at the temperatures of liquid helium, he found that it decreased with decreasing temperature, becoming constant after a certain point. Thinking that this was caused by slight impurities in the samples (which would be present even in gold), Kamerlingh Onnes decided to repeat the experiment with samples of a material that could be prepared to be in an extremely pure state: mercury.

He found that while the resistance was decreasing with decreasing temperature, at 4.2 degrees above absolute zero the resistance *abruptly* became zero—an unexpected result. He considered this to be a new state (in addition to the solid, liquid, and gaseous states), which he termed the "state of superconductivity."

He repeated the experiments in 1913 and discovered new properties of superconductivity. Superconductivity proved to be a property of particular substances: Both tin and lead could be superconductive, but gold and platinum, even in a state of very high purity, were not superconductors. Also, the superconducting state could not be maintained when the applied currents were above a certain value, this value being higher the lower the temperature. When currents above this threshold value were passed through the superconductor, the initial resistance was restored. Kamerlingh Onnes proposed that the resistance was restored because of the heat produced in the wire with the increase of the current density. He was, however, fully aware that the explanation may lie in quantum theory, but instead of trying to provide such an explanation, he concentrated on further experimental work.

Kamerlingh Onnes's work in low-temperature physics had led to one of the most important discoveries of the century, superconductivity. Not until 1957, however, would the reasons for this phenomenon be presented as a complete theory. Another Nobel Prize would be awarded to John Bardeen, Leon Cooper, and Robert Schrieffer for just that accomplishment.

heat transfer to the liquid hydrogen. His remarkable container, which has remained useful for a century, is called a "cryostat thermos" (*cryo* is the Greek word for cold) or, simply, a "dewar." The perfection of this container literally changed the study of matter at low temperatures. Dewar continued his work with hydrogen, subjecting it to a pressure less than 1 percent that of normal atmospheric pressure. At that pressure, hydrogen boiled rapidly and, ultimately, solidified.

This development set the stage for the liquefaction of helium, the only gas with a critical temperature lower than that of hydrogen. For ten years after Dewar's breakthrough, scientists in Poland, Holland, and England tried unsuccessfully to liquefy helium. During that time, however, Heike Kamerlingh Onnes built a large research facility at Leiden, the Netherlands, that was equipped to produce large amounts of liquid hydrogen and liquid air. He used his exceptional laboratory facilities, capable staff, and personal experimental skills to liquefy helium in 1908.

The Ultimate Liquefaction

Kamerlingh Onnes's successful helium experiment began at 5:45 a.m. on July 9, 1908, with the first seven hours devoted to the production of 75 liters of liquid air and 20 liters of liquid hydrogen. These were used to precool the apparatus and the helium gas within it. The circulation of helium through a Joule-Thomson process began at about 4:30 p.m., and the successful production of liquid helium was confirmed about three hours later. In his fourteen-hour experiment, Kamerlingh Onnes achieved the ultimate liquefaction, bringing the helium to a temperature of –268° Celsius.

Kamerlingh Onnes proceeded to the next logical step, which was to boil the helium gas under reduced pressure in an attempt to solidify it. Using a strong vacuum pump, he reduced the pressure above the helium, but solidification did not occur. Later, it was discovered that helium differs from all other known materials in that it solidifies only under a pressure about twenty-five times that of normal atmospheric pressure.

Impact

The liquefaction of helium ended the quest to liquefy all gases. The accomplishment also began the study of the properties of materials near the low-temperature limit of matter, absolute zero (–273.15° Celsius).

At temperatures below –268° Celsius, materials exhibit remarkable physical phenomena that could not be explained by existing physical theories and that led to the development of quantum theory. In 1908, Kamerlingh Onnes found that the electrical resistance of mercury dropped sharply at –268° Celsius. He had detected the phenomenon of superconductivity, a discovery for which Kamerlingh Onnes was awarded the Nobel Prize in Physics in 1913. Liquid helium exhibits the property of superfluidity, or a sharp drop in resistance to fluid flow, at temperatures below –271° Celsius. In 1972, helium 3, an uncommon isotope of helium, was also found to exhibit superfluidity.

Superconductivity has made possible sophisticated imaging techniques in medicine (making it possible to view the interior of a body), various advancements in high-energy physics, and the construction of high-speed trains that levitate magnetically above the tracks that guide them.

See also Kelvin Temperature Scale; Superconductivity; Superconductivity at High Temperatures; Thermodynamics: Third Law.

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—*Harvey S. Leff*

LONGITUDE

The Science: John Harrison's chronometer permitted the first accurate measurement of longitude at sea and thus revolutionized ocean travel. His invention opened up new vistas in cartography, astronomy, world commerce, international timekeeping, and the colonial and imperial ambitions of nations.

THE SCIENTISTS:

John Harrison (1693-1776), inventor of the first practical chronometer
William Harrison (1728-1815), John Harrison's son and assistant
Edmond Halley (1656-1742), British Astronomer Royal, first expert to assist Harrison
George Graham (1673-1751), watchmaker and patron of Harrison
James Bradley (1693-1762), early supporter and later opponent of the Harrisons

NAVIGATION AT SEA

The British Parliament established the Longitude Act in 1714 to encourage the solution of a problem that had vexed mariners, merchants, and governments for hundreds of years. It was their inability to measure longitude accurately, especially at sea.

The concepts of latitude and longitude go back as far as the recognition of the Earth's generally spherical shape. Latitude lines, the ones that parallel the equator and measure degrees north or south of the equator, had long since ceased to be a problem. By the time of Christopher Columbus (1492), mariners had learned that by studying the elevation of the Sun above the horizon and by observing certain "fixed" stars, they could rather easily follow an east-west path corresponding to a latitude line.

For Columbus to measure distance along any latitude line he was traveling, the element of time came into play. One hour—one twenty-fourth of a day—corresponds to fifteen degrees of longitude east or west from a point of reference on an imaginary circumferential line through the poles and intersecting the equator. This reference line is called the prime meridian. It can be any longitude line; in modern times the line passing through Greenwich, England, has come to be generally recognized as the prime meridian.

For Columbus to convert that fifteen degrees into geographical distance, he needed to know not just what time it was aboard the *Santa Maria* but what time was being registered at the same moment in some place of known longitude. Because he had no timepiece capable of this feat, he could not know the distance to India or for that matter to any landmass that might intervene.

A MATTER OF TIME

Although navigators and cartographers had most to gain from the solution of the longitude problem and although it also attracted the attention of learned astronomers, it is not surprising, at least in retrospect, that a clock

JOHN HARRISON: A LIFETIME OF LONGITUDE

In 1761, sixty-eight-year-old John Harrison had succeeded in making a chronometer, which he called H-4, that met the Board of Longitude's requirements to win a £20,000 prize for a device that could determine longitude at sea:

> I think I may make bold to say, that there is any other mechanical or mathematical thing in the World that is more beautiful or curious in texture than this my watch or time-keeper for the longitude.

Harrison was proud of his invention, versions of which he had been perfecting for more than three decades. In order to prove the chronometer successful, however, he needed to test it at sea. Hobbled by age, he enlisted the help of his son William to undertake the necessary ocean trials. Aboard the *Deptford* during a stormy voyage to Jamaica in the winter of 1761-1762, William succeeded in proving the chronometer prizeworthy. His father had spent the better part of his lifetime—and all of William's—perfecting the device.

However, so much time had passed since the contest had been announced that the Board of Longitude had begun to backpedal on its commitment. Several members of the Royal Society, including Astronomer Royal James Bradley and others, believed that Thomas Mayer's lunar tables would solve the longitude problem. Doubtless, issues of class were also involved: John Harrison and his son were mere clock makers.

Fearing that the his success would simply be ignored, John Harrison arranged for another test, this time aboard HMS *Tartar* bound for Barbados on March 28, 1764. Again, Harrison's son William sailed with the H-4, and again the chronometer met the board's requirements. Nevertheless, the board insisted that Harrison meet still more conditions to prove the worthiness of his chronometer. Harrison complied, creating H-5. Not until he petitioned King George III in 1773, however, did the Board of Longitude finally relent and grant the prize money. John Harrison was eighty years old. He would die three years later.

Source: Quotation of John Harrison available at the MacTutor History of Mathematics archive, School of Mathematics and Statistics, University of St Andrews, St Andrews, Fife, Scotland, http://turnbull.mcs.st-and.ac.uk/history. Accessed September, 2005.

maker achieved the feat. John Harrison, who was born in Yorkshire in 1693 but grew up in Barrow, Lincolnshire, made his first pendulum clock in 1713, just one year before the Longitude Act established a reward of £20,000 to the person who could devise a solution to the problem. Specifically, the invention had to prove accurate to within one-half of one degree of longitude on a trip from Great Britain to a port in the West Indies. The fact that over this distance an error of one-half degree would still result in an error of several nautical miles indicates both the need for, and the difficulty of, the task.

Not until 1728, however, did Harrison begin his pursuit of the great prize. In the meantime he concentrated on improving pendulum clocks. Because all metals expand in heat, metal pendulums grow longer and measure time more slowly in hot weather. Harrison overcame this problem by combining long and short strips of two different metals in one pendulum. He also invented a device that virtually eliminated friction from the escapement—that part of the clock that regulates the motion of the wheelwork. Working with his younger brother James and with such inexpensive materials as he could afford, he made clocks of amazing precision, accurate to within one second per month.

When he entered the competition for the prize, Harrison, aware that no pendulum clock would work on a sailing ship at sea, experimented on a mechanism that might be expected to withstand the force of ocean waves. By 1730, armed with drawings of a sea clock, he went to London and called upon the great astronomer Edmond Halley. Halley, knowing that the device of a mere clock maker probably would not impress a Longitude Board inclined to favor the ideas of learned astronomers and mathematicians, sent him to George Graham, an eminent maker of watches and scientific instruments.

Encouraged by Graham, Harrison spent the next five years constructing his first sea clock. Now called H-1, it was a seventy-five-pound contraption with two large brass balances, connected by wires, taking the place of a pendulum. Tested on a sea voyage to Lisbon, it performed well enough to convince Harrison that he was on the right track.

Over the next twenty-five years Harrison strove for a smaller, lighter, and less complex timepiece, and in 1761 completed H-4. He was now sixty-eight years old but had as his assistant his son William, born about the time the project began but grown into an able clock maker under his father's tutelage. It was William who made the sea journey to Jamaica to

Image Not Available

test his father's latest timepiece. H-4 did not bear much resemblance to the first three versions. It looked like a somewhat oversized pocket watch, twelve centimeters in diameter.

Long-Delayed Recognition

William and the chronometer sailed aboard a ship called the *Deptford* in November of 1761. Checked against the local longitude, which had been determined astronomically, H-4 proved to be only five seconds slow, a deviation of only 1.25′ of longitude. For the total trip the error in longitude was 28.5′, probably because on the return trip, completed on January 19, 1762, the *Deptford* had encountered particularly stormy seas. However, H-4 had still come within the limit of one-half of one degree.

This should have been the end of the story, but the Board of Longitude insisted on further inspections and tests of the timepiece. Other claimants, including a prestigious astronomer, James Bradley, originally a Harrison supporter, arose. Harrison was granted only a partial reward, and it was years before he finally received the full prize amount.

Recognition of his feat came slowly but eventually fully. Nearly two hundred years after his death a modern navigator, while being honored at a dinner, proposed a toast to the memory of Harrison as the man who "started us on our trip." That navigator was astronaut Neil Armstrong. Although the even more accurate modern marine chronometer is based on principles different from Harrison's, it was he who proved that an instrument capable of facilitating navigation into previously unknown waters could be made.

Impact

The invention of an accurate chronometer led to the expansion of knowledge of the great waters of the Earth. Soon Captain James Cook, the great eighteenth century maritime explorer, benefited greatly from the chronometer. In addition to increasing geographical knowledge, the capacity to make timed observations of heavenly bodies at sea furthered the work of astronomers.

With the solution of the problem of longitude, mapmakers could accurately represent the configurations and relative positions of land masses. Being lost at sea, the universal experience of mariners up to Harrison's time, became rare. Cartographers could pinpoint geographically small hazards and thus refine the nautical charts of mariners, who for centuries had been running aground with great loss of men, ships, and cargoes. The knowledge of distances between ports and the capacity to chart safe routes between them fostered maritime commerce. Of course the capacity of aggressive nations to carry out colonial and imperial ambitions also increased.

In the long run, the mastery of longitude made possible the simplification and standardization of international timekeeping, although not until the International Meridian Conference of 1884 did the nations of the world agree to designating as prime meridian the one passing through the old Royal Observatory in Greenwich, England, which allowed the opposite 180-degree meridian in the Pacific to serve as the international date line.

See also Pendulum.

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—*Robert P. Ellis*

LUCY

THE SCIENCE: "Lucy," an early hominid skeleton more than three million years old, was the oldest hominid to be discovered at the time, 1974.

THE SCIENTISTS:

- *Donald C. Johanson* (b. 1943), the paleoanthropologist who discovered the skeletal remains of "Lucy"
- *Tim White* (b. 1950), physical anthropologist

Tom Gray, a colleague of Johanson
Maurice Taieb (b. 1935), French geologist
Louis S. B. Leakey (1903-1972), paleoanthropologist who discovered many early hominid fossils
Mary Leakey (1913-1996), paleoanthropologist and wife of Louis Leakey
Richard E. Leakey (b. 1944), their son, a paleoanthropologist

THE EARLIEST HUMAN ANCESTORS

On November 30, 1974, Donald C. Johanson and a coworker discovered small bones on the slope of a desert gully at Hadar in the Afar Triangle region of Ethiopia. These bones belonged to one individual, a unique hominid that did not resemble anything discovered previously. Named "Lucy" (after the Beatles' song "Lucy in the Sky with Diamonds"), the small skeleton was an amazing find and an important link in the search for human ancestors.

The term "hominid" has a very flexible definition, generally meaning an erect-walking primate that is an extinct ancestor of humans. A hominid can be an ancestor of "true" or modern humans, or a relative, such as a modern primate. The few fossils that had been found before 1925 were from different geographical regions. They were also different from one another, and no one knew exactly what they were, how they were related, or their age.

Early efforts to discover the ancestors of humans centered in Europe. Hominid fossils had been found in the Neanderthal Valley of Germany (Neanderthal man), in Beijing, China (Peking man), and in Java (Java man), to name a few of the most famous. Then, in 1924, Raymond Dart discovered a skull was found in South Africa that did not resemble a human skull but was not a baboon's or a chimpanzee's. The skull was nicknamed the Taung baby, since it was found at Taung and was estimated to be the skull of a six-year-old hominid. The official name given was *Australopithecus africanus*. Additional discoveries of fossils by the 1950's convinced most scientists that two types of hominids had existed in South Africa: *Australopithecus africanus*, a slender type, and *Australopithecus robustus*, a more primitive, robust type.

In 1959, Louis S. B. and Mary Leakey discovered the skull of a large *Australopithecus robustus* at Olduvai Gorge in Tanzania. They named their discovery *Zinjanthropus boisei* ("Zinj" also known as Nutcracker man or East Africa man), because they believed the hominid was sufficiently different from the australopithecines that it represented a different species; it was later reclassified as one of the robust australopithecines. It was the first australopithecine found outside South Africa and the first to be reliably dated, at 1.8 million years old. With the publicity surrounding the Leakeys' find, particularly through the National Geographic Society, paleoanthropology became fashionable to the general public and more funding was made available for further studies.

In 1972, Richard E. Leakey, the son of Louis and Mary, discovered a hominid skull at Koobi Foora in Kenya. He asserted that the skull was definitely that of a human and that it was approximately 2.9 million years old. This skull was the oldest known fossil of a human. If the more advanced genus *Homo* (to which humans belong) existed at the same time as the more primitive australopithecines, then theories that *Homo* evolved from australopithecines were wrong. Later, more accurate dating placed the age of the skull at about 1.9 million years.

In November, 1974, during an international expedition in Hadar, Ethiopia, two of the oldest and finest hominid jaw fossils ever found were located. A few days later, a third jaw was found. Richard and Mary Leakey visited the site and confirmed Johanson's suspicion that the jaws could be *Homo* with excessively primitive features. The jaws were dated at approximately three million years old, which made them the oldest known *Homo* fossils.

Image Not Available

“Lucy”

On November 30, 1974, a few days after the Leakeys had left the Hadar excavation site, Johanson found the nearly half-complete skeleton of Lucy. For three weeks, everyone at the site collected several hundred pieces of bone, which made up approximately 50 percent of the skeleton. Lucy was a tiny-brained individual, approximately 3.5 feet (a little more than 1 meter) tall. The sex of the skeleton was confirmed by the pelvic bones, which must be larger in females in order to permit the birth of large-skulled babies. Lucy walked

DISCOVERING LUCY

In Lucy's Child, *Donald Johanson described the day at Hadar in late November, 1974, when he and Tom Gray found the hominid bones they would later name Lucy:*

> Before leaving camp that morning I'd sensed that we might find something significant. I seldom get that feeling. . . . But after surveying for several hours at Locality 162, we had uncovered no more than some horse and antelope teeth. . . .
>
> We headed back to the Land-Rover through a little gully on the other side of a rise. As always, I kept my eyes moving along the ground with every step. I knew that the gully had been worked over a couple of times before, so I wasn't surprised when it appeared to be empty of bones. But just as I turned to leave, I saw what appeared to be a fragment of an elbow joint lying at the bottom of the slope above. Tom and I knelt down to examine the thing. It was small, very small, but unquestionably a hominid. Then I spotted a piece of skull next to Tom's hand, and suddenly we seemed to be surrounded by hominid bones—a femur, a piece of pelvis, ribs, some vertebrae. For a while we just groped around from one bone to the next, too stunned to speak. It occurred to me right away that perhaps all these bones might belong to a single individual. But I was afraid to speak that thought out loud. . . . Tom, on the other hand, could not hold in his excitement. He let out a yell, and then I heard myself yelling too, and we were hugging each other and dancing up and down in the heat.

Source: Donald C. Johanson and James Shreeve, *Lucy's Child: The Discovery of a Human Ancestor* (New York: William Morrow, 1989), pp. 85-86.

erect, which confirmed theories that hominids walked erect three million years ago.

More hominid fossils were found in 1975 and 1976. At site 333, the fragments of at least thirteen individuals of various ages and sexes were found scattered on a slope. These fossils were *Homo* and very different from Lucy. The 1976 season also yielded stone tools, which strengthened the theory that the site 333 fossils were *Homo*, since there is no evidence that australopithecines made or used tools.

Johanson and Tim White carefully compared the Hadar fossils and the fossils found at Laetoli, Tanzania, where Mary Leakey and White were working. These comparisons indicated that the Hadar and Laetoli hominids were similar and represented a developmental stage in between apes and humans. This determination was a departure from Johanson's early belief that the fossils were *Homo*. Johanson and White decided that the

Hadar and Laetoli hominids were an early, distinct australopithecine. They named these hominids *Australopithecus afarensis*.

IMPACT

The discovery of Lucy was a significant development in the search for clues to understanding hominid evolution. Lucy was unique in that she was a very old, primitive, and small hominid that did not fit into the known hominid types. She was also the oldest and most complete hominid skeleton that had been found. Although only 40 percent of the skeleton was covered, bones from both sides of the body were present, allowing paleoanthropologists to reconstruct approximately 70 percent of her skeleton by using mirror imaging. With mirror imaging, existing bones are used to determine what the missing counterpart on the other side of the body looked like.

Because of the evidence of upright walking in a hominid estimated to be millions of years old and because of the small brain size, the question of why hominids began walking upright had to be reexamined. One previous theory was that manual dexterity, increased tool use, and brain development had forced some humans to stand erect in order to carry more with their hands. Lucy's hands were similar to those of modern humans, but no evidence has been found to suggest that australopithecines made or used tools. Various other theories explaining erect walking were suggested or considered.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Neanderthals; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Virginia L. Hodges*

MAGNETISM

THE SCIENCE: In 1600, William Gilbert, physician to Queen Elizabeth I, published the first great work of English science, *De magnete*, in which he presented his investigations into magnetic bodies and electrical attraction, opening up the study of electricity and magnetism and setting an example of experimental methods in science.

THE SCIENTISTS:

William Gilbert (1544-1603), English physician, scientist, and philosopher
Edward Wright (1558-1615), Cambridge cartographer and Gilbert's collaborator
Francis Bacon (1561-1626), English philosopher and statesman

GILBERT'S *DE MAGNETE*

The first great book of English science was *De magnete, magneticisque corporibus, et de magno magnete tellure* (1600; *A New Natural Philosophy of the Magnet, Magnetic Bodies, and the Great Terrestrial Magnet*, 1893; better known as *De magnete*), which emerged during the scientific revolution. The work marks the transition from Renaissance naturalism to experimental science and was the first comprehensive treatment of magnetism since Peter Peregrinus's *Epistola de magnete* (1269; *Epistle of Peter Peregrinus of Maricourt to Sygerus of Foncaucourt, Soldier, Concerning the Magnet*, 1902).

Gilbert emphasized observation and experiment; his book describes about fifty experiments. These probably grew out of his collaboration with practical navigators and cartographers, especially the Cambridge mathematician Edward Wright, England's leading cartographer and an expert on the compass. Wright not only provided practical information but also wrote the introductory address and chapter 12 of book 4, on magnetic declination (variation from true north). He also contributed to book 5, on magnetic dip (vertical inclination of the magnetic needle) and its relation to latitude, and designed an instrument for measuring dip.

The first of the six books in *De magnete* discusses the history of magnetism, refuting legends about the lodestone (naturally occurring magnetic stones) and describing its properties. Characteristically, Gilbert denied the Aristotelian concept of pure elements, particularly elemental earth, to establish and advance his principle that Earth was a giant lodestone. He argued that this principle explained the phenomena of terrestrial magnetism. In so doing, he rejected the accepted view that the compass was attracted to the poles of the celestial sphere about which the stars and planets revolved. He described ways to demonstrate the behavior of the lodestone, marking his own experiments and discoveries with asterisks of varying size to indicate their relative importance. In the other five books, Gilbert discussed five magnetic movements: coition, direction, variation, dip, and revolution.

The Amber Effect

In book 2, chapter 2, Gilbert described his experiments on the amber effect to distinguish between magnetism and electricity, thus opening up a new field of study and naming it after the Greek word *electron* (meaning "amber"). He showed that some thirty different materials—including glass, hard sealing wax, and several semiprecious gems—have an attractive effect when rubbed. He called these materials "electrics" and distinguished them from "nonelectrics," which do not exhibit an amber effect. He also described the first electroscope, or *versorium*, by pivoting a metal needle on a post so that it would be deflected when a rubbed electric was brought near. He used an animate or formal cause to describe magnetism, believing that magnetic materials shared in the basic magnetic form or "soul" of Earth. By contrast, he believed electric attraction had a material cause, holding that electrics emit "effluvia" when rubbed, a kind of vapor that attaches to matter and pulls it inward.

Coition and Direction

In his study of magnetic phenomena, Gilbert assumed that every magnet is surrounded by an invisible "orb of virtue" (*orbis virtutis*) that affects any other magnetic material placed within its orb of virtue. He produced lathe-turned spherical lodestones, which he called *terrellae* (little earths), as laboratory models for the study of terrestrial magnetism. He preferred the word "coition" for magnetic attraction to emphasize that it was a mutual action between two magnetic bodies, each coming within the orb of virtue of the other. The direction or orientation of a magnetic compass is described in book 3 as the alignment of a compass needle with the Earth's magnetic orb of virtue rather than the celestial poles. To support this idea, he gave numer-

William Gilbert, Physician to the Queen

William Gilbert of Colchester in County Essex, northeast of London, was trained in medicine at Cambridge University, completing his master of art degree in 1564 and his doctor of medicine degree in 1569. He became a prominent physician in London, and in 1577 he was granted a coat of arms by Queen Elizabeth I, evidence of his rising social status. Beginning in 1581, he held several important offices in the Royal College over the next two decades, including censor (editor of journal articles), treasurer, and consiliarium (mediator of disputes).

Although Gilbert was active in the Royal College of Physicians and conducted important medical and pharmaceutical work, his most important contribution came from nearly twenty years of research on magnetism and electricity. He was one of four physicians in the Royal College requested by the Privy Council in 1588 to provide for the health of the men in the Royal Navy. His early investigations were in chemistry, in which he developed habits of precision that served him well in his pioneering research on magnetism. In 1589 the Royal College assigned him the topic philulae for their publication *Pharmacopoeia* on the use of drugs. In both 1589 and 1594 he was listed among the examiners for this book.

(Library of Congress)

In London, Gilbert lived at Wingfield House on St. Peter's Hill, probably inherited from his stepmother. He never married and he used the house as a laboratory and perhaps as a center for meetings with other scientists and physicians. His work attracted the attention of Queen Elizabeth I, who is said to have given him an unprecedented annual pension to conduct his philosophical studies.

In 1600 he was appointed royal physician to Elizabeth, and after her death on March 24, 1603, he became physician to King James I. After Gilbert's death, probably from the plague, he left his books, instruments, and other scientific equipment to the library of the Royal College of Physicians. Unfortunately, little is known about the details of Gilbert's life in London because the Great Fire of London of 1666 destroyed Wingfield House and the buildings of the Royal College, including its library.

ous demonstrations with a *terrella*, using small compass needles (*versoria*) to identify its poles as analogous with the Earth's north and south poles.

Variation

In book 4, Gilbert turned to variations in the orientation of the compass, the well-known declination of the magnetic needle from true north. He demonstrated a similar declination with a *terrella* by making a gouge on its surface analogous to the Atlantic Ocean and showing how such deviations from a smooth sphere affected the compass direction. He also discussed the possibility of using declination to determine longitude at sea.

Dip

In book 5, he discussed the magnetic dip (inclination from the horizontal). Again using a *terrella*, he showed that there is no dip at the equator but there is increasing dip as the magnetic needle moves toward either pole. This led to the suggestion of using dip to measure latitude when the skies are clouded.

Rotation and Revolution

The last book of *De magnete*, book 6, discusses magnetic rotation, based on a suggestion in Peregrinus's letter on magnetism that a spherical lodestone perfectly aligned with the celestial poles would rotate once every 24 hours. Gilbert floated a *terrella* on a cork raft and observed the *terrella*'s tendency to rotate into magnetic alignment. He then suggests that magnetic rotation causes a daily rotation of the Earth on its axis. Although he neither accepts nor rejects the heliocentric theory of the Earth's annual revolution around the Sun, he did support Copernican ideas by denying the solid celestial spheres and their daily revolution, suggesting that the fixed stars are spread through space. He also suggested that the tides result from magnetism of the Earth and Moon. These extensions of magnetic philosophy were not as strongly supported by experiment and were the source of later criticisms of Gilbert's work.

Impact

Gilbert not only initiated the study of magnetism and electricity but also rejected natural philosophy and its support of new views of the world, including a mechanical explanation for the daily rotation of the Earth. His strong emphasis on experimental methods preempted ideas later developed by Francis Bacon. Ironically, *De magnete* was criticized by Bacon for its attempt to develop an entire philosophy based on magnetism and for the concept of a moving Earth. The book was especially valuable for providing a modern understanding of terrestrial magnetism and the basis and terminology for later studies of electricity.

Most of Gilbert's contemporaries, both in England and on the Continent, praised *De magnete* for its new experimental methods as well as its content. A second edition was published in 1628 and a third in 1633; it was widely distributed and strongly influenced the emerging scientific revolution. Galileo Galilei (1564-1642) was greatly impressed and turned his attention to magnetic studies. Johannes Kepler (1571-1630) tried to incorporate Gilbert's magnetic theory into an explanation of planetary motions in the Copernican system. Although the theory of the magnetic movement of the planets was later rejected, it provided a good explanation until the concept of gravitation could be further developed.

See also Conductivity; Electric Charge; Electrodynamics; Electromagnetism; Electrons; Geomagnetic Reversals; Ionosphere; Isotopes; Seafloor Spreading; Solar Wind; Van Allen Radiation Belts.

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—Joseph L. Spradley

MANIC DEPRESSION

THE SCIENCE: The work of David Janowsky and his coworkers improved the understanding and the treatment of manic depression, also referred to as bipolar disorder.

THE SCIENTISTS:

David Steffan Janowsky (b. 1939), American psychiatrist who developed the cholinergic-adrenergic hypothesis of mania and depression

John Marcell Davis (b. 1933), American psychiatrist who collaborated with Janowsky

AN ELUSIVE DISORDER

Hospitals and mental institutions are filled with the victims of serious mental illness. The problem of overcrowding is so severe that many people affected by milder forms of mental illness have been released from these institutions. Many wander the streets of American cities, mentally impaired and often homeless.

Mental illness is often divided into two basic kinds: the "organic" and the "functional" types. Organic mental illness results from an injury or a known disease (for example, diabetes) that alters the structure of the brain, changes its ability to function correctly, or affects some other part of the nervous system. Cure of this type of mental illness depends upon surgery and other methods.

The causes of functional mental illness—often called "affective disorder"—are subtler and therefore have evaded clear understanding. One of the most common affective disorders is manic-depressive psychosis, or manic depression, also called bipolar disorder. The manic-depressive person alternates between an excessively happy (manic) state and a severely depressed (depressive) state. Consequently, such people are incapable of coping with the world around them. Attempts to explain such affective disorders date back to the father of medicine, the Greek physician Hippocrates, who coined the term "melancholia" to describe severe depression. Hippocrates suggested that melancholia was caused by the accumulation of "black bile and phlegm, which darkened the spirit and made it become melancholy."

NERVE IMPULSES

The human nervous system is composed of a central computer—the brain—made up of cells called neurons and a network of nerves that communicate signals to the rest of the body via nerve impulses. Neurons are separated from one another by tiny spaces called synaptic gaps. The passage of nerve impulses through nerves requires them to cross thousands of these gaps.

The movement of nerve impulses across synaptic gaps is conducted by biochemicals called neurotransmitters. One of the principal neurotransmitters is acetylcholine, which acts in "cholinergic" nerves. Cholinergic chemicals inhibit the transmission of nerve impulses, causing, among other things, the slowing of the heartbeat. Scientists have speculated that the interference of cholinergic chemicals with acetylcholine action is one cause of mental disease. This idea arose, in part, from observations of impaired mental function in people who had been exposed to chemicals that disrupt acetylcholine production and use.

Other neurotransmitters associated with mental disease include catecholamines and indoleamines. Catecholamines control the transmission of nerve impulses by adrenergic portions of the nervous system. Adrenergic chemicals, in contrast to cholinergic chemicals, stimulate the transmission of nerve impulses, causing the heart to speed up. The indoleamines function in neurons related to sleep and sensory perception. They are believed to be associated with symptoms of affective disorders that include sleep and sensory dysfunction.

Cholinergic-Adrenergic Imbalance

In 1972, David Steffan Janowsky, John Marcell Davis, and coworkers at Vanderbilt University's Psychiatry Department proposed a theory of manic depression. Central to their theory was the relationship between the body's cholinergic and adrenergic chemicals. In particular, their study focused on acetylcholine. These ideas expanded the understanding of the basis of manic depression.

Janowsky's theory, unlike others before it, recognized the importance of understanding how the various systems involved in nervous transmission interacted with one another. Janowsky suggested that a person's mental health depended on the maintenance of a proper balance between these systems. He described depression as a disease of "relative cholinergic predominance" and mania as one of "relative adrenergic predominance." According to Janowsky, manic-depressive illness is caused by the body's overreaction to an imbalance in the cholinergic-adrenergic relationship: Upon detecting an imbalance, the central nervous system compensates by producing more of the missing chemical, whether cholinergic or adrenergic; in manic depressives, however, the body overcompensates, producing cyclical swings between mania and depression.

Impact

Bipolar disorder affects millions of people worldwide; its victims exhibit severe emotional disturbances and mood swings that make it difficult for them to function within the framework of reality. Their symptoms include greatly disordered thought processes, delusions and hallucinations, and feelings of grandeur as well as the opposite, severe depression. The chronic nature of these symptoms, which occur episodically, places manic depressives at serious social risk, and victims of severe forms of the disease are often confined to mental institutions.

Janowsky's explanation of the causes of manic depression helped to spur the discovery of many concepts and treatments now used by psychiatric practitioners to treat the illness. Such methods include drug treatment with tricyclic antidepressants, lithium, and inhibitors as well as innovative cognitive therapies. None of these methods cures the disease, but various combinations often prove effective in helping manic depressives to live relatively normal lives.

See also Pavlovian Reinforcement; Psychoanalysis; REM Sleep; Split-Brain Experiments.

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—*Sanford S. Singer*

MARS EXPLORATION ROVERS

THE SCIENCE: The Mars Exploration Rovers (MERs), twin robotic expeditions exploring the surface of Mars, landed on different locations on opposite sides of Mars to maximize the scientific return. With the ability to trek the length of a football field each day, they explored a larger portion of the Martian surface than previous missions.

The Scientists:

Jim Erickson, project manager
Joy Crisp, project scientist
Albert Haldemann, deputy project scientist
Steve Squyres, science instrument principal investigator

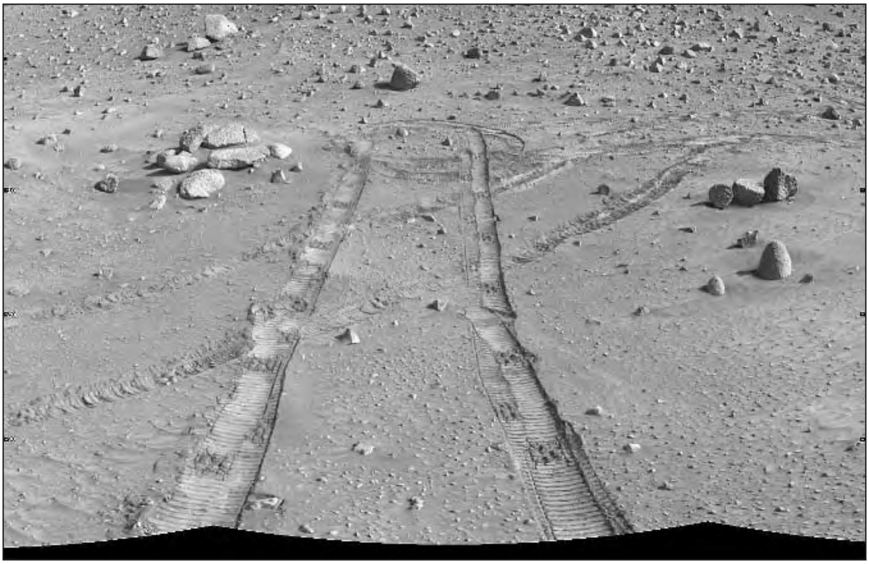
A Trip to Mars

The Mars Exploration Rovers (MERs) were launched about a month apart in the summer of 2003 and reached Mars in early 2004. The first rover, Spirit (MER-A), was launched on June 10. The second, Opportunity (MER-B), was launched on July 7. Both were launched from Cape Canaveral, Florida. Both missions were timed to take advantage of the closest Mars approach to Earth in approximately sixty thousand years.

The probes took the fastest possible trajectories to Mars and arrived in January, 2004. After a seven-month journey, the rover Spirit landed at Gusev Crater on January 3, 2004. Opportunity soon followed by landing on Mars at Meridiani Planum on January 25, 2004. After a parachute was opened to provide initial slowing, the rockets fired to bring the landers to a stop about 10 to 15 meters above the surface. Finally their airbags inflated to cushion the remaining fall. The landers bounced several times before finally coming to rest on the Martian surface and deflating the airbags. The lander petals were then free to open, allowing the rovers to deploy their solar arrays and begin exploring Mars. Shortly after landing, the computer on board Spirit experienced some memory difficulties, which mission controllers were soon able to resolve. Thereafter, both rovers performed well for their originally scheduled ninety-day mission and beyond.

Mission Objectives

The primary scientific objective of the MER missions was to find evidence of past water on Mars by looking for signs of past water activity in Martian rocks and soils. Other important scientific goals included understanding the environmental conditions when liquid water was present on Mars; understanding the composition and distribution of minerals, particularly those containing iron, near the landing sites; and understanding the geologic processes that formed the minerals and terrain at the landing



Tracks left on the Martian surface in May, 2005, by the Mars rover Spirit. (NASA/JPL)

sites. Finally, the studies on the ground were designed to check the conclusions reached about the local Martian geology from orbiter studies and thereby provide confidence that conclusions reached from orbital studies elsewhere on Mars were correct.

INSTRUMENTS AND DATA

Each 170-kilogram rover had been loaded with a suite of instruments designed to allow it to explore the geology of Mars. The nine cameras on each rover include six engineering and three scientific cameras. The cameras provided dramatic images, but the information provided by the other scientific instruments was equally important. The Miniature Thermal Emission Spectrometer (Mini-TES) provided infrared spectra of the Martian rocks, soil, and atmosphere and was particularly important in searching for minerals that were produced in the presence of water. The Mössbauer Spectrometer (MB) was designed to study the iron abundance in the mineral content of Martian rock and soil samples. Magnet arrays mounted at various positions on the MERs collected magnetic samples for analysis by the MB. Chemical compositions other than iron were determined using the Alpha Proton X-ray Spectrometer (APXS). The Rock Abrasion Tool (RAT), located on the end of the robotic arm, was used to expose and study the interior structure of rocks.

In late October, 2004, the MER mission passed the 50,000-picture milestone. This number represented more than twice as many pictures as taken by all previous Mars landers. Some rover components were beginning to show signs of age, but they were still exploring Mars's surface. By April, 2005, with both rovers suffering from only minor problems and each covering greater and greater distances during translations across the Martian surface, National Aeronautics and Space Administration (NASA) announced that the MER program was being extended for the third time.

Water, Water Anywhere?

The Gusev Crater and Meridiani Planum landing sites were chosen for their potential as sites where water once existed. Gusev Crater, the landing site for the Spirit rover, is an impact basin about the size of the state of Connecticut and was thought once to have been a giant lake. However, during the three-month primary mission Spirit failed to find any lake-related deposits at this site. If they ever existed, they have apparently been disrupted by subsequent impacts. Rocks at the Spirit landing site are olivine-bearing basaltic rocks, a type of volcanic rock not previously seen on Mars. The RAT ground off surface layers on rocks at this site, revealing subsurface veins possibly altered by the presence of water. The rock coatings were also consistent with brief periods of moisture in the past, even if not indicative of a large, long-term lake. Spirit also found evidence that subsurface water had percolated to the surface at Gusev Crater.

After exploring Gusev Crater, Spirit started the trek for the nearby Columbia Hills (named after the crew of the ill-fated space shuttle flight destroyed upon reentry on February 1, 2003) to search for clues to the early history of Gusev Crater. Initial indications were that the hills were composed of layers of volcanic ash.

Meanwhile, Opportunity found evidence for water at Meridiani Planum inside a crater named Eagle. The rocks, containing sediments from evaporation, appeared to have formed in a body of slow-moving salt water, perhaps at the shoreline of a salty sea. The rocks at this site contain high concentrations of hematite, which forms in wet conditions. These rocks provided direct evidence of liquid water in Mars's past.

Samples collected by the rovers' magnets indicated that most of the rocks on Mars contain iron. Oxidized iron gives Mars its rusty red color. Studies of patterns on the rocks also helped mission scientists understand the wind erosion on Mars, currently the most significant source of Martian erosion. Some rocks found on Mars also resemble meteorites found on Earth that are thought to originate from Mars, bolstering the evidence that they originated on Mars.

IMPACT

The MER missions, part of NASA's long-term program to explore Mars, were assigned four main scientific goals:

(1) to determine if there was ever life on Mars
(2) to understand the Martian climate
(3) to understand the Martian geology
(4) to pave the way for human exploration of Mars

With their ability to trek across the Martian surface and take samples of both surface and subsurface materials, the MER missions found evidence of geologic processes requiring liquid water on the surface of Mars. These accomplishments far surpassed previous Mars missions, from the Viking landers (1976) to the Mars Pathfinder (1997), and paved the way for future missions to the Red Planet.

Spin-off benefits from the MER mission included practical applications as well. Engineers at the Jet Propulsion Laboratory (JPL) worked to modify the software used to support the rovers in order to create a virtual pediatric intensive care unit, a database that pediatricians around the world could access to find the latest research needed to treat difficult pediatric cases.

See also Cassini-Huygens Mission; Earth Orbit; Galileo Mission; International Space Station; Moon Landing; Space Shuttle; Voyager Missions; Wilkinson Microwave Anisotropy Probe.

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—*Paul A. Heckert*

MASS EXTINCTIONS

THE SCIENCE: Luis W. and Walter Alvarez discovered evidence that the Earth was hit by a large asteroid 65 million years ago.

THE SCIENTISTS:

Luis W. Alvarez (1911-1988), professor emeritus of physics at the University of California, Berkeley
Walter Alvarez (b. 1940), professor of geology at the University of California, Berkeley
Frank Asaro and
Helen Michel, nuclear chemists
Eugene Merle Shoemaker (1928-1997), geologist with the U.S. Geological Survey
David Malcolm Raup (b. 1933) and
John Sepkoski, paleontologists at the University of Chicago

DISAPPEARING SPECIES

Throughout Earth's history, a number of mass extinctions have occurred in which large numbers of different species disappeared at nearly the same time. These mass extinctions have been recognized for more than one hundred years and are used to mark the major time boundaries of the last 600 million years of Earth's history.

The most intensively studied mass extinction was the one that occurred at the end of the Cretaceous period about 65 million years ago. (The Cretaceous period began about 136 million years ago; the mass extinction that took place at its end and marked the beginning of the Tertiary period took place in the time marked by stratigraphic layer known as the Cretaceous-Tertiary boundary.) The dinosaurs made their last stand at this time. Many explanations for this mass extinction have been suggested—supernova explosions, climate change, receding seas, and disease, among others—but a generally accepted theory has eluded geologists. Until the 1980's, most professional geologists believed that the extinction was the result of significant but gradual environmental changes in the oceans and on the continents that were too severe for many animals to survive.

In 1980, a hypothesis was put forth by four scientists at the University of California, Berkeley, who revolutionized the study of the Cretaceous extinctions and changed the way scientists think about evolutionary and geologic change. Luis W. Alvarez, Walter Alvarez, Frank Asaro, and Helen Michel published a paper in the June 6, 1980, issue of *Science* that suggested

Luis Alvarez. (The Nobel Foundation)

that the extinction was caused by the impact of a large asteroid.

As so often happens in science, this discovery resulted from research that initially was conducted on an entirely different problem. Walter Alvarez, a geologist, was working on paleomagnetism in the marine limestones that are very well exposed in Battacione Gorge near Gubbio. These limestones contained fossils that clearly were from the Cretaceous extinction and were covered by a peculiar 1- to 2-centimeter-thick layer of clay formed at the same time as the extinction. Alvarez wanted to know how long it took for the clay layer to be deposited. Unfortunately, the techniques developed by geologists and geophysicists to determine the general ages of rocks and fossils were not precise enough to date the boundaries of an event that happened over a span of only a few thousand years 65 million years ago.

METEORITIC DUST

Walter Alvarez's father, Luis, was a brilliant scientist of enormous curiosity and drive who had won the 1968 Nobel Prize in Physics for his work on subatomic particles. Captivated by the problem, the elder Alvarez suggested to his son that they have the clay analyzed for meteoritic dust. Luis Alvarez knew that dust from meteorites settles on the Earth at a nearly constant rate, and he reasoned that in slowly accumulating sediments such as marine clay, the amount of meteoritic dust in the layer would show how long it had taken for the layer of clay to be deposited.

They enlisted the help of two nuclear chemists at Berkeley, Asaro and Michel. These scientists found that the clay layer, while having similar amounts of twenty-seven other elements, had an astonishing several hundred times more iridium than was found in the surrounding limestones. This amount was far too high to allow accurate dating because it clearly was not the result of a normal buildup of meteoritic dust. It was, however, the key to the latest Cretaceous extinction.

Walter Alvarez at first thought the iridium was produced by the explo-

DID AN ASTEROID KILL THE DINOSAURS?

In 1977, Luis W. Alvarez and his son Walter began an investigation of a single-centimeter layer of clay that was sandwiched between two limestone strata containing large deposits of Cretaceous-Tertiary fossils. Such fossils were significantly absent elsewhere in the sample. The clay deposit dated from the boundary between the Cretaceous and Tertiary periods, referred to as the "K/T boundary," roughly 65 million years ago, when the dinosaurs disappeared and modern flora, apes, and large mammals appeared.

Alvarez and his son used a trace of iridium in the composition of the clay sample to determine how long it had taken for the clay to be deposited and so to calculate the time that had elapsed during the Cretaceous-Tertiary transition. Iridium is basically an extraterrestrial substance. All the iridium in Earth's crust is only one ten-thousandth of the iridium abundant in meteorites. Alvarez selected iridium because it was the best material to use in determining the amount of debris that fell on Earth during this crucial period. Iridium is deposited uniformly around Earth, and Alvarez wanted to account for these uniform deposits. He began with the theories of Sir George Stokes, who formulated the viscosity law, a calculation of the rate at which small particles fall in the air. Stokes had based this law on his observations of the fallout of ash from the huge eruption of the Krakatoa volcano near Java in the 1880's. After discounting many possible hypotheses, such as a gigantic volcanic eruption, a supernova, or Earth's passing through a cosmic cloud of molecular hydrogen, Alvarez developed the hypothesis that an asteroid had collided with Earth.

According to his calculations, the asteroid had to be 10 kilometers in diameter. Its impact would have been catastrophic, far exceeding the worst nuclear scenario yet proposed. As Alvarez said,

> The worst nuclear scenario yet proposed considers all fifty thousand nuclear warheads in U.S. and Russian hands going off more or less at once. That would be a disaster four orders of magnitude less violent than the K/T asteroid impact.

Alvarez knew that the margin for error in discoveries was exponential, because of the possibility of mistakes in the data. As more data were collected from other sources, however, the argument only became stronger. Although the asteroid hypothesis has not been fully accepted by the scientific community, a number of predictions based on the theory have been verified experimentally and by computer simulation.

sion of a nearby supernova. Detailed analysis of the elements, however, showed that this was highly improbable. The Berkeley scientists then proposed that the iridium was exported directly to Earth with the impact of a large asteroid, approximately 10 kilometers in diameter.

Chicxulub Crater

Eugene Merle Shoemaker—an American geologist and the foremost authority on asteroid and meteorite impacts—calculated that the impact envisioned by the Berkeley group was possible (even highly likely), but the crowning piece of evidence—the crater—was missing. The scientists had calculated that the crater would have been approximately 150 to 200 kilometers in diameter. Only three craters of this size were then known, and none was of the right age. During the 1990's, however, evidence gradually emerged for an impact crater meeting all the missing crater's characteristics in Mexico's Yucatán Peninsula. Lying buried below more than one thousand meters of limestone, this 200-300-meter crater has been named Chicxulub after a nearby Maya village. Many scientists now accept it as the long-missing killer-asteroid crater.

The Berkeley group suggested that the asteroid impact was the central cause for the late Cretaceous mass extinction. The asteroid would have blasted both terrestrial and meteoritic debris into the atmosphere, and the smaller dust particles would have quickly encircled the Earth. The dust would later have settled to the Earth to form the clay layer. While in the atmosphere, the dust would have darkened the skies for up to three years (later, the time was revised to a few months), thereby essentially shutting down all photosynthesis in the oceans and on the continents. The loss of photosynthesis—the basis of nutrition for all living things—would have rapidly collapsed the food chains of the world, and the catastrophic extinction of animals would have followed.

Impact

David Malcolm Raup and John Sepkoski, both paleontologists at the University of Chicago, found that a mass extinction appears to have occurred about every 26 million years. These cycles are of such long duration as to suggest that extraterrestrial causes are largely responsible. If impacts are cyclic, then there must be some astronomical process that periodically sends asteroids (or comets) hurtling toward the Earth. Astronomers proposed several ideas, including the presence of a dim, distant companion star of the Sun. Astronomers have dubbed this hypothetical star "Nemesis." This theory remains controversial, however, largely advocated by Richard Muller.

The concepts of geologic and evolutionary change have also been altered by the asteroid impact hypothesis. Scientists in these areas have traditionally adhered to the idea that change is caused only by processes still at work and is generally gradual. Impacts, however, are not gradual, and they are now seen as major factors in the history of Earth and life on Earth. Catastrophic events, therefore, are now thought of as possible and plausible causes of some major events of Earth's past.

See also Evolution; Fossils; Human Evolution; Lamarckian Evolution; Oort Cloud.

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—*Jay R. Yett*

MATHEMATICAL LOGIC

THE SCIENCE: Bertrand Russell and Alfred North Whitehead attempted to formulate all mathematics within formal logic and set theory.

THE SCIENTISTS:

Bertrand Russell (1872-1971), mathematician and philosopher
Alfred North Whitehead (1861-1947), mathematician and philosopher
Giuseppe Peano (1858-1932), Italian mathematician and logician
Gottlob Frege (1848-1925), German mathematician and logician

MATHEMATICAL LOGIC SLUMBERS

For about 2,100 years, from the time of Euclid to the nineteenth century, the relationship between logic and mathematics was simple: Logic was something the mathematician used to discover and to present mathematics. In the "axiomatic method," the mathematician states a few "axioms," or statements about the subject of the theory with which reasonable people would be likely to agree, and then deduces further statements, called "theorems," from these axioms. The deductions are governed by the "rules of inference" allowed by the logic.

By the early nineteenth century, it began to dawn on geometers that the objects and relations referred to in geometrical axioms did not necessarily correspond to "real" objects and relations in only one "reality," or model of the axioms. For example, in projective geometry, which has axioms that refer to points and lines, one can find models of those axioms in which points look like lines and lines look like points. In other models of geometrical axioms, sometimes the points or lines do not look like anything at all; they may be functions or formulas that cannot be pictured in ordinary ways.

The axiomatic method thus gained an unexpected charge of power. Axioms formed by abstraction from one reality might have meaning and be valid in many different realities. Therefore, if the rules of inference were valid and were correctly applied, the theorems proceeding from those axioms would be truths that were applicable in many different settings.

The price of this new power was that informal proofs based on diagrams depicting scenes from only one of the axioms' models were no longer acceptable, because such proofs might innocently use properties of that particular model that were not shared by other models, thus giving rise to theorems that were not valid in every model of the axioms. Proofs had to be more precise.

BOOLEAN LOGIC

The first great success in improving the quality of proofs was *The Mathematical Analysis of Logic*, by George Boole (for whom Boolean algebra is named), which was published in 1847. The primary idea contained in the volume had been examined by Gottfried Wilhelm Leibniz and a succession of others, but it was Boole who finally crystallized it. The idea was that logical inference should be algebraic. In other words, it should consist of a series of transformations that would be executed on strings of symbols according to certain rules; the meanings that were assigned to those symbols should not affect the rules that govern the transformations.

This idea was exactly what was needed to breathe new life into the axiomatic method. Boole's work became much honored, although it was not much applied, because most mathematicians continued to use informal proofs based on informal postulates. The idea that it might be possible to create a formal axiomatization of all mathematics, however, began to generate excitement. Mathematicians wondered what axioms would underlie such an endeavor and what previously unimagined realities would be laid open to the human mind by such an undertaking.

In the 1870's and 1880's, Georg Cantor proved some very surprising results that related to infinite sets, and this led some mathematicians to seize upon set theory as the foundation from which all mathematics might arise by formal deduction. Sets seemed to be fundamental both mathematically and philosophically. The difficulty was that, before Cantor, no one had known how to begin. For example, how could the positive integers (the positive whole numbers 1, 2, 3, and so forth) be defined in an axiomatic theory of sets? Cantor did not demonstrate precisely how to do this, but he paved the way for others to follow.

After Cantor, Gottlob Frege, a German logician, set out to formulate arithmetic in an axiomatic theory of sets. At the same time, the Italian Giuseppe Peano was developing an axiomatic theory of arithmetic of a less fundamental kind.

In the summer of 1900, Bertrand Russell, then a young lecturer at Cambridge University, attended a philosophical symposium in Paris in the company of Alfred North Whitehead, his colleague and former teacher. At that time, Russell was acquainted with the work of Boole and Cantor but not with that of Frege. Russell and Whitehead heard Peano speak in Paris, and they were so impressed with the sophistication of his work that they resolved to follow and to surpass him, to create a more formal axiomatic theory of arithmetic. The following year, Russell discovered that Frege had already done this, but he also discovered a shattering contradiction in Frege's system. Now known as Russell's paradox, the contradiction arises because in Frege's system it is permissible to speak of the set R of sets that are not members of themselves. By the defin-

Alfred North Whitehead.

ing property of R, R is a member of itself *only* if it is not a member of itself.

Russell and Whitehead were both stimulated and chastened by this discovery. After ten years of hard work, they produced *Principia Mathematica*, three large volumes of formal logical deduction that purport to develop arithmetic from a very bare foundation. They took great pains to avoid contradictions such as Russell's paradox. It may never be known whether their system is free of contradictions. The effort involved in creating *Principia Mathematica* was enormous. For example, it required more than two hundred pages of dense logic to prove that one plus one equals two.

Impact

Principia Mathematica is to mathematics what Egypt's pyramids are to architecture—a monument to an obsession that still exists, but in an evolved form. The lasting mathematical contribution of *Principia Mathematica* is to set theory, although modern set theory is not based on the foundation created by *Principia Mathematica*. After Russell and Whitehead's work, formal axiomatics became an object, rather than a tool, of mathematical study. The fact that the work had been done, rather than the substance of the work itself (which is somewhat stupefying), stimulated the efforts that led to the development of Gödel's theorems in the 1930's and the brave new era of mathematical logic.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Pendulum; Polynomials; Probability Theory; Russell's Paradox; Speed of Light.

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—*Peter D. Johnson, Jr.*

MAYAN ASTRONOMY

THE SCIENCE: The multistory observatory tower in this prominent Mayan ruin is testimony to the activity of this civilization's scientific elite, who developed an impressive body of astronomical and mathematical knowledge.

THE SCIENTISTS:
Mayan astronomers (seventh century C.E.)

THE MAYA AT PALENQUE

The Maya were an advanced Mesoamerican culture noted for their achievements, skills, and knowledge in areas such as architecture, engineering, artistic design, mathematics, and astronomy, and for their elaborate hieroglyphic writing system with phonetic elements.

Located on the western fringe of the area occupied by the Maya, Palenque is now one of the more popular archaeological sites associated with that great ancient American civilization. Palenque's ruins, stretching for about 2 miles (3.2 kilometers) east to west, lie in the humid, lush green foothills of the southern Sierra Madre range, bordering plains stretching down to the Gulf coast. The haunting beauty of Palenque's partially restored and surprisingly well-preserved ruins is enhanced by the backdrop of a highland tropical forest from which steaming mists rise and by its spectacular dawns and dusks.

The site's history as a permanent center spans the period from around 100 B.C.E. to the early ninth century C.E. Palenque expanded in size during the Early Classic period (c. 300-600) and flourished as a major Mayan center in the Epiclassic or Late Classic period (c. 600-950), which witnessed the construction of its now famous ruins. At its peak, Palenque held political sway over much of present-day Chiapas and the neighboring state of Tabasco.

Palenque's harmoniously proportioned buildings and monuments represent the work of some of the Maya's most talented architects and sculptors. A few of Palenque's significant monuments are the Temple of the Inscriptions, the Palace with its famous tower, the Temple of the Cross, Temple of the Sun, and Temple of the Foliated Cross. Some of these structures are associated with the long reign of King (or Lord) Pacal (Jaguar Shield), one of the center's most influential rulers. Pacal, born in 603, ruled sixty-eight years, between 615 and 683, and died at age eighty. The Temple of the Inscriptions is an attractive pyramid containing Pacal's magnificent tomb, and it includes an elaborate sarcophagus. The burial chamber near the base is reached by a long hidden internal stairway leading from the top platform.

Another very important structure partially linked with Pacal's reign is the palace, with its famed tower. This elaborate complex of buildings, galleries, and courtyards dominates the site's central area and rests on a platform about 300 feet (91.5 meters) long and 240 feet (73 meters) wide, accessible by two stairways leading up from a courtyard. Nearly all these structures were built in stages under several rulers over a period extending from around 600 to 720.

THE OBSERVATORY AT PALENQUE

The most prominent and central feature of the palace complex is its four-story tower, unique in Mayan architecture. Inside the tower is a stairway leading from the second story to the top. The three upper rectangular levels contain four large, doorlike openings for external viewing in each cardinal direction. Many experts believe that the tower, which commands a good long-distance view of the surrounding region, including nearby plains that descend northward toward the Gulf coast, probably performed the dual function of watchtower and astronomical observatory.

Mayan scientific and religious leaders dedicated much time to observing the night skies and identifying the most prominent stars, the planets, the Sun and Moon, major constellations, and the Milky Way. The recurring cyclical movements of these celestial objects were carefully recorded with mathematical formulas. In this manner, a body of celestial knowledge was constantly expanded to the point where the Mayan intellectual elite could gauge the orbits of major heavenly bodies with astounding accuracy and successfully predict solar and lunar eclipses. The elite's monopoly on this type of knowledge legitimized their power over the masses of farmers and ordinary believers whose labor constructed the great Maya centers. This responsibility for keeping track of solstices, equinoxes, and other significant solar or lunar occurrences also allowed the ruling class to direct major activities, such as determining the optimal times for planting, cultivating, harvesting, performing various necessary rituals, and conducting military campaigns.

MAYAN CHRONOLOGY

The Maya believed that celestial bodies were linked with deities who influenced natural phenomena and human destiny. Mayan astronomy and cosmology were integrated with religious beliefs and, therefore, were often used for astrological purposes. This outlook contributed to an obsession on the part of the intellectual elite with the concept of time, chronology, and recurring celestial patterns. To measure time accurately and to predict future possible cataclysmic developments, the class of priestly astronomers utilized higher mathematics to conduct time probes that could determine cyclical alignments of celestial bodies at given periods in the distant past and project them into the future.

The Maya developed a solar calendar whose eighteen months each contained twenty days. Five so-called unlucky days were attached at the end and additional corrections were made periodically so that the calendar conformed closely with the actual solar year of approximately 365.25 days. Linked with this accurate solar calendar was a more important ritual or sa-

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cred calendar of 260 days that guided and influenced human activity. Each day was assigned a name and number and connected with a particular deity shown bearing time (the burden of the day) on his back. After the passage of 260 days, the two calendars would no longer mesh until completing a 52-year cycle, an event that indicated the possibility of a traumatic event, such as the destruction of the world.

The Maya had a dot-bar numbering system based on divisions of twenty to record statistical material and dates. Dates could be determined using a system called the long count. The year equivalent to 3114 B.C.E. in what is now the Western world's calendar system was used as a reference point. Contemporary events were then dated by subtracting a sum obtained from adding and multiplying Mayan numerical symbols arranged in rows from the number representing this starting point in time.

COSMOLOGY AND RELIGION

In Mayan cities and ceremonial centers, the alignment and placement of buildings as well as features of monuments were symbolic representations of the Mayan worldview. In the case of Palenque, its Palace tower was located so that it could also have served as a vantage point from which the ruler and his top officials observed the arrival of the winter solstice. At sunset on each December 22, these royal dignitaries could observe a glowing orb (the Sun) seemingly "drop" into the Temple of the Inscriptions containing Pacal's tomb.

Also, many modern scholars of Mayan civilization believe that Mayan art, such as that found at Palenque, often represented a map of the sky and that local rituals were timed in accord with this pictorial symbolism. The imagery adorning Pacal's elaborately decorated sarcophagus may be interpreted as a picture of the sky on August 31, 683, the very night he died. Moreover, the symbolism depicting the ruler's death conforms closely with the Maya creation myth. Pacal is shown entering the Road to Xibalba by passing through the jaws of a monster and falling down the Milky Way into the Great Hole in the south. In accord with the creation myth, he will lose his struggle with the lords of death in the underworld, and his son will then need to ensure his resurrection and continue the royal line through a ritual ball game.

IMPACT

Although Palenque was a large Maya ceremonial site, it is rather small in comparison with great Classic period urban centers such as Tikal. Although its multistoried Palace observatory tower is a unique architectural structure, observatories are also found at other centers. Palenque's importance is enhanced, however, by the well-preserved state of its abundant records in stone and stucco bas-reliefs. Advances in deciphering Mayan hieroglyphics have allowed archaeologists to learn much from these texts in stone about the names, dates, and accomplishments of Palenque's rulers, the political and diplomatic highlights of the site's past, and valuable cultural information about its sacred rituals, calendar, and mythology.

Scholars probably know more about the history of Palenque and its rulers than any other Mesoamerican center. Recorded information at the site includes a complete listing of a nearly four-hundred-year-old dynasty of seventeen kings with data on dates of birth, dates of ascension to the throne, and death dates. The last recorded ruler took office on November 7, 799, and may have been connected with Palenque's downfall, which probably occurred within the next two or three decades.

See also Greek Astronomy; Medieval Physics.

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—*David A. Crain*

MEDIEVAL PHYSICS

THE SCIENCE: Developments in kinematics and dynamics in England between 1328 and 1350 exercised a deep influence on late medieval physics and natural philosophy in Western Europe, which flourished in the fourteenth and subsequent centuries.

THE SCIENTISTS:

Thomas Bradwardine (c. 1290-1349), English mathematician and natural philosopher

William Heytesbury (before 1313-1372), English logician and philosopher

Richard Swineshead (fl. fourteenth century), English mathematician and natural philosopher

John Dumbleton (fl. fourteenth century), English mathematician and natural philosopher

Jean Buridan (1300-1358), French scholastic philosopher

Nicholas Oresme (c. 1320-1382), pupil of Buridan

Albert of Saxony (c. 1316-1390), nominalist philosopher

THE ANCIENT FOUNDATIONS

Thomas Bradwardine's *Treatise on Proportions* of 1328 set forth his dynamic law of movement. It stands as a marker at the beginning of a period of intense speculation in "natural philosophy"—areas of scientific study that would now be relegated mainly to physics—at Merton College, Oxford. Speculation in natural philosophy was still associated closely in the late medieval period with classical scientists as well as their Greek and Arabic commentators, whose works gradually appeared in the Latin West after the twelfth century.

Of first importance was Aristotle, whose *Physica* (335-323 B.C.E.; *Physics*, 1812), widely known and commented on in antiquity and the later medieval period, would serve as a fundamental text for students well into the seventeenth century. According to Aristotle, all things were composed of matter and form. From his postulates that the form of a substance determines its essence, that each substance has a natural inclination that dominates all the changes or movements it experiences, and that every motion presupposes a mover, Aristotle propounded a dynamic law of movement postulating that the velocity of a moving body is directly proportional to the moving force and inversely proportional to the resistance of the medium traversed. Aristotle's law implied that in a vacuum movement would take place instantaneously since the density, hence the resistance, of the medium would be zero. The impossibility of an instantaneous movement led Aristotle, in turn, to deny the existence of a vacuum.

In the sixth century, John Philoponus, in attempting to demonstrate that movement in a vacuum was possible, criticized Aristotle's dynamic law. In place of Aristotle's assertion that velocity was indirectly proportional to the resistance, he proposed that velocity was proportional to the motive force (referred to by late medieval scholars as "impetus") minus the resistance. Accordingly, movement in a vacuum was possible because the absence of a resisting medium merely reduced arithmetically the time needed to move through a given space. Philoponus's views were transmitted to the West indirectly through Averroës' commentary on Aristotle's *Physica*, which rejected criticism of Aristotle's law made by Avempace (a twelfth century Arabian scholar living in Spain), who repeated the views of Philoponus.

Mathematical Reasoning at Merton

Not until Bradwardine's *Treatise on Proportions*, however, was an attempt made to reformulate Aristotle's law in precise mathematical language. Bradwardine followed Aristotle and Averroës in characterizing the relationship between force and resistance, the parameters determining velocity, as a kind of proportion or ratio. In so doing, he rejected Avempace's and Aquinas's postulations of a law of simple arithmetical difference.

Moreover, Bradwardine went beyond earlier treatments of the Aristotelian dynamic law of movement by giving it a mathematical expression that adequately reflected the observed results in cases in which the motive force is equal to or less than the resistance. In such critical cases, the simple Aristotelian proportion yielded erroneous conclusions. While Aristotle's law would predict some value greater than zero when force and resistance are equal, the velocity would in fact be zero. Even though Bradwardine used the medieval language of proportions, he expressed results more or less equivalent to the exponential function used today to define velocity.

The importance of this application of mathematical reasoning to problems of dynamics must not be underestimated. Bradwardine was followed at Merton College by such distinguished natural philosophers as William Heytesbury, Richard Swineshead, and John Dumbleton, scholars who made significant contributions to medieval kinematics.

Scientific Ferment Across Europe

Furthermore, interest spread to Paris, where it stimulated the work of Jean Buridan of his pupil Nicholas Oresme, and of Albert of Saxony. All these scholars helped to impart to late medieval physics a characteristic form perceptible in the key physical problems discussed, such as the laws of falling bodies, the principle of inertia, and the question of the center of gravity, as well as in the extensive use of the logical-mathematical methods of analysis and measurement. The brilliant Oresme, who was a precursor of René Descartes in the development of analytical geometry, by emphasizing the daily rotation of the Earth introduced a basic alteration of Ptolemaic cosmology.

The scientific ferment also spread to the universities of Italy. The ardent fifteenth century German Humanist Nicholas of Cusa, in doubting the geocentric theory and in proposing that the Earth moved in rhythm with the heavens, helped to form the tradition against which the physics of Galileo developed as well as the doctrines of relativity in space and motion supported later by Giordano Bruno.

Science in the late Middle Ages had its last great exponent in Johann Müller, or Regiomontanus, and his school at Nuremberg in the latter half of the fifteenth century. His work in mathematics became the basis of trigonometry in western Europe as previously it was developed in the Arab world, and his scientific astronomical observations and charts were used by Christopher Columbus.

IMPACT

The significance of the intellectual events described here for the study of the history of science lies in the fact that until the beginning of the twentieth century it was universally taken for granted that the history of modern mechanics began with Galileo, at the beginning of the seventeenth century. However, at the beginning of the twentieth century, the outstanding French historian and philosopher of science Pierre Duhem, himself a physicist of first rank, uncovered the largely forgotten work of the Oxford and Parisian scholars here described. He then proposed the view that the scientific revolution, at least in mechanics, really began in the fourteenth century. This view ascribes to Galileo a much less dominant role than usually accepted. Duhem's thesis has been vigorously opposed by other scholars, and the dispute continues.

See also Ballistics; Copernican Revolution; Falling Bodies; Gravitation: Newton; Greek Astronomy; Mayan Astronomy; Scientific Method: Aristotle; Scientific Method: Bacon.

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—*Joseph M. Victor*

MENDELIAN GENETICS

THE SCIENCE: Reginald Crundall Punnett published *Mendelism*, explaining how traits are inherited.

THE SCIENTISTS:

- *Gregor Johann Mendel* (1822-1884), Austrian monk and botanist who performed pioneering research into heredity
- *Reginald Crundall Punnett* (1875-1967), English geneticist who crusaded for the acceptance of Mendel's theories
- *Hugo de Vries* (1848-1935), Dutch botanist and horticulturalist, who became famous for his mutation theory for the mechanism of evolution
- *Carl Erich Correns* (1864-1933), German botanist, who made significant contributions to the modern theory of Mendelian genetics in its early years

Erich Tschermak von Seysenegg (1871-1962), Austrian botanist and plant breeder who contributed to the improvement of various crop plants and ornamental flowers

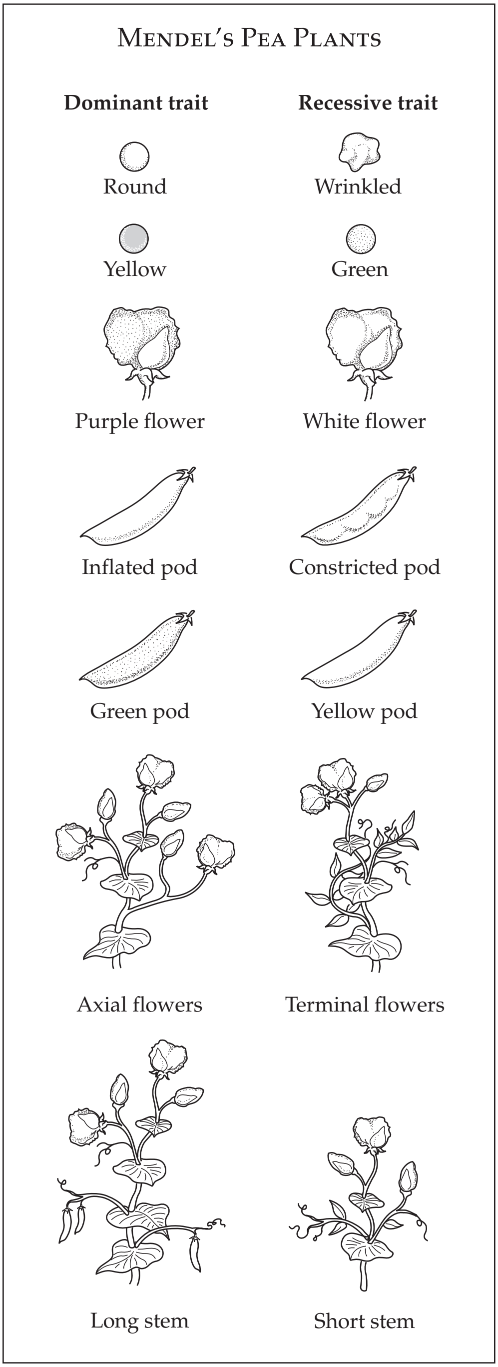
The Heredity of Peas

In 1905, Reginald Crundall Punnett's landmark book *Mendelism* was published. This small book stated clearly the principles of heredity espoused by the Austrian botanist Gregor Johann Mendel in his classic paper of 1865. Mendel's original paper, long ignored because it had been published in an obscure journal, was independently rediscovered in 1900 by three botanists: Hugo de Vries, Carl Erich Correns, and Erich Tschermak von Seysenegg. Yet although Mendel's ideas were intriguing, early twentieth century biologists did not agree on the universality of his proposed laws of heredity, and they searched for an understanding of the significance of the Mendelian patterns. Punnett's work played a major role in earning acceptance of Mendel's theories, and his book became an excellent learning tool for the rediscovered Mendelism.

In 1856, Mendel began his experiments with garden peas in an effort to study the inheritance of individual characteristics. It was known at the time that the first generation reproduced from hybrids, or crossbred plants, tended to be uniform in appearance, but that the second generation reverted to the characteristics of the two original plants that had been crossbred. Such facts were observable, but the explanations remained unsatisfactory. Before Mendel, the concept of "blending" inheritance predominated; that is, it was assumed that offspring were typically similar to their parents because the essences of the parents were blended at conception. Mendel's work with pea plants suggested another theory, that of "particulate" inheritance; according to this theory, a gene passes from one generation to the next as a unit, without any blending.

Gregor Mendel. (National Library of Medicine)

Mendel laid the groundwork for his experiments by testing thirty-four varieties of peas to find the most suitable varieties for research. From these, he chose twenty-two to examine for two different traits, color and texture. He



Mendel evaluated the transmission of seven paired traits in his studies of garden peas.

was then able to trace the appearance of green and yellow seeds, as well as round and wrinkled ones, in several generations of offspring. By counting the results of his hybridization, he found that the ratio of "dominant" genes to "recessive" ones was three to one. In effect, he demonstrated that there were rules governing the process of inheritance.

Punnett Squares

Punnett's work served to explain Mendel's theories of sex determination, sex linkage, complementary factors and factor interaction, autosomal linkage, and mimicry. He also had a number of other notable scientific and practical achievements; in World War I, for example, when food was in short supply in Great Britain, he devised an ingenious scheme to distinguish the sex of very young chickens. He realized that by noting sex-linked color factors that would appear in the plumage of only male chicks, the unwanted males could be distinguished and destroyed so that food supplies would not be wasted on them. His work with *The Journal of Genetics*, which he founded jointly with the British geneticist William

Bateson in 1911, also contributed significantly to the advancement of genetics. Yet it was Punnett's invention and use in his book of a simple diagrammatic scheme that helped to ensure the acceptance of Mendelism and most directly influenced the understanding of genetics.

In his book, Punnett included simple charts to illustrate the inherited characteristics that would appear in offspring when particular characteristics are crossbred. The diagrams are explicit, clear, and convincing. These "Punnett squares," as they came to be known, soon became a valuable tool for teaching genetics students the rudiments of the subject.

IMPACT

During the late nineteenth century, cytologists, or scientists who study cells, began to observe the behavior of chromosomes in cell division. Although some of these scientists suspected that chromosomes might play a part in heredity, they had no real understanding of how traits were distributed among offspring. Although Mendel had already determined some of these relationships, his ideas remained generally unavailable to cytolo-

A PUNNETT SQUARE SHOWING FLOWER PIGMENTATION

White CCpp × White ccPP

↓

F$_1$ Purple CcPp

↓

		CP	Cp	cP	cp
	CP	CCPP purple	CCPp purple	CcPP purple	CcPp purple
	Cp	CCPp purple	CCpp white	CcPp purple	Ccpp white
F$_2$	cP	CcPP purple	CcPp purple	ccPP white	ccPp white
	cp	CcPp purple	Ccpp white	ccPp white	ccpp white

When white-flowered sweet pea plants were crossed, the first-generation progeny (F1) all had purple flowers. When these plants were self-fertilized, the second-generation progeny (F2) revealed a ratio of nine purple to seven white. This result can be explained by the presence of two genes for flower pigmentation, P (dominant) and p (recessive) and C or c. Both dominant forms, P and C, must be present in order to produce purple flowers.

gists. Before the rediscovery of Mendel's work, therefore, many theories of heredity were competing for acceptance by the scientific community; no single theory could be agreed upon as adequately explaining all the observed facts. Even after Mendelism was rediscovered, it was by no means universally accepted; critics argued that rules that seemed to explain the inheritance of color traits in pea plants did not seem to apply to the inheritance of other traits in other species.

With the aid of his convincing diagrams, Punnett engaged in a crusade

BATESON DEFENDS MENDEL

Gregor Mendel conducted his experiments with pea plants more than three decades before his theories were finally given a serious audience by the scientific community—and even then, detractors sought to bury the unknown priests achievement. In his preface to Mendel's Principles of Heredity, *William Bateson stated why he felt compelled to defend the work of Greagor Mendel, whose work had laid the foundation for modern genetics.*

In the Study of Evolution progress had well-nigh stopped. . . . Such was our state when two years ago it was suddenly discovered that an unknown man, Gregor Johann Mendel, had, alone, and unheeded, broken off from the rest—in the moment that Darwin was at work—and cut a way through. . . .

In the world of knowledge we are accustomed to look for some strenuous effort to understand a new truth even in those who are indisposed to believe. It was therefore with a regret approaching to indignation that I read Professor [Raphael] Weldon's criticism. Were such a piece from the hand of a junior it might safely be neglected; but coming from Professor Weldon there was the danger—almost the certainty—that the small band of younger men who are thinking of research in this field would take it they had learnt the gist of Mendel, would imagine his teaching exposed by Professor Weldon, and look elsewhere for lines of work.

In evolutionary studies we have no Areopagus. With us it is not . . . that an open court is always sitting, composed of men themselves workers, keenly interested in every new thing, skilled and well versed in the facts. Where this is the case, doctrine is soon tried and the false trodden down. But in our sparse and apathetic community error mostly grows unheeded, choking truth. That fate must not befall Mendel now.

Source: William Bateson, *Mendel's Principles of Heredity: A Defence* (New York: Cambridge University Press, 1902). Facsimile at Electronic Scholarly Publishing. http://www.esp.org/books/bateson/mendel/facsimile/contents/bateson-mendel-1-frontmat.pdf. Accessed September, 2005.

for Mendelism, showing how apparent exceptions to the rules proposed by Mendel could be explained. Mendel's theories thus won gradual acceptance and were combined with other ideas to explain the inheritance process more fully still. For example, it soon became understood that chromosomes were the physical basis for the ratios of inheritance that Mendel had observed. Punnett's work played a key role in making possible this fusion between Mendelian genetics and cytology and helped to establish the basis for modern genetic theory.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Marilyn Bailey Ogilvie*

MICROFOSSILS

THE SCIENCE: Elso Barghoorn and Stanley Allen Tyler's fossil discoveries were the first in a series of discoveries crucial to understanding the origin and early development of life on Earth.

THE SCIENTISTS:

Elso Barghoorn (1915-1984), American paleontologist

Stanley Allen Tyler (1906-1963), American geologist

Charles Doolittle Walcott (1850-1927), the head of the U.S. Geological Survey

PRESERVED IN CHERT

On April 30, 1954, the American journal *Science* published a brief article by Elso Barghoorn and Stanley Allen Tyler describing five distinct types of fossil microorganisms. These included slender, unbranched filaments and spherical colonies made up of filaments, which were judged to resemble living blue-green algae, and branched filaments and spherical bodies, which were compared with living aquatic fungi.

These fossils had first come to the attention of Tyler, a geologist, while he was working with banded iron deposits of Precambrian age (more than 570 million years old) on the shores of Lake Superior. A puzzling circumstance was the occurrence of coal with the iron ore deposits. The iron ore was known to be approximately 2 billion years old, and no life-forms that could have produced coal had been proved to have existed that long ago. Examination of the coal revealed what appeared to be microscopic plants. Tyler showed a specimen to William Schrock of the Massachusetts Institute of Technology, who thought it resembled living fungi. Schrock suggested that Tyler consult with Barghoorn in the Harvard University botany department.

Barghoorn agreed that the material appeared to be microbial. As a biologist, he recognized that convincing proof of life-forms so early in geologic time would be immensely significant. He suggested returning to the site and conducting a systematic search for life-forms in the coal-bearing rocks.

Following the coal seams into Canada, they collected samples of black Gunflint chert, which were cut into thin slices with a diamond saw for microscopic observation. Chert is a sedimentary rock whose qualities make it an excellent preserver of organic remains. Organic cell walls remain intact, preserving cellular structures and traces of surface ornamentation.

FOSSILS OF ALGAE AND FUNGI

When examined under the microscope, the thin sections revealed spheres and filaments. Both clearly were hollow and bounded by a sturdy wall of organic material; there was no doubt that these were microorganisms. In the 1954 publication, some specimens were identified as blue-

LOCATIONS OF THE EARLIEST FOSSILIZED LIFE-FORMS

Cherts are hard, well-cemented sedimentary rocks produced by recrystallization of siliceous marine sediments buried in the seafloor. These cherts—such as the 3-billion-year-old Fig Tree Churt, the 2-billion-year-old Gunflint Chert, and the 1-billion-year-old Bitter Springs Formation—are believed to contain microfossils of early bacteria and other more complex, life-forms.

green algae, with a bacterial level of cellular organization, and others as relatively more advanced aquatic fungi. (Subsequent detailed investigations have cast doubt on the identification of fungi in this or any other assemblage more than 1.5 billion years old.) In papers published in 1965 and 1971, Barghoorn attributed a bacterial or blue-green algal origin to all the Gunflint organisms.

Tyler and Barghoorn were not the first to report microorganisms from Precambrian rocks of the Canadian shield. Between 1922 and 1925, John W. Gruner had described and illustrated filaments of algal specimens of about the same age. Gruner's papers attracted less attention than Tyler and Barghoorn's for several reasons. First, the material was not as well preserved or illustrated and was not completely convincing. Second, prior to the routine use of radioactive decay as a means of dating rocks, the extreme antiquity of the specimens was not appreciated. Finally, although students of evolution and the geologic history of life are aware now that about five-sixths of biological evolution on Earth took place in the Precambrian era, few people in the 1920's were actively interested in the Precambrian.

By 1960, there was a small body of evidence for Precambrian life, but none of it was universally accepted or completely convincing. Radiometric dating had confirmed what had already been suspected from stratigraphic evidence: that the Precambrian encompassed a far longer time than the Phanerozoic (literally, the age of "evident life"—everything since the Precambrian). Estimates suggest that Earth was created 4.5 billion years ago.

IMPACT

In the absence of a fossil record, scientists turned to the laboratory and to comparisons of living forms in an effort to formulate hypotheses about the origins and early evolution of life on Earth. American chemists Harold C. Urey and Stanley Miller postulated in the early 1950's that nonbiological processes early in Earth's history had created an "organic soup" in which electrical discharge produced complex molecules capable of replicating themselves and in which the precursors of the earliest cells developed.

It was recognized that there was a fundamental distinction among living organisms between those that lack nuclei (prokaryotes), including bacteria and blue-green algae, and those having nuclei (eukaryotes), including plants, animals, fungi, and most algae, and that the transition from prokaryote to eukaryote was a major evolutionary hurdle. Assuming that life as it is known in the twenty-first century evolved on Earth (a debatable assumption as long as there is no convincing Precambrian fossil record), then the most fundamental milestones in biological history, the evolution of cells and the evolution of eukaryotes, must have taken place in the enigmatic Precambrian.

It has been recognized for some time that living organisms have transformed the face of the Earth in the Phanerozoic; the importance of their role in geological processes in the Precambrian was evident only when a usable fossil record became available. The fossil record provides information about the types and in some cases the abundance of microorganisms that were present at various stages in geologic time; the inorganic geologic record provides evidence for atmospheric and climatic changes, and comparison of the biochemistry of living forms provides clues as to probable conditions at the time various metabolic processes evolved.

See also Amino Acids; Fossils; Geologic Change; Ribozymes.

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—*Martha Sherwood-Pike*

MICROSCOPIC LIFE

THE SCIENCE: Leeuwenhoek's pioneer work in designing, building, and using microscopes and his discoveries of protozoa and bacteria laid the foundation for the modern science of microbiology.

THE SCIENTISTS:

Antoni van Leeuwenhoek (1632-1723), Dutch biologist and microscopist
Pierre Borel (1620?-1671/1689), French physician and botanist
Regnier de Graaf (1641-1673), Dutch physician and anatomist
Nehemiah Grew (1641-1712), English physician and botanist
Robert Hooke (1635-1703), English mathematician and general scientist
Zacharias Janssen (1580-c. 1638), Dutch lens grinder and inventor of the compound microscope
Giovan Battista Hodierna (1597-1660), Italian astronomer, naturalist, and Roman Catholic priest
Henry Oldenburg (1619-1677), German-English diplomat and first secretary of the Royal Society of London
Francesco Stelluti (1577-1646/1652), Italian mathematician and naturalist who coined the term "microscope"
Jan Swammerdam (1637-1680), Dutch physician and naturalist

THE MICROSCOPIC WORLD

Microscopy began in the late sixteenth century but did not become widespread and respected among scientists until the middle of the seventeenth century. The first published illustrations of microscopic specimens appeared in 1625, as drawings of parts of bees in Francesco Stelluti's *Melissographia*. Giovan Battista Hodierna invented the technique of sectioning anatomical structures for microscopic examination, and he published his studies of sectioned insect eyes in 1644.

Pierre Borel was the first to apply microscopy to medical problems. In

1653, he published his discovery of red blood cells, and in 1655, motivated by historical interest, he traced the origin of microscopy to Zacharias Janssen's invention of the compound microscope around 1590. Jan Swammerdam recorded his description of red blood cells in 1658 and published the results of his microscopic investigations of insects in 1669.

The most important event in microscopy before Antoni van Leeuwenhoek was the publication in 1665 of Robert Hooke's magnificently illustrated *Micrographia: Or, Some Physiological Descriptions of Minute Bodies Made by Magnifying Glasses*, which announced Hooke's discovery and naming of the cell as the basic biological structure.

Leeuwenhoek's Research

Leeuwenhoek was working as a draper, merchant, and minor government official in Delft when he began grinding lenses sometime between 1668 and 1672. By 1672 his lenses were as powerful as any that then existed. What started as a hobby soon made him famous. Inspired in part by *Micrographia*, Leeuwenhoek examined all kinds of substances and concoctions, carefully recording his observations in his diary.

In an April 28, 1673, letter to Henry Oldenburg, Regnier de Graaf brought Leeuwenhoek's work to the attention of the Royal Society of London, then the most prestigious scientific organization in the world. Oldenburg published an excerpt from this letter in *Philosophical Transactions of the Royal Society* (May 19). As the readers reacted enthusiastically to its descriptions of molds, bees, and lice, Leeuwenhoek followed with a letter to Oldenburg about the legs and stingers of bees (August 15). Part of this letter appeared in the October 6 issue and was accompanied by illustrations. A selection of extracts from these letters were published by the society as *A Specimen of Some Observations Made by a Microscope* (1673). Thereafter, Leeuwenhoek was a popular and frequent contributor to the journal.

"Little Animals": Protozoa and Bacteria

Excerpts from some of Leeuwenhoek's letters of 1673 and 1674 dealt with microscopic aspects of blood, hair, milk, saliva, brain tissue, bone, and other animal components. The subject matter of his letter of September 7, 1674, was similar, but the last paragraph described his examination of water from Lake Berkel. Leeuwenhoek noted that he observed an "abundance of little animals . . . some of these little creatures were above a thousand times smaller than the smallest ones, which I have hitherto seen. . . ." This was the first mention in any scientific literature of independent unicellular life. It is believed that Leeuwenhoek had seen alga spiro-

ANTONI VAN LEEUWENHOEK, AMATEUR LENS GRINDER

Antoni van Leeuwenhoek was a middle-class Dutch burgher, a draper (cloth dealer) by trade, as well as chamberlain of Amsterdam city hall, a municipal surveyor, and inspector of weights and measures. He wore respectable clothing and a wig and possessed the keen eyesight needed for detailed observation through the microscope. Well enough off that he could indulge his scientific interests, Leeuwenhoek began experimenting with microscopes in the late 1660's, and by 1673 he had made enough startling observations that he began writing up his findings. Soon the famous scientist Robert Hooke nominated him for membership in the Royal Society of London.

Leeuwenhoek had not invented the microscope, but his skill at lens grinding, along with his patient and insightful mind, made him the father of modern microscopy. The instrument Leeuwenhoek employed was the simple microscope with a single, beadlike lens mounted in a hole between two small metal plates. His lenses reached magnifications of 266 to 500 (as compared to Hooke's 50), and his microscopes were so simple that he made more than five hundred of them, which he used to scrutinize his "animalcules" as they danced, darted, floated, and vibrated under the lens. During grueling hours of observation, Leeuwenhoek was both patient and accurate at estimating the sizes of the inhabitants of his microscopic world. For example, he correctly calculated the diameter of the red blood cell at about one three-thousandth of an inch. His observations also led him to criticize some of his fellow scientists, including Hooke, for accepting the notion of the "spontaneous generation" of life. Leeuwenhoek had observed that maggots in meat do not simply appear but are produced from eggs laid by adult flies.


(Library of Congress)

The homegrown scientist not only studied how microbes and microscopic insects reproduced but also experimented with what would kill them. He found that pepper water would kill many microbes, that nutmeg would kill mites, and that sulfur dioxide would kill moths. He never suspected, however, that some of these tiny animals might be able to kill him. That microbes could and transmit human diseases remained unknown for another two centuries. Asking himself how microbes came to inhabit a previously sterile medium, Leeuwenhoek concluded that they were borne on the very dust motes of the air. In fact, there were few questions that Leeuwenhoek did not ask, but as a solitary and untutored investigator ahead of his time, the miracle is that Leeuwenhoek did what he did in the first place.

gyra and some species of protozoa. An undated letter published September 26, 1675, reported his observations of the optic nerve, blood, sugar and salt crystals, and plant sap.

Increasingly encouraged throughout the 1670's by Nehemiah Grew, Leeuwenhoek turned more attention toward botanical phenomena. His letter of April 23, 1676, concerned mostly plant life and mentioned Grew several times, but it also recounted that he had found in wine "small living Creatures, shaped like little eels."

Leeuwenhoek's most celebrated contribution to the Royal Society was his letter of October 9, 1676, "Concerning Little Animals by Him Observed in Rain- Well- Sea- and Snow- Water; as Also in Water Wherein Pepper Had Lain Infused" (pb. March 25, 1677). In this letter he described "animalcula or living Atoms," reporting that he had first noticed them in standing rainwater in 1675, and provided clear measures of their tiny size. Most of the creatures depicted in this letter were protozoa, but at least one type was a bacterium. In stagnant pepper water that had been still for several days, he saw "incredibly small" animals that he computed were each smaller than one-millionth of a grain of sand. This was the first published mention of bacteria. Leeuwenhoek's March 23, 1677, letter (pb. April 23) answered some questions and clarified some points about these various "little animals."

In 1677 and 1678, Hooke confirmed Leeuwenhoek's results by reproducing several of these experiments with protozoa in water infusions. While doing this, Hooke may have been the second scientist to see bacteria. He wrote privately to Leeuwenhoek in December of 1677 of having seen through the microscope what appeared to be "gygantick monsters in comparison of a lesser sort which almost filled the water." The former were certainly protozoa and the latter were likely bacteria.

Although Leeuwenhoek probably discovered bacteria in 1676, the earliest published illustrations of these findings did not appear until his letter of September 17, 1683. This letter included the first specific descriptions and drawings of the round, rod-shaped, and spiral forms of bacteria, which later scientists named cocci, bacilli, and spirochaeta, respectively.

Impact

Along with Hooke, Leeuwenhoek can be considered the founder of microbiology. In his long and fruitful career, he discovered protozoa, bacteria, spermatozoa, and the crystalline lens of the eye. He gave the first accurate descriptions of red blood cells and many other basic components of life, and he invented the technique of staining microscopic specimens to better observe their features. Although the function and physiology of most of the living structures that Leeuwenhoek saw would not begin to be understood until the nineteenth century, he proved in his own time the indispensability of the microscope for science in general and underscored the importance of using the most powerful lenses available, in the best possible light, and with the keenest attention to observed detail.

See also Antisepsis; Contagion; Germ Theory; Microscopic Life; Optics; Spontaneous Generation.

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—*Eric v.d. Luft*

MID-ATLANTIC RIDGE

THE SCIENCE: Using a newly developed echo sounder, the Meteor made the first transoceanic crossing, leading to the discovery of the Mid-Atlantic Ridge.

THE SCIENTISTS:

Alfred Merz (1880-1925), German geographer who was the scientific leader of the Meteor expedition

Fritz Haber (1868-1934), German chemist who proposed the Meteor expedition

Hermann Wattenberg (1901-1944), German oceanographer who was the chemist on the expedition

Georg Wüst (1890-1977), German oceanographer and student of Merz

GOLD FROM SEAWATER?

The initial purpose of the German *Meteor* expedition was economic. In 1872, E. Sonstadt reported that the oceans contained a gold concentration of 65 milligrams per metric ton of seawater. The Treaty of Versailles (1919), which ended World War I, required that Germany repay its enormous war debt in gold. Therefore, Fritz Haber, a German chemist, proposed that gold extracted from the international seas might solve the problem.

The Treaty of Versailles prohibited the German navy from sending ships to foreign ports; however, in 1919, a member of the German admiralty, Captain Nippe, persuaded authorities to allow a German vessel to be outfitted and sent on a major peacetime oceanographic expedition. The *Meteor*, a class C gunboat, was selected for the study. Alfred Merz, an adviser to the German navy, was named the chief scientist of the *Meteor*. After his death, Georg Wüst took over leadership of the oceanographic data and study, which was to take place in the Atlantic Ocean.

The *Meteor* was to be equipped with a newly developed echo sounder. This device is used to find the distance and direction of objects under or partially under the water. It does this by measuring the time it takes a sonic or ultrasonic pulse emitted by the sounder to reach the object below and then return to the sounder. The time intervals and other data are then converted into numerical reference points of distance and direction. The navies of the world use echo sounding to chart the positions of foreign ships and submarines. During peacetime, the device is used to locate sunken ships, find schools of fish, and map the profile of the seafloor.

This expedition marked the first use of echo sounders to map the profile of the deep seafloor. With the exception of the *Meteor*, no such detailed maps were available before World War II (1939-1945). The profiles aboard *Meteor* were closely spaced echo soundings taken by extremely diligent workers, which only made the recordings that much more accurate and detailed. Moreover, the new anchor system had been developed that enabled the ship to anchor in deep water.

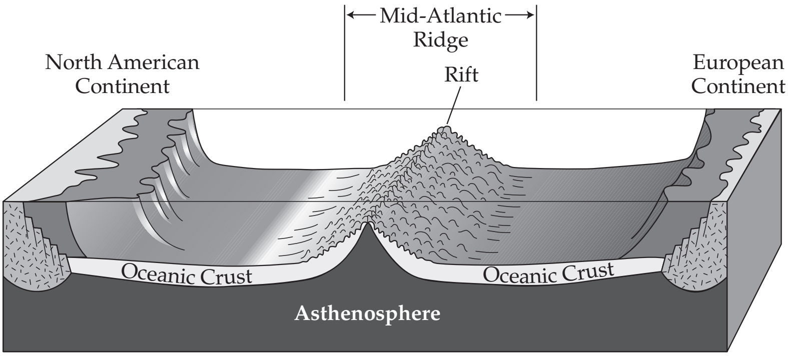
TRUE RUGGEDNESS

On April 26, 1925, the *Meteor* left for Buenos Aires, Argentina, to start work on the planned sections in the South Atlantic. Actual surveys began on June 3, 1925. Merz was in charge in spite of his illness; however, by the time the vessel arrived at the fifth hydrographic station, his condition had worsened to the point that the captain ordered the ship to return to Buenos Aires so that Merz could receive medical attention. Merz then turned the leadership of the scientific part of the expedition over to the captain. In reviewing the work along the first section, the captain found that the acoustic depth sounder had revealed that much of the bottom had been incorrectly charted.

After completing the thirteenth traverse in the equatorial Atlantic Ocean, the *Meteor* sailed for Germany, arriving home on May 29, 1927. In two years, the *Meteor* had traveled more than 67,500 kilometers, had collected data at 310 hydrographic stations, had anchored 10 times in deep ocean, and had made approximately 70,000 soundings of ocean depths. As a result, the expedition was the first to reveal the true ruggedness of the ocean floor.

The significant discovery of the *Meteor* was that a continuous ridge (the Walvis Ridge) runs in a southwesterly direction from the vicinity of Walvis Bay, southwest Africa. (A ridge is a long, narrow elevation on the seafloor.) This in turn led to the discovery of the Mid-Atlantic Ridge. It runs along the north-south axis of the Atlantic and is basically a long, curving zone of

THE MID-ATLANTIC RIDGE



The Mid-Atlantic Ridge is a major site of seafloor spreading, where the North American and European plates pull apart.

mountains, volcanoes, and fractured plateaus. This ridge's now-familiar herringbone pattern was first suggested in 1935 by Wüst and Theodor Stocks.

IMPACT

The *Meteor* expedition, which led to the discovery of the Mid-Atlantic Ridge, was a significant event. Unfortunately, this finding was not recognized widely at the time as being enough to support the theory of continental drift.

That theory had continued to generate controversy and debate among scientists ever since 1912, the year it was first proposed by the German geophysicist and meteorologist Alfred Lothar Wegener. Wegener's theory stated that the Earth was once made up of one large ocean and one large land mass. Gradually, this supercontinent split into two parts. Additional separations and "drift" continued to occur across many millions of years, eventually resulting in the seven continents as they have come to be known.

As modern science now recognizes, these massive continental "plates" tend to drift apart at divergent boundaries. These boundaries may be seen as the midoceanic ridges such as the Mid-Atlantic Ridge. Such rending of the Earth's crust brings with it great earthquakes and great flows of volcanic materials that, as they pile up in the "cracks," slowly create the ridge.

In the 1950's, a new generation of equipment and instruments was introduced that led to an explosion of data supporting continental drift, or "plate tectonics," as it is now called. Continuously recording echo sounders, magnetometers, temperature probes, explosion seismometers, piston corers, dredgers, and deep-sea submersibles were used not only to discover additional evidence to support the theory of continental movement but also to add to the sum of knowledge about deep-sea activity.

The *Meteor*'s discovery was a midpoint during the development of the proposed theory of continental drift in 1912 and the concept of plate tectonics that became widely accepted in 1968. Earth scientists realize now that the positions of land masses are not fixed. The separation of continental plates has resulted in the formation of new ocean basins, while older segments of the seafloor are being recycled continually in areas where deep-ocean trenches are found. This profound reversal of scientific opinion has been described as a scientific revolution, one in which the *Meteor* expedition played a pioneering role.

See also Continental Drift; Earth's Core; Earth's Structure; Geomagnetic Reversals; Hydrothermal Vents; Plate Tectonics; Radiometric Dating; Seafloor Spreading.

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—*Earl G. Hoover*

MITOSIS

THE SCIENCE: In the wake of discoveries by Charles Darwin and Gregor Mendel, investigation into the genetic basis for heredity increasingly centered on the role played by chromosomes. Wilhelm Roux argued that differentiation of cell types was linked to the distribution of chromosomes following cell division in the process termed mitosis.

THE SCIENTISTS:

Charles Darwin (1809-1882), English naturalist whose ideas on natural selection became the basis for his theory of evolution

Éduard Strasburger (1844-1912), German cytologist who described and named the phases of cell division that occur during mitosis

Wilhelm Roux (1850-1924), German anatomist who, while applying Charles Darwin's theory to cell competition, argued the process of mitosis was essential to proper distribution of chromatin

August Weismann (1834-1914), German zoologist instrumental in the early theoretical work describing the function of chromosomes

Walther Flemming (1843-1905), German anatomist who, in 1882, coined the term mitosis

Wilhelm Waldeyer (1836-1921), German anatomist who coined the term chromosome to describe threadlike structures in the cell nucleus

Theodor Boveri (1862-1915), German zoologist who applied his observations of the movement of chromosomes during cell division to forming the chromosomal theory of inheritance

CHROMOSOMES AND CELL DIVISION

In 1859, the publication of Charles Darwin's *On the Origin of Species by Means of Natural Selection* resulted in what is arguably among the most important of modern scientific discoveries: an explanation of evolution as a result of natural selection. Darwin's theory of evolution suggested that physical traits that provide reproductive advantage to an organism will be maintained in a selective environment. Darwin's ideas initially applied primarily to complex organisms such as plants and animals, but the idea of natural selection was increasingly applied to other areas of biology, including that of individual cells.

Improvements in microscopes combined with the implementation of staining techniques during the nineteenth century to allow for more precise observational studies of cell structures and organelles. Using newly developed aniline dyes, Walther Flemming, in 1882, observed the presence of threadlike structures from the nucleus of animal cells. Since these structures became visible during cell division, Flemming named the process "mitosis," from the Greek word meaning thread; in 1888, Wilhelm Waldeyer named these structures chromosomes. Éduard Strasburger, carrying out similar observations using cells from plants, noted the presence of specific stages during cell division, and in 1884, named these phases prophase, metaphase, anaphase, and telophase, terms used to the present day.

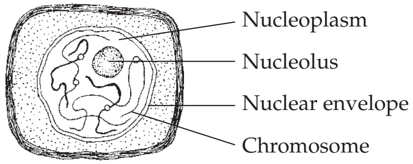
ROUX: EVOLUTION AT THE CELLULAR LEVEL?

Wilhelm Roux was born in 1850, the only son of a university fencing master. Following service in the Franco-Prussian War, Roux entered a medical program at the University of Jena, completing his medical examinations in 1877. In 1879, Roux joined the institute at the University of Breslau, where he was to remain some ten years. Roux's work was primarily in the emerging field of embryology, and his designation as the "father of experimental embryology" is a tribute to his contributions.

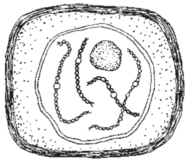
Roux was well aware of the importance of Darwin's ideas of natural selection. Incorporating his work on the development and differentiation of the embryo, he began to apply these ideas at the microscopic level. He was curious to see whether events that occur at the cellular level represent the result of processes likely to increase the chances of survival of the cell.

It had been only recently that Strasburger and Flemming had described

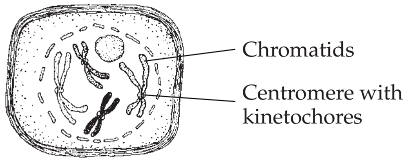
MITOSIS



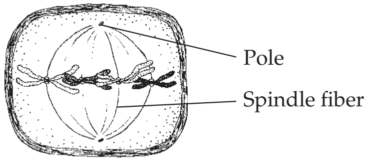
(1) Early prophase



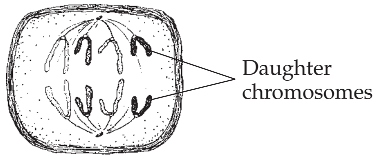
(2) Mid-prophase



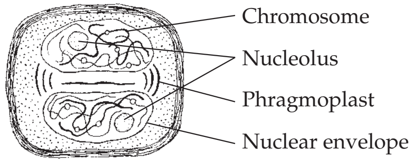
(3) Late prophase/ prometaphase



(4) Metaphase



(5) Anaphase



(6) Telophase

(Kimberly L. Dawson Kurnizki)

their work on mitosis. It was Roux's belief that the complex processes described by these colleagues could be accounted for in the context of natural selection—that there was a function behind mitosis that enhanced survival of the cell and the more complex organism. One application of this idea, albeit incorrect, was that stronger cells would crowd out weaker ones in the developing embryo.

In an 1883 essay, Roux described the events associated with what we now call chromosomes during cell division. Each chromosome divides longitudinally, with the separated material distributed to each daughter cell. It appeared to Roux that during this process, chromosomes were randomly distributed throughout the nuclear region, and perhaps were passed in like manner to the daughter cells. That is, Roux was unsure whether distribution of the chromosomes during cell division was equal, and he speculated that differentiation may in part be the result of an unequal distribution.

The pattern of movement of chromosomes to daughter cells also led to Roux's speculation that their primary role in the cell was that of heredity. This idea was further applied by August Weismann in his theories on the role of chromosomes in development; Weismann argued that the maintenance of hereditary characteristics over generations was the result of chromosomes being passed from parent to offspring, an idea largely proved correct. However, Weismann incorrectly believed each chromosome was the equivalent of the others.

Boveri: Sorting out the Chromosomes

Roux's incorrect assumption that differentiation is the result of alternative arrangements of chromosomes in cells is largely the reason that he remains a footnote in this area of biology. Much of his work during the later years at Breslau followed the same idea, that unequal chromosomal separation was necessary to explain the events during embryonic development. It remained for Theodor Boveri, in the first years of the twentieth century, to clarify the role played by chromosomes in development, as well as to provide an explanation for their distribution.

After establishing that chromosomes were both necessary and sufficient to maintain genetic characteristics in fertilized sea urchin eggs, Boveri demonstrated that fertilization with two sperms resulted in abnormal development of the organism. His interpretation of these results was that the inability of the sea urchin to develop normally was the result of unequal distribution of the chromosomes during cell division. If chromosomes were equivalent, as suggested earlier by Weismann, simply having extra chromosomes should not interfere with normal development. Boveri concluded that normal development required a precise number of chromosomes, and that individual chromosomes probably carried different, specific characteristics. Boveri later refined this work in what would become his chromosomal theory of heredity.

Impact

Roux's observation of events associated with cell division, mitosis, produced one of the first reports explaining how chromosomal material is distributed to daughter cells. It had only been a year since Flemming had reported the presence of such structures in the nucleus of cells, and while there were suspicions that chromosomes somehow played a role in heredity, their precise function remained to be confirmed. Roux's work was significant in providing further evidence for this function, as well as allowing for a mechanism by which chromosomal material may be passed to daughter cells—the duplication or division of chromosomes along a longitudinal axis, which ensured their distribution to daughter cells following the completion of mitosis. In the context of natural selection, Roux's ideas, largely theoretical, addressed the question of why such a complex mechanism might be beneficial for a cell.

Though Roux would be proven wrong in suggesting chromosomes were distributed unequally, he was the first to demonstrate the sorting of chromosomes during division. Roux's work was lacking in one significant detail: an explanation for the process of differentiation. In his studies of embryology, Roux showed that cells underwent two separate divisions, in which the final set of daughter cells did not contain the same quantity of chromosomes as the original parent cell. This led to the mistaken hypothesis by Weismann, that differentiation in part is the result of unequal distribution of chromosomes. Roux's ideas required subsequent revision. Nevertheless, his work bridged the period between the discovery of chromosomes, and elucidation of their role in the heredity of both the cell and larger organisms. Others would build on that work to achieve a better understanding of mitosis and heredity.

See also Cell Theory; Chromosomes; Gene-Chromosome Theory; Genetic Code; Mendelian Genetics; Microscopic Life; Stem Cells.

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—*Richard Adler*

MOON LANDING

THE SCIENCE: On July 20, 1969, the world watched the Apollo 11 lunar mission on television as Neil A. Armstrong and Buzz Aldrin became the first human beings to set foot on the Moon.

THE SCIENTISTS:

Neil A. Armstrong (b. 1930), the Apollo 11 commander
Michael Collins (b. 1930), the Apollo 11 command module pilot
Edwin E. "Buzz" Aldrin, Jr. (b. 1930), the Apollo 11 lunar module pilot

THE CHALLENGE

On May 25, 1961, President John F. Kennedy challenged the National Aeronautics and Space Administration (NASA), and the American people, with a goal seemingly out of the pages of science fiction:

> I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish.

The United States' program to land a human on the Moon was named "Apollo," after the Greek god of music, prophecy, medicine, light, and progress, because the "image of the god Apollo riding his chariot across the Sun gave the best representation of the grand scale of the proposed program." The early Apollo missions (Apollo 1-6) were unmanned test flights. They were the means by which NASA scientists developed spaceflight technology for the eventual safe transport of astronauts to the Moon. Apollo 7 would be the first manned flight in the series; Apollo 11 would deliver the astronauts to the lunar surface.

The command module (CM) of the Apollo series was a cone-shaped spacecraft that carried the three astronauts to and from the Moon. The service module (SM) contained the engines used for maneuvers, oxygen and water, the electrical power system, and the large communications antenna. The lunar module (LM), a two-stage, spiderlike vehicle, was designed to carry two astronauts to the lunar surface, provide a shelter for them during their stay, and return them to the CM.

The manned Earth-orbital flight of Apollo 7 (1968) was quickly followed by the Apollo 8 mission (1968), which orbited the Moon. Apollo 9 tested the command, service, and lunar modules in Earth's orbit, while Apollo 10 did the same in lunar orbit. By mid-1969, everything was ready for Apollo 11. Apollo 11 began its journey at 9:32 A.M. eastern daylight time on July 16, 1969, atop the Saturn V rocket, the height of which equaled the length of a football field. It rode a flame three times its length and climbed slowly into the warm Florida air. Twelve minutes later, the spacecraft and its crew were safely in Earth orbit. Two and one-half hours later, the third stage propelled the command and service module (CSM) toward the Moon. Seventy-six hours after launch, the spacecraft entered lunar orbit. At 1:44 P.M., on July 20, the LM separated from the CSM and began its descent to the lunar surface.

Meeting the Challenge

The LM, named *Eagle*, was first placed in a brief lunar orbit. As it began its trip to the surface, *Eagle* was 15 kilometers above the lunar surface, 554 kilometers from the landing target, flying face down. At an altitude of 12 kilometers, the LM rolled face up and the crew could no longer see the lunar surface. At 2.4 kilometers above the surface on its final approach, *Eagle* was pitched upright and Armstrong began to look for the landing site. At 1,500 meters above the surface, the hovering phase began and Armstrong had to decide where to land. Several alarms sounded in the cockpit—the computer was being overloaded with data. Finally, a probe attached to one of *Eagle*'s legs contacted the surface, and a blue light illuminated the cabin.

The LM settled onto the lunar surface in the Sea of Tranquillity at 4:17 P.M. on the evening of July 20, 1969. Immediately, the crew began procedures for an emergency liftoff. Things went well, and the two astronauts were given a "go" for the moonwalk. They ate their first lunch on the Moon but skipped a rest period because they were anxious to get on with the walk.

Armstrong, the mission commander, was the first out of the LM. He opened a compartment containing a television camera, then climbed down the ladder attached to the front leg of the LM and stepped from the foot pad. It was 10:56 P.M. "That's one small step for a man, one giant leap for mankind," he told mission control. Cautiously, Armstrong began moving around on the surface. He took photographs and collected a small sample of soil and rocks, which he placed in a pocket on the leg of his space suit.

Eighteen minutes later, Edwin E. "Buzz" Aldrin, Jr., joined him on the surface. "Beautiful view. Magnificent desolation," he reported. The two astronauts walked, hopped, and loped around the landing site for two and one-half hours, collecting samples and preparing experiments. They climbed back aboard *Eagle*, and at 2:54 P.M. on July 21, the ascent stage's engine ignited and carried them back to the orbiting *Columbia*, piloted by Michael Collins. They entered the command module with their cargo of moon rocks, sealed the connecting hatch, and jettisoned *Eagle*. At fifty-five minutes past midnight on July 22, Apollo 11 headed home. On July 24, the CM separated from the SM and began its fiery reentry. Later, the three

Neil Armstrong: What Is, and What Can Be

Born to Stephen and Viola Louise Armstrong in Wapakoneta, Ohio, on August 5, 1930, Neil Armstrong, the first man on the Moon, was an enthusiast of flying from an early age, receiving his student pilot's license even before his driver's license. In 1947, he entered the aeronautical engineering program at Purdue University with a scholarship from the U.S. Navy.

Two years later, he was called to active duty and in 1950 flew seventy-eight combat missions over Korea from the flight deck of the USS *Essex*. He won three Air Medals for his combat duty. At the end of the war, Armstrong earned his baccalaureate degree from Purdue in 1955 and then joined NASA's Lewis Flight Propulsion Laboratory in Cleveland, Ohio, later transferring to NASA's High-Speed Flight Station at Edwards Air Force Base, California. There he test-flew the X-15, X-1, F-100, F-101, F-102, F-104, F-5D, B-47, and the experimental X-20 Dyna-Soar.

(NASA/USAF)

In September, 1962, Armstrong was one of the first two civilians selected for the astronaut training. He served as a backup command pilot for the Gemini GT-5 mission, command pilot for Gemini 8, backup command pilot for Gemini 11, and backup commander Apollo 8. Armstrong's most memorable mission occurred during his command of Apollo 11 with fellow astronauts Buzz Aldrin and Michael Collins. On July 20, 1969, the human race accomplished what many consider the single greatest technological achievement of all time. Six hours after landing on the lunar surface at about 4:18 P.M. eastern daylight time, Armstrong stepped off the Lunar Module onto the surface of the Moon and uttered the immortal words, "That's one small step for man, one giant leap for mankind."

Following his historic moonwalk, Armstrong received a master's degree in aeronautical engineering from the University of Southern California, taught aerospace engineering at the University of Cincinnati, served as the chairman of the board of Cardwell International Corporation, became chairman of the board of Computing Technologies for Aviation, joined the National Commission on Space (a presidential panel created to develop goals for the space program in the twenty-first century), and served as vice chairman of the Presidential Commission on the Space Shuttle *Challenger* Accident.

An intensely private and unassuming man, Armstrong avoided public appearances after his astronaut days but on the thirtieth anniversary of the first lunar landing, July 20, 1999, gave a lighthearted speech before the National Press Club in Washington, D.C., on behalf of the National Academy of Engineering. Describing the mission as one of humanity's greatest engineering achievements, observing that while "science is about what is, engineering is about what can be."

main parachutes opened, slowing the CM for a soft water landing. At 12:50 P.M., the goal set by President Kennedy eight years earlier was met.

IMPACT

The first manned lunar landing is one of humankind's greatest achievements. There would be five more landings, and ten other astronauts would stay longer, travel farther, perform more experiments, and collect more samples. Someone had to be first, and it was this distinction that separated the flight of Apollo 11 from the rest. Three men traveled where no human had gone before, putting their lives in the hands of the technology that had carried them so far.

The remaining Apollo flights would contain two more firsts. Apollo 14 took two astronauts, including Alan B. Shepard, to a region of the Moon called "Fra Mauro." Shepard, America's first astronaut in space, became the first lunar golfer when he attached a specially made club head to the end of a sample-return container handle and swung at a genuine golf ball. The final three lunar landing missions utilized the first lunar "dune buggies," battery-powered roving vehicles that could extend to 10 kilometers the distance traveled from the LM.

On July 24, 1975, six years after Apollo 11 had returned to Earth, America's last flight of an expendable manned spacecraft took place. The Apollo-Soyuz Test Project was a joint Soviet American venture. The space race had given way to international cooperation.

See also Cassini-Huygens Mission; Earth Orbit; Galileo Mission; International Space Station; Mars Exploration Rovers; Space Shuttle; Voyager Missions; Wilkinson Microwave Anisotropy Probe.

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—*Russell R. Tobias*

Mössbauer Effect

The Science: Physicists made use of the Mössbauer effect to confirm the gravitational redshift that had been predicted by Einstein's general theory of relativity.

The Scientists:
Rudolf Ludwig Mössbauer (b. 1929), German physicist who won the 1961 Nobel Prize in Physics
Albert Einstein (1879-1955), American physicist who won the 1921 Nobel Prize in Physics
Robert Vivian Pound (b. 1919) and
Glen A. Rebka, American physicists

Einstein's Space-Time

In 1916, Albert Einstein published the general theory of relativity. It was his contention that gravitation is a consequence of the shape of what he called space-time, a continuum in which the location of any object or event can be determined. Space-time, according to Einstein, consists of three spatial dimensions and time, which is the fourth dimension.

In 1665, the English physicist and mathematician Sir Isaac Newton had worked out the universal law of gravitation. This law and Newton's laws of motion were extremely successful in predicting the motion of both falling bodies and orbiting bodies. One of the most spectacular successes of

Newton's laws occurred in 1846, when the planet Neptune was discovered. The planet had been discovered within one degree of the position predicted by Newton's laws. At about the same time, a detailed study of the orbit of the planet Mercury was initiated. Although Newton's laws predicted that the orbit of Mercury would rotate very slowly around the Sun, there was a small orbital advance that did not agree with those laws. Some members of the scientific community began to question the validity of Newton's laws. Others speculated that a planet might exist inside the orbit of Mercury, while still others proposed that the Sun is not symmetrical about its core. When the curved space-time of the general theory of relativity was applied to the problem of Mercury's orbit, however, the observations and the calculations agreed.

To understand Einstein's concept of gravity, one might imagine a sheet stretched out and held tightly by each of its four corners. A ball placed in the center of the sheet would cause a slight depression in the sheet. The more massive the ball, the deeper the depression. Another ball that was rolled near the depression would naturally follow the curve of the depression. It was Einstein's contention that the Sun warps the space-time around it and that Mercury follows this curvature in space-time.

Other confirmations of the general theory of relativity were to follow in the years after its introduction. In 1919, the English astronomer Sir Arthur Stanley Eddington led an expedition to an island off the coast of Africa to photograph a total eclipse of the Sun. The photographs revealed an apparent shift in the background field of stars that matched the prediction of the general theory of relativity. Einstein had said that light from the stars would bend in the curvature of space-time caused by the Sun; Eddington's work proved that Einstein was correct.

Redshifts and Gamma Rays

The general theory of relativity also predicted a phenomenon known as "gravitational redshifting," or the "Einstein shift." According to the theory, as light escapes from the surface of a star, opposing the force of gravity, it loses some of its energy. This causes the lengthening of the light waves. Because the longest visible light waves are red, lengthened waves would appear to be redder—hence the term "redshift."

All the early tests of the general theory of relativity were astronomical in nature. In 1960, however, an experiment was designed to test the validity of the theory in the laboratory. This test would make use of the Mössbauer effect.

In 1958, the German physicist Rudolf Ludwig Mössbauer discovered a method in which atomic nuclei could be used as extremely sensitive clocks. Because atoms emit light at specific wavelengths and frequencies, they can function as clocks. It is known that when a radioactive isotope of some element emits a gamma ray (a form of radiation), it can absorb another gamma ray of exactly the same energy. This fact alone, however, does not allow the redshift to be measured. Thermal energy within a sam-

Uses of the Mössbauer Effect

In 1961, when he won the Nobel Prize in Physics, Rudolf Mössbauer was a thirty-five-year-old senior research fellow at the California Institute of Technology (Caltech) in Pasadena, California. On the day the prizes were announced, cowinner and well-respected Stanford physicist Robert Hofstadter wired Mössbauer to say that he was "delighted to share this award with you."

The popular press was delighted with Mössbauer's youth and good looks. *Current Biography 1962* noted that he looked more like a student than a teacher on the Caltech campus. *The Christian Science Monitor* described his "handsome plumes of jet black hair and his penetrating black eyes." Unfortunately, the press was also frustrated by the complexity of the Mössbauer effect. Almost all articles cited the experimental use of the Mössbauer effect to prove the general theory of relativity, but that was only one of many important uses of the Mössbauer effect. *The Christian Science Monitor* quoted Mössbauer himself as saying, "It's always a little tricky to say. . . . We still have fights among the scientists to describe it." His wife, Elizabeth Mössbauer, said, "My husband can make his work very plain and exciting, but sometimes even physicists don't understand."

What is clearer is that the impact of Mössbauer's discovery of recoilless emission and absorption of gamma radiation—on physics, chemistry, geology, and biology—has been monumental. Annual conferences are held on results achieved with the technique, which has been combined with such other techniques as Coulomb excitation to extend its utility and the isotopes to which it applies. An annual publication, *The Mössbauer Effect Data Index*, lists thousands of studies on the uses of the effect: for solid state physics, nuclear structure, and a variety of high-precision measurements. In chemistry, it has been used to probe the geometry of chemical bonds in a variety of molecules. In biology, it has been used to study details of such interactions as that of oxygen with the iron in hemoglobin. In geology, Mössbauer techniques have been used to examine the behavior of iron in lunar rocks. The effect has been used to examine the techniques employed in ancient metallurgy and the glazes on prehistoric pottery. In sum, it has become a pervasive technique in all the sciences.

ple of any element will cause the nuclei of the atoms to oscillate. This motion will cause a redshift in gamma-ray frequencies. When a nucleus gives off or receives a gamma ray, there is a slight recoil motion. This motion also causes a redshift. It was Mössbauer's discovery that if the nuclei in question were embedded in the correct type of crystal, then the forces exerted by the surrounding atoms would reduce the thermal oscillations and virtually eliminate the recoil during the emission and absorption of gamma rays. The gravitational redshift experiment was one of many applications of this discovery, for which Mössbauer was awarded the 1961 Nobel Prize in Physics.

In 1960, Robert Vivian Pound and Glen A. Rebka conducted an experiment that provided the first accurate measurement of the gravitational redshift to be performed under laboratory conditions. The experiment was performed in the Jefferson Physical Laboratory at Harvard University, in Cambridge, Massachusetts. Gamma rays, which were emitted from a radioactive source located in the basement, traveled upward through holes drilled in the various floors to an absorber located in the penthouse. For the total distance of 22.5 meters, the calculated redshift was approximately two parts in a thousand trillion. If there was redshifting of the gamma rays from the emitter, these rays would not be absorbed by the absorbing crystal. It was found that gamma rays emitted at the bottom underwent a gravitational redshifting and were rarely absorbed at the penthouse level. The emitter was placed on a hydraulic lift that could be raised or lowered. Slowly moving the emitter upward set up a Doppler shift that compensated for the gravitational redshift and permitted absorption.

IMPACT

Prior to the Pound-Rebka experiment, the gravitational redshifting predictions made by the general theory of relativity had not been verified under laboratory conditions. The problem with measuring the redshift was that infinitely small increments of time had to be measured. With the discovery of the Mössbauer effect in 1958, the measurement of a gravitational redshift became possible.

This experiment not only confirmed the gravitational redshift predictions of the general theory of relativity but also confirmed Einstein's contention that there is no such thing as a universal time. Atoms give off light that has a definite wavelength and a definite frequency. By measuring this frequency, it is possible to make an accurate measurement of time. Pound and Rebka found that radiation from atoms is redshifted as it travels upward against gravity. When any form of electromagnetic radiation is redshifted, its wavelengths become longer and its frequency becomes lower. In other words, Pound and Rebka had found that gravity causes the flow of time to slow. Thus, the concept of a universal time was shown to be invalid.

See also Gravitation: Einstein; Relativity.

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—*David W. Maguire*

NEANDERTHALS

THE SCIENCE: Marcellin Boule's reconstruction of a near-complete Neanderthal skeleton called into question the possibility of finding the "missing link" between higher apes and humans.

THE SCIENTISTS:
Marcellin Boule (1861-1942), French paleontologist
Rudolf Virchow (1821-1902), German professor of anatomy
A. Bouyssonie,
J. Bouyssonie, and
L. Bardon, the French priests who discovered the Neanderthal skeleton

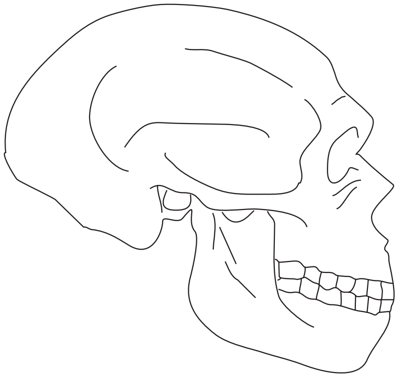
THE "MISSING LINK"

Late in the fall of 1908, the French paleontologist Marcellin Boule reconstructed a nearly complete skeleton of *Homo neanderthalensis* in his Paris laboratory. The fossil remains had been brought to him by three priests, who had found the bones in a cave at La Chapelle-aux-Saints in the

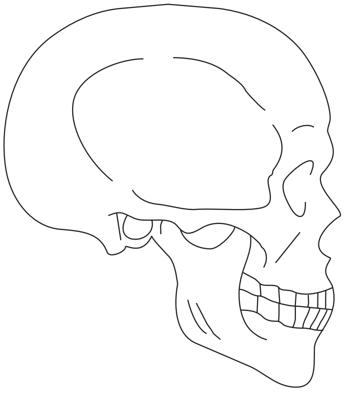
Corrèze in France. By determining the age of the layer of earth in which the fossils were found, as well as the age of the artifacts found nearby, Boule could tell that the bones were from the Mousterian period (between 100,000 and 40,000 B.C.E.). This dating supported Boule's theory that *Homo neanderthalensis* was the "missing link" in the evolution of humans from the higher apes. This theory would be debated for nearly half a century.

Boule had very few firm guidelines to follow when reconstructing the Neanderthal skeleton. Nevertheless, a book that he published with fellow paleontologist Henri Vallois, *L'Homme fossile*, makes it clear that Boule believed that any later discoveries would support his theory. After he had set forth his ideas, several new discoveries were made: at Le Moustier and La Ferrassie, both in Dordogne, in 1909; at La Quina in the French Charente district in 1911; and in Palestine and on the Italian peninsula in the 1920's and 1930's.

Skull Comparison



Homo sapiens neanderthalensis



Homo sapiens sapiens

Human or Ape?

When Boule finished piecing together the Chapelle-aux-Saints fossil, he noticed several things that seemed to indicate links between apes and humans. These included a bent-over skeletal posture, a very large jaw, a prominent brow ridge, a sloping forehead, and little or no chin. Finally, the curvature of the leg bones, as well as a certain "pigeon toe" effect in the feet, suggested basic simian (apelike) features that have disappeared in *Homo sapiens* (modern human beings).

Boule knew that considerable support existed for different theories about *Homo neanderthalensis*. In the mid-nineteenth century, the German anatomist Rudolf Virchow had argued that Neanderthal remains should be assigned

A LITTLE NEANDERTHAL IN SOME OF US?

Paleoanthropologists continue to debate the degree to which Neanderthals contributed to modern humans, with some arguing for strict replacement and others citing evidence for the mixing of Neanderthals with other early human species. In 2004, paleoanthropologist Milford Wolpoff and his colleagues cited evidence against strict replacement:

> Specifically, the evidence of skeletal anatomy, mitochondrial DNA, morphology and genetics of speech, and archaeological evidence of behavior all suggest that Neandertals are indeed among the ancestors of some modern human populations. This does not mean that the modern humans are Neandertals, or that the Neandertals are the only ancestors of any group of modern humans. The existence of differences between Neandertals and modern humans is repeatedly advanced as evidence for the impossibility of Neandertal ancestry in modern populations. . . . This is a straw man. While we certainly recognize a number of such differences, they are fully consistent with an evolving lineage: ancestors are never identical to their descendants. Do modern Europeans have a single unique African ancestry, or are European Neandertals among their ancestors? . . . [T]he hypothesis that Neandertals are a significant part of the ancestry of Europeans is well supported, and . . . it has not been disproved.

Source: Wolpoff, M., et al. "Why Not the Neandertals?" *World Archaeology* 36, no. 4 (2004): 527-546.

a place along with fossils of *Homo sapiens*, as a "cousin" who lived at the same time as modern humans. It was wrong, according to this school of thought, to limit the main period of *Homo neanderthalensis* to the Mousterian age simply to support the theory of evolution proposed by the English naturalist Charles Darwin. Neanderthals were not necessarily early humans who had been replaced by modern humans. Instead, they may simply have been unable to adapt to the same conditions as those that confronted modern humans.

Evolutionists, including Boule, wanted very much to find a pre-*sapiens* link between apes and *Homo sapiens*. They were willing to overlook the ideas of Virchow and others in order to find one. Boule's reconstruction of the Chapelle-aux-Saints skeleton seemed to meet this need.

IMPACT

There were two main theories about where *Homo neanderthalensis* belonged in the theory of evolution. Boule suggested that *Homo sapiens* had replaced *Homo neanderthalensis*. The other theory was that the two species existed side by side until the superior adaptive qualities of *Homo sapiens* allowed them to survive while *Homo neanderthalensis* declined in numbers and eventually disappeared.

Well before Boule's time, many scientists were unwilling to accept *Homo neanderthalensis* as an evolutionary "cousin" of *Homo sapiens*. One of these was the geologist Thomas Huxley, who believed that *Homo neanderthalensis* was more like an ape than a human. Virchow, on the other hand, refused to see *Homo neanderthalensis* as belonging to a species separate from *Homo sapiens*. Virchow believed that some of the Neanderthal's apelike features could be explained by "ailments"—specifically, the effects of rickets from malnutrition—suffered by the basically human individuals.

With the passage of time and the discovery of additional Neanderthal specimens, scientists began to grow skeptical of Boule's theory. In 1957, when W. L. Strauss and A. J. E. Cave took a close look at the skeleton Boule had reconstructed, they found that Virchow might be right in suggesting that disease had affected some of the Neanderthal's features. They also questioned the accuracy of Boule's work, especially in the foot area, where angles may have been exaggerated to make the foot look more like that of an ape. Strauss and Cave's work helped to lift *Homo sapiens neanderthalensis* to the status of a branch of *Homo sapiens*, rather than a "missing link." Today, paleoanthropologists continue the debate, with some arguning that Neanderthals were simply replaced by modern *Homo sapiens* and others citing genetic and anatomical evidence for a mixing of the gene pools.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Peking Man; Qafzeh Hominids; *Zinjanthropus*.

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—*Byron D. Cannon*

NEBULAR HYPOTHESIS

THE SCIENCE: In *The System of the World*, Pierre-Simon Laplace put forward a theory of the origins of the solar system. He demonstrated mathematically that Sir Isaac Newton's laws of motion and gravity could result in a simple cloud of dust transforming over time into the Sun and planets.

THE SCIENTISTS:

Pierre-Simon Laplace (1749-1827), French mathematician, astronomer, and physicist
Jean le Rond d'Alembert (1717-1783), French mathematician and encyclopedist
Claude Louis Berthollet (1748-1822), French chemist

OUT OF GAS AND DUST

When Pierre-Simon Laplace published his *Exposition du système du monde* (1796; *The System of the World*, 1809), he brought Sir Isaac Newton's astrophysics to a broad audience. The publication was a huge accomplishment, a series of five books in two volumes targeted at a semipopular audience and devoted to the analysis of the apparent motions of celestial bodies, the movement of the sea, the actual movements of celestial bodies, and the formation of the solar system.

In this work, Laplace first promulgated his now famous nebular hypothesis on the origin of the solar system. Laplace noticed in *The System of the World* that the planets known at the time (only the seven innermost planets had been discovered) had elliptical trajectories and were almost all in the same plane. Also noting the relatively slow rotation of the Sun itself, Laplace proposed that the solar system had been formed out of a rotating cloud of dust and gas, the *nébuleuse primitive*. Very hot, this nebular cloud flattened as its rotation increased in speed over time, ejecting small amounts of its particles that would become the planets and their moons. The condensing center of the cloud became the Sun.

Image Not Available

PIERRE-SIMON LAPLACE: SOLVING THE UNSOLVABLE

Pierre-Simon Laplace was born on March 23, 1749, to a well-off farming family in Normandy who could provide their children with educational opportunities. He studied mathematics at the University of Caen, taught at his former priory school, and then met the famous mathematician Jean le Rond d'Alembert, who in 1770 recommended him to the École Royale Militaire in Paris.

Turning to astronomy, in 1773 Laplace solved a problem in celestial mechanics that had puzzled many scholars, including the famous Leonhard Euler and Joseph-Louis Lagrange: Apparent variations in the speeds at which the planets revolved around the Sun seemed to have no reasonable explanation and indicated a worrisome instability in the solar system. Sir Isaac Newton himself had concluded that the solar system required intermittent divine intervention to keep it going. Laplace demonstrated that this planetary instability was only apparent; in fact, the variation in the speed of the planets was a periodic phenomenon that could be predicted. This work opened the door to the Académie des Sciences, and he would become its president in 1812.

Laplace's scientific reputation placed him in an intellectual, social, and political position that enabled him to have a profound influence on the changes that occurred in France during the revolution of 1789. In 1790, Laplace was instrumental in developing the metric system, and in 1795 he was a cofounder and first director of the Bureau des Longitudes. He also served as the director of the Paris Observatory. In 1806, Napoleon named Laplace a *comte d'empire* and gave him the position of minister of the interior in his government. Much more a scientist than an administrator, Laplace kept his ministerial position for only six weeks before gracefully withdrawing. In 1807 Laplace, along with the well-known chemist Claude Louis Berthollet, organized a group of famous scientists and young researchers called La Société d'Arcueil to encourage promising young graduates of the Polytechnique to continue their research.

Laplace was elected to the French Academy in 1816, and in 1817 Louis XVIII named him a marquis. When he died at the age of seventy-eight, Laplace not only had revolutionized astronomy but also had profoundly transformed the fields of probability, weights and measures, and mathematics. In a eulogy presented at the French Academy on November 13, 1827, Laplace's successor, Pierre-Paul Royer-Collard, said:

> Laplace was born to perfect everything, to deepen everything, to push back the limits, and to solve all of the things people believe unsolvable. He would have completed the study of astronomy if this science could be completed.

IMPACT

Pierre-Simon de Laplace's nebular hypothesis is still broadly accepted today as the most probable origin of the solar system. When combined with his demonstration that the solar system is stable and its motion is fully self-perpetuating without divine intervention, Laplace's work represents the first rigorous, mathematically precise, and fully secular description of both the creation and the functioning of the solar system. Laplace perfected the Newtonian theory of mechanics and gravitation and applied it in ways of which Newton himself was incapable. *The System of the World* was the springboard for the apotheosis of his work, *Traité de mécanique céleste* (1798-1827; partial translation as *A Treatise upon Analytical Mechanics*, 1814; full translation as *Mécanique céleste*, 1829-1839), a five-volume set on which he would labor for the rest of his life.

See also Cassini-Huygens Mission; Copernican Revolution; Extrasolar Planets; Galileo Mission; Gravitation: Newton; Halley's Comet; Heliocentric Universe; Herschel's Telescope; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Oort Cloud; Planetary Formation; Saturn's Rings; Solar Wind; Speed of Light; Stellar Evolution; Voyager Missions.

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—Denyse Lemaire and David Kasserman

NEURONS

THE SCIENCE: Santiago Ramón y Cajal showed that nerve cells operate as the discrete entities that transmit impulses unidirectionally in the nervous system through specific points of contact.

THE SCIENTISTS:

Santiago Ramón y Cajal (1852-1934), Spanish histologist and physician who was a cowinner of the 1906 Nobel Prize in Physiology or Medicine

Camillo Golgi (1843-1926), Italian anatomist and physician who was the developer of the Golgi staining technique and cowinner of the 1906 Nobel Prize in Physiology or Medicine

Wilhelm Waldeyer (1836-1921), German anatomist who coined the term chromosome to describe threadlike structures in the cell nucleus

Rudolf Albert von Kölliker (1817-1905), Swiss embryologist and histologist who wrote the first formal treatise on histology and who helped disseminate the findings and theories of Ramón y Cajal

Paul Ehrlich (1854-1915), German chemist who developed a new methylene blue stain for living tissues

RETICULAR THEORY

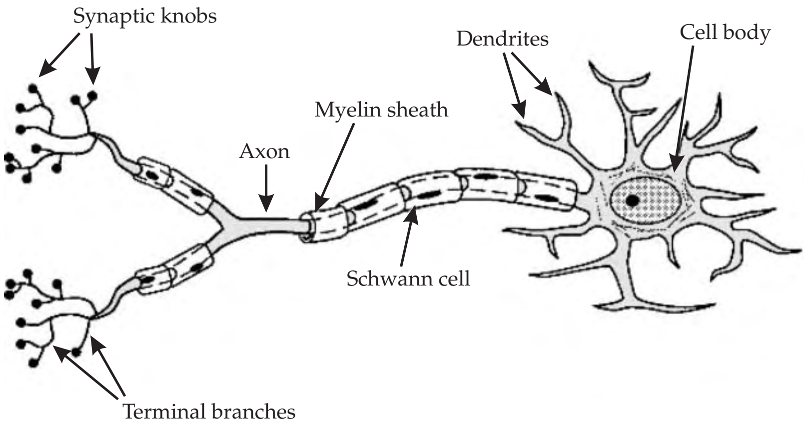
In the late 1800's, a controversy existed among brain scientists as to the nature of impulse transmission through the nervous system. The more popular school of thought began in 1872, when the gray matter of the cerebrum was described as a diffuse nerve net with fusion of dendrites (fine processes). Such notables as Theodor Meynert and Camillo Golgi agreed with this "reticular theory." According to this theory, the proper impulses were directed somehow out from this network of fused fibers to the appropriate muscles and organs, much like the streams flowing out from a lake to specific locations. However, A. H. Forel showed that retrograde degeneration was confined to the damaged cells, and Wilhelm His showed that in embryos the nerve cells behave as centers giving origin to fiber outgrowths.

At the time, the physical evidence was inadequate for determining which theory was more correct. No one had been able to see, with any clarity, the nerve fiber endings. Santiago Ramón y Cajal was able to provide the irrefutable evidence that resolved the issue eventually. He was first to demonstrate the very fine axons of the cerebellar nerve cells. He also demonstrated that the transmission of nerve impulses always flowed from the axon terminals of one nerve cell to the dendrites of an adjacent cell, disproving the reticular theory.

TRANSMISSION BY CONTACT

Ramón y Cajal's legacy was born of the microscope, an instrument with which he first became familiar in 1877 while studying in Madrid. He soon

Structure of a Vertebrate Neuron



became expert in histology, the field of biology devoted to the study of tissues. In the process, he made innovations in the staining techniques of the time. Tissue staining is a technique of applying dyes or other chemicals to the material studied so that particular structures or features are seen more easily.

In 1888, while at the University of Barcelona, Ramón y Cajal made a major finding. He worked with bird and small mammal embryos because embryonic nerve cells have fewer interconnections and are not covered yet with myelin (the fatty layer of insulation that envelops the axons, long processes, of most adult neurons); as a result, individual cells could stand out. Ramón y Cajal also modified the chrome silver staining technique invented by Golgi. Focusing on the cerebellum of the brain, Ramón y Cajal discovered basket cells and mossy fibers. He found that the axons of the nerve cells terminate in proximity, not continuity, with other cells or dendrites. This suggested that the nervous system works by contact, and thus Ramón y Cajal developed his "law of transmission by contact."

For the first time, it was proposed that the cells were the important components of the nervous system, as opposed to the fibers, which previously were believed to be a continuous network that transmitted impulses in the system. The popular notion had been that the cells played a relatively minor, supportive role. Ramón y Cajal's evidence of definitely limited conduction paths in the gray matter would be substantiated by later investigations of the retina, spinal cord, and other brain regions. Yet, the reticular theory proponents would not be defeated so easily.

After giving a presentation to the German Anatomical Society in Berlin in 1889, Ramón y Cajal won the support of Rudolf Albert von Kölliker, then editor of a scientific journal. Kölliker helped to promote the theories of Ramón y Cajal throughout Europe.

Neuron Theory

In 1890, Ramón y Cajal turned to a different set of studies that would support his theory. He demonstrated that developing nerve cells send out axon "growth cones" that later sprout dendrites and make connections, supporting his and Kölliker's theory. An alternate theory favored by the "reticular" advocates stated that developing nerves arise from the fusion of a row of cells.

In 1891, Ramón y Cajal returned to studying the cerebrum, a subject of some investigations several years past. He published a well-received book of his results. Wilhelm Waldeyer coined the term "neuron"; Ramón y Cajal's ideas became known as the "neuron theory." In 1892, Ramón y Cajal proposed his neurotropic theory to explain how the growth cone of the developing neuron is directed to its proper target. For the next few years, he would work on the retinas of various animals and on the hippocampus. The consistency of the results, with respect to his neuron theory, was unequivocal.

Staining Techniques

In 1896, Ramón y Cajal learned of Paul Ehrlich's methylene blue technique for staining tissues. This was a nontoxic substance and thus could be applied to living animals. Ramón y Cajal repeated many of his findings on living specimens using this technique to refute the criticism from such "reticularists" as Golgi that his results were an anomaly of his previous methods on dead tissues. Again, the results were irrefutable: Nerve cells existed as distinct units, making only the barest contact with other nerve cells in the system. Detractors of the neuron theory persisted. They objected on the grounds that Ramón y Cajal had not shown that neuron fibrils (internal structures) were not continuous, as they had claimed in support of the reticular theory.

The beginning of the twentieth century found Ramón y Cajal in Paris to receive the Moscow Prize of the Thirteenth Medical Congress. Not only did he receive the prestigious award, with its monetary bonus, but also the congress assigned Madrid as the venue for the next congress, to be held in 1903. This brought Ramón y Cajal great praise and adulation at home. He was appointed director of the new National Institute of Hygiene, where he promptly convinced the authorities to establish a laboratory of biological research. The government finally was supporting science in Spain.

By 1903, Ramón y Cajal had perfected yet another staining technique—reduced silver nitrate—which made the tissue transparent, allowing him to discover details about the internal structures of the nerve cells, including fibrils. He published twenty-two papers that year on fibrillar discontinuity, consistent with his neuron doctrine. Dozens of other scientists confirmed his work. For all intents, the debate over reticular versus neuron was won, but some die-hard reticular advocates persisted, even into the 1950's.

The recognition of Ramón y Cajal's theories reached a pinnacle in 1906, when he was awarded the Nobel Prize in Physiology or Medicine. Somewhat ironically, he shared the prize with Golgi, whose staining technique had made many of Ramón y Cajal's early findings possible, but who was still an advocate of the reticular hypothesis and a severe critic of Ramón y Cajal, so much so that he embarrassingly used his Nobel lecture to attempt a critique of Ramón y Cajal's methods and results. History would forgive Golgi his myopia and would establish Ramón y Cajal as a scientist of tremendous impact on modern neuroscience.

Impact

The neuron doctrine of Ramón y Cajal had an impact on many different fields within biology and medicine. The knowledge of the actual functional structure of the brain—being made of discrete, contacting units that transmit impulses in one direction—gave a better physical basis for understanding many nervous or mental disorders. Treatment now could be approached with a more accurate perspective on the possible deficiencies in the disorders.

A modern understanding of impulse transmission through the nervous system, from sensory neurons to central nervous system and then to muscle, is directly reflective of Ramón y Cajal's theory. The "black box" that had existed between the reception of a stimulus event and the control of a motor response, while still not completely revealed, was at least partly illuminated by this work. Possible mechanisms of learning and memory were developed with the framework established by the neuron doctrine. The foundation for the concept of the final common pathway of Sir Charles Scott Sherrington, the principle of reflex activity that is adhered to today, was laid by Ramón y Cajal and his microscope.

Ramón y Cajal's neuron doctrine influenced histologists, physiologists, surgeons, pathologists, neurosurgeons, psychiatrists, and psychologists. The concepts of neural inhibition, summation, and facilitation that are ac-

SANTIAGO RAMÓN Y CAJAL: NERVES AND PATRIOTISM

Santiago Ramón y Cajal was born in Petilla de Aragón, a small town in the Pyrenees mountains of Spain, on May 1, 1852. He described himself as a strong child who loved the outdoors and frequently got into trouble. It was largely to curb his troublemaking that his parents sent him to a church-run school at Jaca and later to another school in the town of Huesca. At age fourteen, he was apprenticed to a barber and later to a shoemaker. At his father's insistence, he then studied medicine, receiving his license in 1873. For the next year, he served as an army doctor in Cuba, where he contracted malaria. After he recovered, he received his first academic appointment, as professor of anatomy at Zaragoza. He married Silvería Fanañás García in 1880. They would have eight children.


(The Nobel Foundation)

In 1883, while chair of anatomy at the university at Valencia, he learned new staining methods and applied them to the study of embryos. He contracted tuberculosis and recovered, his illness having sparked an interest in bacteriology, which was making great strides at the time under the leadership of Louis Pasteur, Robert Koch, and others. After a cholera epidemic, Ramón y Cajal investigated the bacteria responsible for cholera and almost chose a career in bacteriology.

In 1887, Ramón y Cajal took a new position at the University of Barcelona, where he made many of his pioneering discoveries on the delicate processes of nerve cells, using his new staining techniques. He began the research on the nervous system that would make him famous. In 1892, he was appointed professor of histology at the University of Madrid, and the family moved there.

As part of his neurological research, Ramón y Cajal investigated the complex organization of the retina of the eye, showing how rod or cone cells communicate with so-called bipolar cells, which in turn communicate with ganglion cells. He also investigated the microscopic anatomy of the cerebellum and the cerebral hemispheres, revealing how a variety of different neurons communicate with each other.

Ramón y Cajal was always patriotic, though not uncritically: He saw the Spanish-American War (1898) as an act of stupidity on his country's part. He always resented the fact that few scientists were able to read Spanish, the language in which most of his many publications were written, and he helped form a Spanish school of histologists. In 1922, he and Silvería retired, staying in Madrid. He died there in 1934, at the age of eighty-two.

cepted now are possible only within the context of the neuron doctrine. The English physiologists were led to their work on the synapse, the site of neuron-to-neuron communication, by Ramón y Cajal's studies, and this knowledge of the synapse has had a great impact on medicine, such as in drug therapy and in the treatment of neurological disorders. Ivan Petrovich Pavlov's famous treatise on conditioning was molded, at least in part, by the neuron doctrine, as was the work of Walter Bradford Cannon on the physiological aspects of emotion. Ramón y Cajal's work could be said to have had an impact on education because his neuron doctrine has influenced subsequent theories on mechanisms for learning.

In the course of developing his neuron doctrine, Ramón y Cajal made a number of advances and innovations in histological staining techniques, many of which are still the techniques of choice. The work conducted on regeneration in the nervous system has played a seminal role in nerve damage therapy.

It is possible that had it not been Ramón y Cajal, someone else would eventually have discovered the truth about the structure of the nervous system and the nature of impulse transmission. Nevertheless, this man of meager means and modest beginnings had the inspiration and fortitude to pioneer the murky waters of the time, to bring science out of the ignorance of complacency. His work had a domino, rippling effect on the direction of science, such that the rate of progress in the field of neuroscience has been phenomenal. If Ramón y Cajal had not paved the way, scientists may have been stumbling along into untold dead-ends for many years.

See also Cell Theory; Pavlovian Reinforcement; Split-Brain Experiments.

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—*Harold J. Grau*

NEUTRON STARS

THE SCIENCE: Fritz Zwicky and Walter Baade proposed that a neutron star formed during a supernova.

THE SCIENTISTS:
Walter Baade (1893-1960), German American astronomer
Fritz Zwicky (1898-1974), Swiss astronomer
Lev Davidovich Landau (1908-1968), Soviet physicist
Rudolf Minkowski (1895-1976), German American astronomer

NOVAE AND SUPERNOVAE

The Greek philosopher Aristotle taught that the stars, the Sun, and the planets were located on crystal spheres that moved around the stationary Earth. On rare occasions, a new star would appear in the sphere, shining so brightly that it was visible during the day, and finally growing dim over several months. These were called “novae,” from the Latin word for “new,” because they seemed to be new stars. (Research, centuries later, would reveal how wrong that name is.)

In the past two thousand years, there were only seven bright novae that remained visible in the northern sky for at least six months each. In 185 C.E., for example, the Chinese recorded the appearance of a “guest star” that lasted for twenty months. Another such star in 393 C.E. lasted for eight months. The nova of 1006 was visible for several years and was recorded by the Chinese, Japanese, Europeans, and Arabs. The nova in 1054 lasted twenty-two months and was noted by the Chinese and Japanese; there is evidence from several petroglyphs in the American Southwest that Native Americans also observed the event.

A nova that appeared in 1572 was observed by the last great astronomer before the age of telescopes, Tycho Brahe. It was Brahe who gave novae their name. Because of his study of that nova, known as Brahe’s star, and his subsequent book titled *De Nova Stella*, Brahe’s reputation was made. The German astronomer Johannes Kepler, who was Brahe’s assistant in later years, studied the 1604 nova, Kepler’s star. After Brahe’s death in 1601, Kepler used the astronomer’s data to explain the motion of the planets. The appearance of the nova drove Kepler to greater efforts that resulted in three laws of planetary motion.

Over the centuries, advances in telescopes and other astronomical instruments led to a better understanding of novae. Studies suggested that novae were not a simple class of stars. Some novae were bright and rare, while others were much fainter and more common. Fritz Zwicky and Walter Baade recognized in 1934 that a division was necessary and renamed the brighter novae supernovae.

Fritz Zwicky. (California Institute of Technology)

Stars are "born" from collapsing clouds of gas and dust. As they become older, the interior pressure and temperature increases, producing chemical reactions in which hydrogen fuses into helium. Energy is released from this reaction in the form of light and other electromagnetic radiation. The length of a star's life cycle is determined by its mass. Low-mass stars such as the Sun fuse the hydrogen slowly and have lifetimes of tens of billions of years. The most massive stars have lifetimes of tens of millions of years. As the star "dies," it can do so in one of several ways. The low-mass star depletes its hydrogen supply, grows in size to become a "red giant," and then collapses to a "white dwarf" phase. It shines by its stored heat until eventually it cools and reaches the "black dwarf" stage. A star the size of the Sun will shrink to the size of Earth.

Walter Baade. (California Institute of Technology)

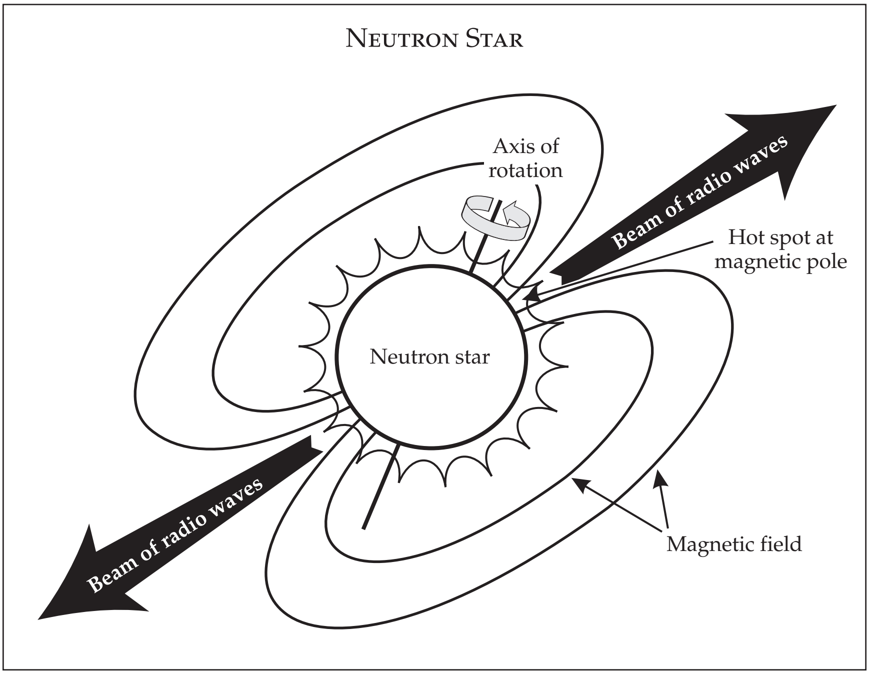
OLD STARS

A binary star system is a pair of stars that orbit a common center of gravity. A binary star system whose stars are near the end of their life cycles is the common source of nova explosions. Material from one of the stars is pulled onto the surface of the other star. When enough of it accumulates, it will fuse to helium and produce the brightening that can be seen as a nova. That is why the word "nova" is not really correct—a nova is not a new star, but rather the death of a star in a binary system.

A supernova, however, is the very rapid explosion of a very massive star near the end of its life cycle. This is evident because in the constellation Taurus, the location of the 1054 nova, lies a gaseous mass known as the Crab nebula. This gas cloud is expanding outward. Calculations of the velocity of the cloud's gas show that, after the explosion, it started its outward journey in 1054.

When a massive star depletes its supply of hydrogen, it collapses and its internal heat and pressure increase until helium is converted to carbon. Elements with increasingly higher atomic numbers are formed as the collapse continues. Once the core becomes the element iron, the process cannot continue until more energy is added. At this point, the collapse continues because of gravity; in the last stages, the star's outer layers hit the core and bounce. The star explodes, sending a large part of its mass into space. The remainder of the supernova collapses to become a neutron star or a black hole, depending on its mass.

Zwicky and Baade, and independently Lev Davidovich Landau, postulated that, after this explosion, the pressure of the star's collapse overcomes the atoms' electrical forces and fuses protons and electrons into neutrons. This explanation was not verified experimentally until Jocelyn Bell, a grad-



A diagram of a neutron star showing its strong magnetic field, which generates radiation that can be detected on Earth as radio waves.

uate student at Cambridge, discovered the first pulsar in 1967. A pulsar is a neutron star that spins very rapidly, emitting radio waves from its rotating magnetic field. First thought to be signs of extraterrestrial intelligence, these pulsars were the first observational evidence of Baade and Zwicky's theory.

Impact

For thousands of years, people have tried to figure out how the planets came into being. The discovery and understanding of neutron stars and supernovae have helped scientists to solve the puzzle. The "big bang theory" suggests that the universe began about 15 billion years ago. At that time, all the energy and matter in the universe were contained within a small sphere that exploded. As the universe—the pieces of matter sent flying by the explosion—cooled and expanded, hydrogen and helium began to form. Eventually, clouds of hydrogen and helium collapsed to form stars, and these formed into galaxies.

As these stars aged, the more massive ones exploded as supernovae. The blast spewed into the surrounding space all the chemical elements contained in the star, enriching the interstellar medium with essential ingredients. After enough stars had become supernovae, planets could begin to form. So, too, could the next generation of stars, which would benefit from the enriched gas and dust clouds of the planets. Before this time, planets could not exist. Life as it is now known could not exist because there were no carbon, nitrogen, and other essential elements on which life depends.

See also Big Bang; Black Holes; Brahe's Supernova; Cassini-Huygens Mission; Cepheid Variables; Chandrasekhar Limit; Copernican Revolution; Extrasolar Planets; Galactic Superclusters; Galaxies; Hubble Space Telescope; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; X-Ray Astronomy.

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—*Stephen J. Shulik*

NEUTRONS

THE SCIENCE: James Chadwick discovered that there is a fundamental particle in the atom that has no electrical charge and that has a mass approximately equal to that of the proton.

THE SCIENTISTS:

James Chadwick (1891-1974), British physicist who won the 1935 Nobel Prize in Physics

William Draper Harkins (1873-1951), American chemist

Ernest Rutherford (1871-1937), English physicist

Frédéric Joliot (1900-1958), French physicist who shared the 1935 Nobel Prize in Chemistry

Irène Joliot-Curie (1897-1956), French physicist who shared the 1935 Nobel Prize in Physics

Walther Bothe (1891-1957), German physicist

MISSING MASS

Although the word *atom* actually means "indivisible," discoveries in the late nineteenth century indicated that the atom has a divisible and very complex structure. By 1914, Ernest Rutherford, an English physicist, had developed a model of the atom based on his own work as well as on the work of many scientists before him. In this model, nearly all the mass of the atom and all the positive electrical charge are concentrated in an extremely

James Chadwick: From Neutrons to Cyclotrons

James Chadwick majored in physics instead of mathematics because of a mistake in the registration procedure at the Victoria University of Manchester. However, after attending lectures on electromagnetism by Ernest Rutherford, the world leader in the investigation of radioactivity, he decided his major was no mistake, and he received a first-class honors degree in that subject in 1911. That year, Rutherford made one of the most important scientific discoveries of this century: the nuclear structure of the atom. In 1913, Chadwick received his master's degree as well as a scholarship that sent him to study radioactivity with Hans Geiger, in Germany. There he discovered that the spectrum of beta rays was continuous. World War I began, and Chadwick was interned in a camp for enemy aliens. Despite brutal conditions, he conducted experiments using a German brand of toothpaste.


(The Nobel Foundation)

After the war, Chadwick worked in the Cavendish Laboratory of Cambridge University under his old mentor, Rutherford. There they investigated elements by alpha-particle bombardment. A notable exception to this line of work was his confirmation in 1920 that the charge on the atomic nucleus was equal to the atomic number, as had been suggested by A. van den Broek and Henry Moseley several years before. Chadwick's most important scientific discovery was his identification of the neutron in 1932, for which he received the Royal Society's 1932 Hughes Medal and the 1935 Nobel Prize in Physics. The neutron not only explained the hitherto unresolved problem of just what particles composed the nuclei of atoms but also gave impetus to Enrico Fermi's studies in nuclear reactions in uranium, which led to the 1938 discovery of nuclear fission by Otto Hahn and Fritz Strassmann.

In 1935, Chadwick accepted the Lyon Jones Chair of Physics at the University of Liverpool, where he had the opportunity to create his own laboratory and build a cyclotron, a machine that accelerates nuclear particles to great energies and then directs the beam upon a target. After World War II began, Chadwick was influential in furthering the atom-bomb projects of both the British and U.S. governments. As head of the British mission in Washington, D.C., he formed a remarkable friendship with General Leslie Groves, an able but tactless man whom most scientists disliked. Their rapport helped minimize the inevitable policy differences any two nations would have. Chadwick left Liverpool in 1948 to become master of Gonville and Caius College, Cambridge University. A decade later he retired to a cottage in North Wales, and in 1969 he made his final move, back to Cambridge, where he died in 1974.

small part of the atom, the nucleus. Rutherford estimated the diameter of the nucleus to be one ten-thousandth of the diameter of the atom. Consequently, the electrons associated with the atom occupied a much larger volume than the nucleus and carried all the negative electrical charge, but had very little mass. He named the carrier of the positive charge in the nucleus the "proton" ("first" in Greek).

At this point, then, there were two elementary particles: the proton, with a positive charge, and the electron, with a negative electrical charge of the same magnitude as the positive charge of the proton. The atom, therefore, had to be built up with only these two particles. Helium, for example, would have two protons and two electrons. However, because the mass of the helium atom was known to be four times the mass of the hydrogen atom (which has one proton and one electron), the nucleus of the helium atom needed two more protons to produce the appropriate mass. In order to keep the electrical charge of the nucleus equal to that of two protons, it was suggested there were also two electrons in the nucleus, which neutralized the charge of the additional two protons.

As early as 1920, Rutherford speculated that there might be another elementary particle with about the same mass as the proton, but with no charge. Perhaps it was somehow produced by the combination of a proton and an electron. In 1921, American chemist William Draper Harkins named this hypothetical particle the neutron, because it was electrically neutral.

The Search for the Neutron

English physicist James Chadwick began his search for the neutron at the Cavendish Laboratory under Rutherford's guidance. At first, his search was unsuccessful; however, he was not the only one searching. In 1930, Walther Bothe of Germany found that when beryllium and boron were bombarded by high-energy alpha particles, radiation with no electrical charge but with great penetrating power was produced. Only two years later, Irène Joliot-Curie and Frédéric Joliot reported that this radiation could cause protons to be ejected from paraffin. These scientists concluded that the radiation was a type of gamma ray—that is, electromagnetic energy of very high frequency.

When Chadwick read the account of the experiments performed by the French scientists, he immediately decided to examine this phenomenon further. He found that when boron and beryllium were bombarded by alpha particles from polonium, the mysterious radiation from these two substances could eject protons from any materials that contained hydrogen. He also discovered, from calculating the energy acquired by nitrogen atoms bombarded by the unknown radiation, that the radiation could not be gamma rays, as previously reported.

Chadwick then showed that his experimental results were completely consistent with the assumption that each proton ejected from the paraffin had undergone a collision with an unknown particle of approximately equal mass (very much like what happens when billiard balls collide). When Chadwick was unable to deflect this particle in a magnetic field, he concluded that it had no electrical charge. Since it did not correspond to any previously known particle, it must be the long-sought neutron.

Impact

The discovery of the neutron, in 1932, marked the beginning of nuclear physics—that is, the study of the nuclear structure of the atom. It was readily seen that, since the nuclei of most elements are extremely stable, there were forces of attraction hitherto unknown between the "nucleons" (the word coined to designate the particles in the nucleus). Until the discovery of the neutron, the only known forces in physics were those of gravity, electricity, and magnetism. After 1932, it was necessary to speak of a new kind of force: the nuclear force.

With the discovery of the neutron came a much clearer understanding of atomic structure, specifically the structure of the nucleus. German physicist Werner Heisenberg proposed that envisioning the nucleus of an atom as being constructed of neutrons and protons resolved a number of difficulties. These included the problem of the missing mass of the helium atom—the answer is that two neutrons make up the additional mass. Neutrons also provide an explanation for isotopes, which are atoms of the same element that have different atomic masses. Clearly, the additional mass is caused by the presence of more neutrons in the nucleus.

In 1939, it was discovered that when uranium atoms are bombarded by neutrons, they undergo fission. Shortly thereafter, physicists showed that this fission would release considerable energy. When it was also discovered that the fission process produced additional neutrons, scientists realized that a chain reaction of great power was possible. Consequently, the discovery of the neutron ushered in the atomic age.

See also Alpha Decay; Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Electric Charge; Electron Tunneling; Electrons; Electroweak Theory; Exclusion Principle; Heisenberg's Uncertainty Principle; Isotopes; Mössbauer Effect; Nuclear Fission; Periodic Table of Elements; Plutonium; Quantum Mechanics; Quarks; Radioactive Elements.

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—*Wilfred Theisen*

NUCLEAR FISSION

THE SCIENCE: Enrico Fermi's team demonstrated nuclear fission—the release of nuclear energy in a sustained chain reaction—which led to the development of the atomic bomb and nuclear power plants.

THE SCIENTISTS:

Enrico Fermi (1901-1954), Italian American nuclear physicist
Walter Henry Zinn (b. 1906), Canadian physicist
Herbert L. Anderson (1914-1988), American physicist
Arthur Holly Compton (1892-1962), American physicist

"TRANSURANIC" ELEMENTS

In December, 1938, Enrico Fermi, a professor of physics in Rome, took advantage of his 1938 Nobel Prize in Physics to leave his native Italy and escape Adolf Hitler's increasing domination of Italy. With his family, Fermi arrived in New York City and settled down to continue his research at Columbia University.

Fermi and his associates in Rome had been studying the new nuclei produced when various chemical elements are bombarded by neutrons. In 1934, experiments on uranium produced a new radioactive isotope. Fermi and his collaborators demonstrated chemically that the new isotope did not belong to any of the elements immediately below uranium on the periodic table. They concluded that they had produced the first element ever found that was heavier than uranium.

The idea of a "transuranic" element caught the imagination of the scientific community and the popular press. When, for example, German chemist Ida Noddack published an article suggesting that Fermi had not ruled out the possibility that his new radioactivity came from a lighter (non-transuranic) chemical element produced when a uranium nucleus split into two parts, she was largely ignored.

Fermi and other scientists, including Irène Joliot-Curie and Paul Savitch in Paris, and Otto Hahn, Lise Meitner, and Fritz Strassmann in Berlin, continued to study the effects of irradiating uranium with neutrons. All the experimenters gradually compiled a list of several different radioactive species that were produced when uranium was bombarded.

In December, 1938, Hahn wrote to Meitner and informed her that he and Strassmann had incontrovertible evidence that the bombardment of uranium with neutrons produced lighter elements, not transuranic elements. Meitner and her nephew, Otto Robert Frisch, a young physicist working with Danish physicist Niels Bohr in Copenhagen, concluded that when a uranium nucleus absorbed a neutron, that nucleus split or fissioned into two lighter nuclei and some extra neutrons, releasing a hundred million times as much energy as was released in a typical chemical reaction between two atoms.

Chain Reactions and Superweapons

Fermi and Leo Szilard, a Hungarian physicist also driven into exile by Hitler's advance in Europe, realized immediately that if the neutrons from one fission could be used to trigger a second fission, the resulting chain reaction could be used to produce energy. If the multiplication could be made geometric, so that each fission produced at least two fissions, each of which produced at least two more fissions, and so on, the chain reaction would yield a powerful explosion. Szilard feared that Hitler's Germany would construct a superweapon based on these principles. He persuaded his American colleagues, including Fermi, to delay publication of their experimental results on fission.

Meanwhile, the physics community measured the energy released, the number of new nuclei produced, and the number of neutrons released dur-

Enrico Fermi. (The Nobel Foundation)

ing each fission. In August of 1939, Szilard and fellow Hungarian émigré Eugene Paul Wigner persuaded physicist Albert Einstein to send a letter to U.S. president Franklin D. Roosevelt urging a research program to consider the possibility of developing a superweapon. The American government hesitated while the physicists determined that only the rare isotope uranium 235 underwent fission, while the common isotope uranium 238, which composed 99.3 percent of naturally occurring uranium, did not.

In July, 1941, Fermi and his group received funding to begin experiments in constructing a graphite-uranium "pile" designed to sustain a chain reaction. In December, 1941, Arthur Holly Compton, the American Nobel laureate in physics, was placed in charge of the project. He moved the experiments to the University of Chicago in early 1942. Construction of the pile began in November in a squash court, the only area available that was large enough to hold the 771,000 pounds of graphite, 80,590 pounds of uranium oxide, and 12,400 pounds of uranium metal that were to compose the pile.

Construction crews headed by Walter Henry Zinn and Herbert L. Anderson worked around the clock machining and stacking the graphite and uranium blocks. Control rods that absorbed neutrons were built into the pile and would be withdrawn once it was time to start the chain reaction. Each day, the control rods were withdrawn and measurements were taken to see how close the system was to sustaining a chain reaction.

On the evening of December 1, 1942, Anderson and Zinn decided that the layer of uranium and graphite that the night crew had placed on the pile should be sufficient to sustain a chain reaction. The crew went home for a few hours of sleep and reassembled at 8:30 the following morning. Fermi ordered the main control rods withdrawn, and the final control rod was moved foot by foot out of the pile as the assembled physicists gathered to watch the neutron counters. At about 3:25 P.M., the last foot of the final control rod was removed. The counting rate climbed exponentially. A controlled fission chain reaction had been achieved and was sustained until Fermi ordered the control rods inserted back into the pile at 3:53 P.M. As the group celebrated, they realized that the success of their experiment had inaugurated a new atomic age.

THE FIRST ATOMIC PILE

An eyewitness account of the first atomic pile recalls the historic day on which the first self-sustaining nuclear reaction took place:

On December 2, 1942, man first initiated a self-sustaining nuclear chain reaction, and controlled it. . . .

Construction of the main pile at Chicago started in November. . . . At Chicago during the early afternoon of December 1, tests indicated that critical size was rapidly being approached. At 4:00 P.M. [Walter] Zinn's group was relieved by the men working under [Herbert L.] Anderson. Shortly afterwards the last layer of graphite and uranium bricks was placed on the pile. Zinn, who remained, and Anderson made several measurements of the activity within the pile would become self-sustaining. . . . That night the word was passed to the men who had worked on the pile that the trial run was due the next morning.

About 8:30 on the morning of Wednesday, December 2, the group began to assemble in the squash court. At the north end of the squash court was a balcony about ten feet above the floor of the court. [Enrico] Fermi, Zinn, Anderson, and [Arthur H.] Compton were grouped around instruments at the east end of the balcony. The remainder of the observers crowded the little balcony. R. G. Noble, one of the young scientists who worked on the pile, put it this way: "The control cabinet was surrounded by the 'big wheels'; the 'little wheels' had to stand back. . . ."

At 11:35, the automatic safety rod was withdrawn and set. The control rod was adjusted and "Zip" was withdrawn. Up went the counters, clicking, clicking, faster and faster. . . . At 2:50 the control rod came out another foot. . . . "Move it six inches," said Fermi at 3:20. Again the change—but again the leveling off. Five minutes later, Fermi called: "Pull it out another foot." . . .

Fermi computed the rate of rise of the neutron counts over a minute period. He silently, grim-faced, ran through some calculations on his slide rule. . . . [Finally,] Fermi closed his slide rule—

"The reaction is self-sustaining," he announced quietly, happily. "The curve is exponential." . . . "O.K., 'Zip' in," called Fermi to Zinn, who controlled that rod. The time was 3:53 P.M. Abruptly, the counters slowed down, the pen slid down across the paper. It was all over.

Source: The First Atomic File: An Eyewitness Account Revealed by Some of the Participants and Narratively Recorded, by Corbin Allardice and Edward R. Trapnell (Washington, D.C.: U.S. Atomic Energy Commission, 1949).

IMPACT

The successful operation of the atomic pile provided physicists with a tool for studying the behavior of nuclear fission chain reactions. These studies were essential for the design and construction of an atomic bomb, since details of critical mass and neutron absorption by materials could be easily measured using atomic piles. Moreover, atomic piles produced a second fissionable isotope, plutonium 239, and the design of large-scale piles for the production of plutonium was soon under way. Plutonium was to prove more efficient than highly enriched uranium 235 as a fuel for bombs. Finally, the first atomic pile demonstrated that it was possible to produce a sustained energy source from nuclear fission, making it possible to construct nuclear electric generating plants.

See also Alpha Decay; Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Isotopes; Plutonium; Radioactive Elements.

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—*Ruth H. Howes*

OIL-DROP EXPERIMENT

THE SCIENCE: The oil-drop experiment, which Robert Andrews Millikan devised to measure electrical charges on tiny oil drops, determined that the electron is the fundamental unit of electricity.

THE SCIENTISTS:

Robert Andrews Millikan (1868-1953), American physicist
Harvey Fletcher (1884-1981), American physicist

MEASURING ELECTRIC CHARGE

The first measurement of the electric charge carried by small water droplets was made in 1897 at Cambridge, England. The method timed the rate of fall of an ionized cloud of water vapor inside a closed chamber. The experiment was improved in 1903 by using a beam of X rays to produce the cloud between horizontal plates charged by a battery. The rate of descent of the top surface of the cloud between the plates was measured with an electric field that was switched on and off. The procedure, although an improvement, suffered from instabilities and irregularities on the top of the cloud. The cloud surface was difficult to delineate and resulted in measurements that fluctuated as much as 100 percent.

In 1909, a young graduate student, Harvey Fletcher at the University of Chicago (then College of Chicago), went to his physics professor, Robert Andrews Millikan, to receive suggestions for work on a doctoral thesis in physics. Millikan suggested improving upon the measurement of electronic charge previously performed in Cambridge, England. Millikan's initial plan was to use an electric field not only strong enough to increase the speed of fall of the upper surface of the ionized cloud but also powerful enough to keep the top of the cloud surface stationary when the electric field was reversed. This would allow the rate of evaporation to be easily observed and compensated for in the computations. This technical improvement would permit the researcher for the first time to make measurements on isolated droplets and eliminate the experimental uncertainties and assumptions involved in using the cloud method.

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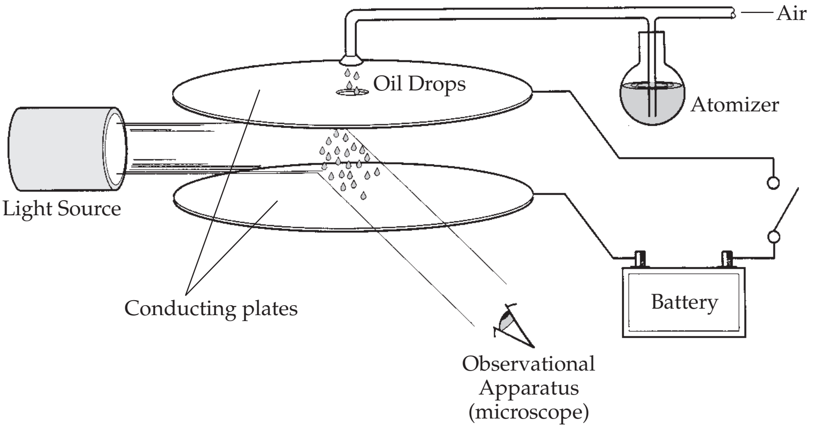
Millikan's improvement included the construction of a 10,000-volt small cell storage battery with

Millikan’s Oil-Drop Experiment



enough strength to hold the top surface of the cloud suspended long enough to measure the rate of evaporation of the droplets. When the electric field was turned on, however, the result was a complete surprise to Millikan. The top of the cloud surface instantaneously dissipated, and because the experimental result assumed a rate of fall for the ionized cloud, Millikan saw this result as a complete failure. Repeated tests showed that whenever the cloud was dispersed, a few droplets would remain. By nature, however, these droplets had the proper charge-to-mass ratio to allow the downward force of gravity or weight of the droplet to be balanced by the upward pull of the electric field on the droplet’s charge. This procedure became known as the “balanced drop method.”

With practice, Millikan found that he could reduce evaporation by turning off the field shortly before certain droplets in the field of view changed motion from slow downward to upward. This made it possible to time the motion for a longer period. From Stokes’s law, he found the weight of the droplet. Also, by knowing the strength of the electric field, Millikan calculated the electric charge necessary to balance its weight. The experimenters soon realized that the droplets always carried multiples of whole-number (1, 2, 3, 4, and so on) charges—never fractional amounts.

“Little Starlets”

The actual experimental arrangement used by Millikan and Fletcher consisted of a small box with a volume of 2 or 3 centimeters fastened to the end of a microscope. A tube led from the box to an expansion chamber secured by an adjustable petcock valve that allowed a rapid expansion of air to form a water vapor cloud in the box. Surrounding the box on both ends were two brass conducting plates about 20 centimeters in diameter and 4 millimeters thick. A small hole was bored into the top plate to allow the oil mist from an atomizer to enter the region between the plates, which were separated by approximately 2 centimeters. A small arc light with two condensing lenses created a bright, narrow beam that was, in turn, permitted to pass between the plates.

An instrument called a "cathetometer" was placed on the microscope so that the microscope could be raised or lowered to the proper angle for best illumination (which from practice turned out to be about 120°). The plate separation made it possible to apply a potential difference and produce an electric field. The apparatus was operated by turning on the light; focusing the microscope, which was placed about 1 meter from the plates; and then spraying oil over the top plate, while switching on the battery. When viewed through the microscope, the oil droplets looked like "little starlets" that had the colors of the rainbow.

When the electric field was first switched on, one would notice that the droplets would move at different speeds; some moved slowly upward, while the others moved rapidly downward. Superimposed on the droplets' downward fall was a small random back-and-forth movement (now known as Brownian motion) caused by the collision of the tiny droplets with thermally agitated air molecules within the chamber. When the electric field was reversed by changing the polarity of the battery, the same droplets that were moving downward moved upward, and vice versa. The experimenters deduced that the nature of this motion indicated that some of the droplets were negatively charged, while the others carried a positive charge.

Impact

No fractional amounts of the basic charge of oil droplets were ever observed—only whole-number increments. This implied that the unit charge obtained could not be subdivided into smaller charges and was independent of the droplet size. These exact values showed that the electronic charge was not merely a statistical mean, as previous experimenters had believed. The experiment was, in fact, direct evidence for the existence of the electron as a finite-sized particle carrying a fundamental charge. It also made it possible to examine the attractive or repulsive properties of isolated electrons and to determine that electrical phenomena in solutions and gases are caused by electrical units that have fundamentally the same charge.

The experiment was an improvement over previous measurements in that Millikan was able to control precisely the strength of the electrical field while varying the droplet size. He also demonstrated that a completely discharged oil droplet fell at the same rate as an uncharged droplet with the electric field on. This indicated that something fundamental, which he chose to call "electricity," could be placed on or removed from the droplet only in exact amounts.

See also Alpha Decay; Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Electric Charge; Electron Tunneling; Electrons; Electroweak Theory; Exclusion Principle; Heisenberg's Uncertainty Principle; Isotopes; Mössbauer Effect; Neutrons; Nuclear Fission; Quantum Mechanics; Quarks; Radioactive Elements.

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—*Michael L. Broyles*

ONCOGENES

THE SCIENCE: Oncogenes are a group of genes originally identified in RNA tumor viruses and later identified in many types of human tumors. The discovery of oncogenes revolutionized the understanding of cancer genetics and contributed to the development of a model of cancer as a multistage genetic disorder. The identification of these abnormally functioning genes in many types of human cancer has also provided molecular targets for therapeutic intervention.

THE SCIENTISTS:

Peyton Rous (1879-1970), American pathologist who shared the 1966 Nobel Prize in Physiology or Medicine

David Baltimore (b. 1938), American virologist who shared the 1975 Nobel Prize in Physiology or Medicine

Renato Dulbecco (b. 1914), Italian-born geneticist who shared the 1975 Nobel Prize in Physiology or Medicine

Howard M. Temin (1934-1994), American virologist who shared the 1975 Nobel Prize in Physiology or Medicine

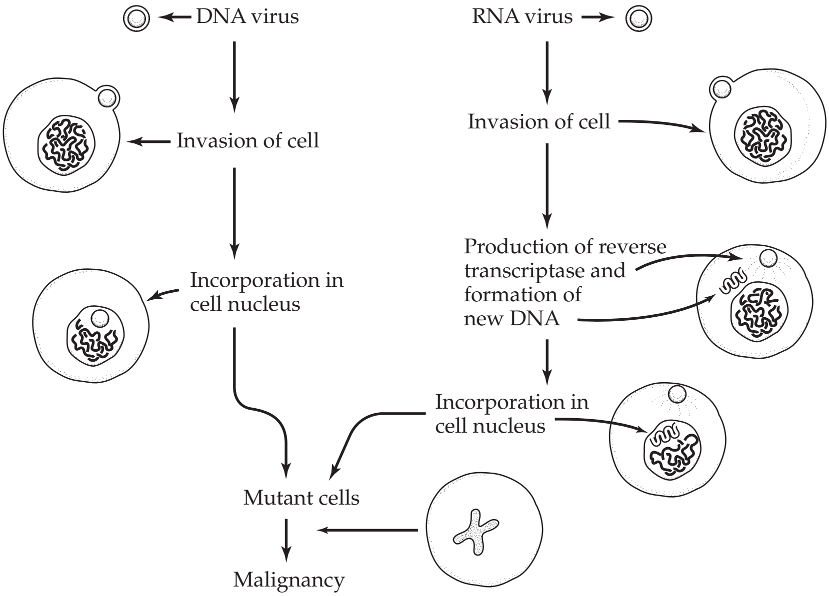
Harold E. Varmus (b. 1939), American virologist who shared the 1989 Nobel Prize in Physiology or Medicine

J. Michael Bishop (b. 1936), American virologist who shared the 1989 Nobel Prize in Physiology or Medicine

SMALLER THAN LIFE

In the early twentieth century, viruses were shown to be noncellular in structure, consisting only of nucleic acid—that is, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)—wrapped within a protective protein

ONCOGENIC VIRUSES



(Electronic Illustrators Group)

covering. Viruses are immobile and inactive outside cells. They can function only within a host cell, and then only to reproduce and destroy the host cell. They are intracellular parasites, always invading cells, robbing cellular resources, reproducing, and destroying. Because of the noncellular structure and unusual nature of viruses, there is considerable debate over their classification as a life-form.

Once a virus is carried by air or fluid to the cells of a given host species, it may be only by chance that it physically contacts a cell. Once physical contact is made, a rapid series of chemical reactions between the virus protein covering and the cell membrane triggers the injection of the viral DNA or RNA into the cell. Once it is inside the host cell, the viral nucleic acid can follow two possible infection routes, depending upon cellular conditions and certain enzymes encoded by the viral nucleic acid: the lysogenic cycle and the lytic cycle. In the lysogenic cycle, the viral nucleic acid encodes a repressor enzyme that prevents viral reproduction, followed by the viral DNA inserting itself into the host cell DNA and lying dormant indefinitely. During cellular stress, the dormant virus can enter the lytic cycle. In the lytic cycle, the viral nucleic acid commandeers the cell's resources, which are directed to synthesize up to several thousand new viruses, each of which can infect new cells.

Viral Chicken Cancer

In 1909, Peyton Rous began research in pathology at the Rockefeller Institute for Medicinal Research (now Rockefeller University) in New York City. Rous was interested in the physiology of cancer within mammals and birds. He discovered a type of connective tissue cancer in chickens, later called Rous sarcoma, which causes gross hypertrophy (enlargement) of certain organs, particularly the liver and gallbladder. Rous sarcoma eventually is fatal.

In his experiments, Rous grafted sarcoma tumor cells from diseased hens to healthy hens; the healthy hens contracted the disease. He then cultivated hen tumor cells, extracted a fluid not containing cells, and injected this fluid into healthy hens. Again, the healthy hens contracted the disease. His results pointed toward one possible conclusion: Some noncellular component of the tumor extract was capable of producing cancer in healthy hens. The most plausible explanation was a virus. Further experiments yielded identical results.

Rous hypothesized that a Rous sarcoma virus caused this chicken sarcoma. Nevertheless, his work was derided by his peers, who unsuccessfully repeated his experiments with other species. The failure of many to accept his conclusion reflected a considerable lack of understanding of both viruses and cancer by the medical and scientific community of that time. Despite the negative reactions, Rous continued his studies of liver and gallbladder physiology.

With greater understanding of viruses during subsequent decades of the twentieth century, Rous's viral theory of cancer began to be recognized. From his studies of Rous sarcoma virus, his theory maintained that some cancers could be caused by viruses. The discovery of more tumor-causing viruses during the 1950's resulted in Rous sharing the 1966 Nobel Prize in Physiology or Medicine.

IMPACT

Rous's discovery won him the 1966 Nobel Prize in Medicine "for his discovery of tumour-inducing viruses" and, more important, paved the way for a better understanding of the origin of viruses. Viruses most likely evolved from cells because viruses are noncellular, because they must reproduce inside cells, and because they have the same genetic code as living cells. It is possible that, more than one billion years ago, a small group of genes capable only of reproduction and of manufacturing a protective protein covering escaped from a cell and temporarily existed outside cells in an inactive, dormant state. Viruses could be intercellular messengers whose functions went awry.

The Rous sarcoma virus was the first of many oncogenic viruses discovered during the twentieth century. Several of these viruses can, in addition to causing cancer, also cause various other diseases. For example, the Epstein-Barr virus can cause a rare type of lymph node cancer called Burkitt's lymphoma. This virus also causes infectious mononucleosis and may be responsible for certain cases of chronic fatigue. Similarly, the hepatitis B virus can cause liver cancer. Hepatitis is also a noncancerous liver disease that afflicts about two hundred million people worldwide every year.

In the 1960's, molecular virologists Howard M. Temin, Renato Dulbecco, and David Baltimore demonstrated that RNA retroviruses, such as Rous sarcoma virus, could encode DNA from RNA using a special viral enzyme called "reverse transcriptase." This phenomenon went against established scientific dogma, which maintained that DNA encodes RNA. For their "discoveries concerning the interaction between tumour viruses and the genetic material of the cell," Baltimore, Dulbecco, Temin, and The list of such RNA retroviruses includes the notorious human immunodeficiency virus (HIV), the causative agent of acquired immunodeficiency syndrome (AIDS) in humans. While HIV causes AIDS, it does not cause cancer; instead, it destroys an individual's immune system cells such that a person's body is unable to defend itself from secondary infections, such as pneumonia and spontaneous cancers.

Much research on oncogenes and retroviruses was spurred by these early investigations, including that of Harold Varmus and J. Michael Bishop, who in 1989 won the Nobel Prize in Physiology or Medicine for their discovery of the cellular origin of retroviral oncogenes.

See also Viruses.

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—*David Wason Hollar, Jr.*

OORT CLOUD

THE SCIENCE: Jan Hendrik Oort advanced the theory that comets originate in a cloud of comets located a light-year from the Sun.

THE SCIENTISTS:

Jan Hendrik Oort (1900-1992), Dutch astronomer

Fred Whipple (1906-2004), American astronomer

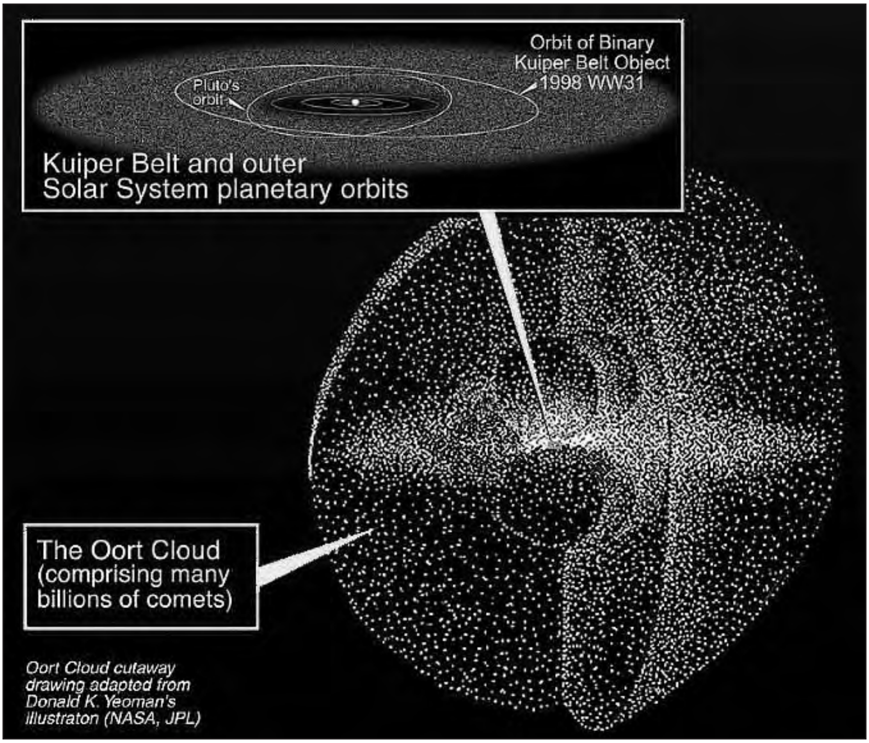
WHAT ARE COMETS?

A comet is an object consisting of a dense nucleus of frozen gases and dust. It orbits the Sun and develops a luminous halo and tail as it nears the Sun. Throughout history, the appearance of a comet has been considered a portent of disaster. When the great comet of 1066 C.E. made its appearance, William the Conqueror, claimant to the throne of England, shrewdly informed his troops that the comet signified the defeat of the English defenders; it also implied that he would become king of England. In the 1500's, scientists began to study comets. More than one hundred years later, the English astronomer Edmond Halley, a friend of Sir Isaac Newton, the English physicist and mathematician, noticed that comets appearing in 1456, 1531, 1607, and 1682 had similar orbits around the Sun and came close to the Sun approximately every seventy-six years. He concluded that these were not several comets, but rather one comet with a period of revolution around the Sun of seventy-six years. In 1705, he predicted that this comet would appear again in 1758. It arrived as scheduled and was christened Halley's comet in his honor.

As technology improved, additional information about comets was gathered: the shapes of their orbits, the directions in which they orbit the Sun, why they have two tails, and why the tails always point away from the Sun. Fred Whipple first described comets as dirty snowballs in 1949. They are composed of ices of ammonia, methane, and other compounds. Mixed in with ices are pieces of rocky material. Each time a comet comes close to the Sun, the heat from the Sun melts some of the icy material. This forms an atmosphere around the comet body, known as a "coma," that may be tens of kilometers in diameter. The solar wind, which is composed of gases expelled by the Sun at high speeds, pushes these gases away from the coma to form one of the comet's tails. Light pressure from the Sun forms the other tail by pushing dust matter away from the coma. This explains why the tails always point away from the Sun.

With the melting and vaporizing of its ices, the comet loses some of its mass each time it passes by the Sun. At a loss of one-millionth of its mass per orbit, Halley's comet would disappear in 76 million years. There are also objects that orbit the Sun that may be burned-out comets, because once the ices melt, most of the rocky material remains.

The length of a comet's orbital period (the time it takes to orbit the Sun) is used to classify it. Long-period comets have a period greater than two hundred years and short-period comets less than two hundred years. Short-period comets were once long-period comets, but the gravitational attraction of the outer planets, such as Jupiter, has altered their orbits.



An artist's rendition showing the Oort Cloud and the Kuiper Belt in relation to the rest of the solar system. (NASA/JPL)

Long-period comets have greatly elongated elliptical orbits that take them far beyond the orbit of Pluto. Even the orbit of Halley's comet, with a period of only seventy-six years, extends beyond the orbit of Neptune.

Where Do Comets Come From?

In 1950, the Dutch astronomer Jan Hendrik Oort first described the source of comets. He reasoned that comets originate in a cloud of comets located a light-year from the Sun. The cloud, he hypothesized, would be a roughly spherical shell and billions of kilometers thick. The number of comets in this group could be in the trillions and their combined mass would be similar to that of the Sun. The individual orbits would be elliptical but not as elongated as those of comets that closely approach the Sun. The orbital period for a comet at a distance of a light-year is 15 million years. Its temperature would be close to absolute zero, the lowest possible temperature, since it receives very little energy from the Sun.

To verify this theory, the known facts about comets can be checked. A comet in the Oort Cloud is moving around the Sun at a velocity of several meters per second. (By comparison, an object such as Earth orbits the Sun at tens of kilometers per second.) If a comet comes close to another comet, the two will gravitationally interact and will change orbital direction and speed. If a comet slows down, it will move closer to the Sun, and its orbit

SEDNA: OORT CLOUD OBJECT OR TENTH PLANET?

On March 15, 2004, a team of three astronomers—Mike Brown of the California Institute of Technology, Chad Trujillo of the Gemini Observatory, and David Rabinowitz at Yale University—announced the discovery of the most distant object known to orbit the Sun. Well beyond the orbit of Pluto, the object, 2003 VB12, was nicknamed Sedna for the Inuit sea goddess believed to live in the frigid ocean depths. Although Sedna is much closer to the solar system than Oort Cloud should be, it suggests the existence of an "inner" Oort Cloud, and astronomers expect that many more objects like it will be discovered in the same region. Sedna may well be the first Oort Cloud object to be identified, making the Oort Cloud a reality, not a theory.

Sedna is no theory, however: The infrared space telescope Spitzer has located it at about 90 astronomical units from the Sun (90 times the distance between the Sun and Earth), with an orbit inclined about 11.9 degrees from ecliptic plane, the plane in which the eight major planets orbit the Sun. Sedna is somewhat smaller than Pluto—about 1,800 kilometers in diameter—and takes approximately 10,500 years to orbit the Sun. Its highly elliptical orbit might have been influenced during the formation of the solar system by the gravity of a nearby star. Strangely, Sedna is red, almost as red as Mars, and seems to lack surficial water and methane ices. In 2005, its rotational speed was calculated to be about 10 hours. Currently it is moving closer to the Sun and should reach 76 astronomical units by the twenty-second century, then begin to recede back toward the inner Oort Cloud.

One question astronomers are debating is whether Sedna can be called a true "planet." In fact, there is no agreed-upon definition of a planet. The definitional problem has become more pressing with discoveries of more and more individual objects in large populations of bodies—the asteroid belt, the Kuiper Belt, the inner Oort Cloud, and the Oort Cloud proper—through increasingly sophisticated space telescopes. Some of these objects—such as the asteroid Ceres and the Kuiper Belt object Quaoar—were initially thought to be planets. Many astronomers now think that even Pluto is not a true planet, but simply the largest known Kuiper Belt object. Likewise, they believe that Sedna will soon be joined by the discovery of many other "inner Oort Cloud" objects.

will become elongated. More gravitational encounters with the outer planets will change its orbit even more, and it will move closer still. At this point, it would be recognized as a long-period comet. Additional encounters with Jupiter will alter the orbit to that of a short-period comet.

In the inner solar system, comets burn out over time and are replaced by new comets from the Oort Cloud. Only several comets per year need to start their journey toward the inner solar system to keep it supplied with comets.

IMPACT

The idea of the Oort Cloud as the source of the solar system's comets fits well with the accepted model of the origin of the solar system. In this model, a huge cloud of dust and gas condensed to form the Sun and planets. An intermediate stage was the formation of "planetesimals," smaller lumps of matter that came together to form planets. Some of these planetesimals were thrown away from the Sun by gravitational interaction with other planetesimals. They escaped totally or became part of the Oort Cloud.

The Oort Cloud may have played a role in the periodic mass extinctions that have occurred on Earth. Sixty-five million years ago, the dinosaurs and many other creatures became extinct. The impact of a 10-kilometer-diameter asteroid or comet may have been the cause. Other mass extinctions have occurred at roughly 26-million-year intervals. An unknown planet with a 26-million-year period of revolution may pass through the Oort Cloud and cause many comets to start their journeys toward the inner solar system. Some could collide with Earth and cause mass extinctions by drastically changing the climate of Earth.

See also Cassini-Huygens Mission; Galileo Mission; Halley's Comet; Kepler's Laws of Planetary Motion; Nebular Hypothesis; Planetary Formation; Pluto; Saturn's Rings; Solar Wind; Stellar Evolution; Van Allen Radiation Belts; Voyager Missions.

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—*Stephen J. Shulik*

OPTICS

THE SCIENCE: The field of optics began in earnest in the early eighteenth century, when Newton began his study of light while still a student at Cambridge. His interest in problems with lens telescopes led him to construct the first reflecting telescope in 1668 and to study the spectrum produced by lenses and prisms. His *Optics* (1704) laid the foundations for the field.

THE SCIENTISTS:

Sir Isaac Newton (1642-1727), English physicist and mathematician

Johannes Kepler (1571-1630), German astronomer who founded modern optics

René Descartes (1596-1650), French philosopher and mathematician

Robert Hooke (1635-1703), first Curator of Experiments in the Royal Society of London

Christiaan Huygens (1629-1695), Dutch mathematical physicist

NEWTON AND HIS GIANTS

Sir Isaac Newton once famously said that if he saw farther than others, it was because he "stood on the shoulders of giants." As a student at Cambridge University from 1661 to 1665, he studied carefully the work of Johannes Kepler, René Descartes, and other giants of the scientific revolution. This led him to a series of optical experiments and a 1672 paper on a new theory of color delivered to the Royal Society of London. A long series of disputes followed, culminating with the publication of Newton's *Opticks* (1704; *Optics*, 1706) by the Royal Society.

At Cambridge, Newton was introduced to optics by reading Kepler's *Dioptrice* (1611; ray optics), which initiated the modern study of optics.

Newton also read Descartes's *Dioptrique* (1637; ray optics), which offered a mechanical theory of light as an instantaneous transmission of pressure transmitted by a luminous medium made up of moving particles. Descartes had claimed that the bending of light in refraction was caused by an increase in the speed of particles as they pass into a denser medium. He proposed that the colors produced in refraction were caused by particle rotations, faster for red and slower for blue. Thus, color was a modification of the pure homogeneous white light coming from these rotations. Newton's teacher at Cambridge, Isaac Barrow, gave lectures on optics in 1664, which also suggested that colors result from modifications of white light.

Newton became interested in colors caused by refraction in lenses when he used lenses to construct a telescope, producing images surrounded by colored fringes. He then obtained a prism to study how colors are formed from white light by refraction. He passed sunlight from a small hole in the window shades through his prism and refracted it to the opposite wall. When he saw that the length of the resulting spectrum was much longer than its breadth, he began to develop the idea that white light is not homo-

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geneous but is a mixture of colors, and that the elongation of the spectrum comes from different colors refracting at different angles. In later years, Newton claimed that his theory of colors, along with his formulation of the calculus and the law of universal gravitation, were all conceived during the plague years of 1665 and 1666, when students were sent home from school for nearly two years.

The Reflecting Telescope

After returning to Cambridge as a fellow, Newton constructed the first reflecting telescope, in 1668, to avoid the problem of image distortion due to refraction. The telescope was only 6 inches long, but it magnified forty times by focusing light with a concave mirror instead of a lens. An urgent request soon came from the Royal Society to examine the telescope, so Newton constructed an improved 9-inch version and sent it to London; the response was enthusiastic. The Royal Society asked for a written account of his invention, leading to Newton's reply, his first scientific paper, "New Theory About Light and Colours," published in the *Philosophical Transactions* of the Royal Society in March of 1672. Although this paper led to his election as a fellow of the Royal Society, it also gave rise to an extended controversy, including ten critical letters from half a dozen authors in the *Philosophical Transactions* and eleven replies by Newton. Robert Hooke led the opposition, which rejected the heterogeneous nature of light and preferred various forms of the wave theory that had been developed by Christiaan Huygens.

Soon Newton became impatient with the philosophical and hypothetical arguments of his critics and insisted that science should be primarily mathematical and experimental. After about four years, he "retreated" for about a decade to do research and teach. In 1684 he was finally persuaded by astronomer Edmond Halley to publish his laws of motion and universal gravitation, resulting in the masterpiece *Philosophiae naturalis principia mathematica* (1687; *The Mathematical Principles of Natural Philosophy*, 1729; best known as the *Principia*, 1848), which resolved the most difficult problems of the Scientific Revolution and established Newton's premiere reputation.

Newton's *Optics*

After Hooke died in 1703, Newton was elected president of the Royal Society. A year later he published the *Optics*, written in English for a more receptive audience, which now recognized the value of his experimental and mathematical arguments. *Optics* described his many experiments on light. His separation of white light with a prism associated quantitative angles of refraction with each of the colors, which he rather arbitrarily designated as seven: red, orange, yellow, green, blue, indigo, and violet. He gave the first complete account of the rainbow, and explained the color of a given object as the combination of colors it reflects after absorbing all others.

While the *Principia* had proved Newton a brilliant mathematician, the easier-to-read *Optics* revealed his skill as an experimenter. In book one of three books in the *Optics*, he describes his experiments with the spectrum. A crucial experiment demonstrated that each color is a pure component of white light by passing a single color in the spectrum through a hole and showing that a second prism refracted it the same amount without changing its color. Another experiment passed the dispersed rays of the spectrum from one prism through an inverted second prism that recombined these rays to form white light again.

In book two he examines the colored rings formed when a lens is pressed against a flat pane of glass, first studied by Hooke but called "Newton rings." Careful measurements showed that the gap between the lens and the glass increases uniformly with each ring so that the "interval of the fits" is related to the colors. Theorizing these "fits" was as close as he could get to a determination of the wavelength of light, but he avoided any such hypothesis. In book three he discusses the 1665 experiments of astronomer Francesco Maria Grimaldi, which produced colored fringes when white light passed through two successive slits (diffraction). Newton attempts to explain this result in terms of attractive forces rather than waves. His preference for the particle theory of light led him to conclude that light travels faster when it passes into denser media. However, the more hypothetical issues about the nature of light were mostly relegated to the sixteen "queries" at the end of the 1704 edition of the *Optics*.

IMPACT

Sir Isaac Newton's *Optics* established a more experimental and quantitative style in science for the eighteenth century, which contrasted with the earlier, more speculative, hypothetical approach. However, in the 1706 Latin edition of the *Optics*, he added new queries that suggested the particle theory of light, and the 1717 and 1730 English editions expanded on these queries. Newton's particle theory influenced other scientists, delaying the acceptance of the wave theory for nearly a century. In the nineteenth century the wavelength of light was finally measured, and light was shown to slow down in denser media as predicted by the wave theory.

Newton's early ambivalence between particle and wave theories is reflected in modern quantum theory, which attributes both particle and wave properties to light.

The careful reasoning and experimental approach of the *Optics* became a paradigm for the eighteenth century Enlightenment, including its central metaphor of light. Newton's work was widely celebrated in literature and poetry, and he was considered a prophet for future progress. The laws of nature, both of motion and of light, soon came to be seen as a reflection of order and beauty, and the spectrum became a new symbol for the descriptive poet. Where the *Principia* had been viewed as cold philosophy, the *Optics* opened up the literary imagination to light and color, demanding the muse.

See also Diffraction; Gravitation: Newton; Lasers; Magnetism; Spectroscopy; Speed of Light; Wave-Particle Duality of Light.

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—Joseph L. Spradley

OSMOSIS

THE SCIENCE: Known primarily for his work on the nature of electricity, Jean-Antoine Nollet was the first to demonstrate the process by which a solvent passed selectively through a cell membrane. René Henri Dutrochet later termed this process osmosis.

THE SCIENTISTS:

Jean-Antoine Nollet (1700-1770), Carthusian abbot noted for his work in experimental physics and electricity

Benjamin Franklin (1706-1790), American statesman and naturalist who demonstrated lightning to be a form of electricity

Henri Dutrochet (1776-1847), French physician and naturalist who coined the term osmosis

Wilhelm Pfeffer (1845-1920), German botanist who explained the movement of liquids in plants

Jacobus Henricus van't Hoff (1852-1911), Dutch chemist who described the mathematics of diffusion and osmosis

From Electrical Flow to Water Flow

In the 1750's, the Carthusian abbot Jean-Antoine Nollet adapted his interest in physics, particularly electrical flow, to crude experimentation in biological systems. He was aware of German experiments observing the effects of electricity on the flow of water. Water in a thin capillary tube would simply drip from the open end. However, if electricity was applied to the tube, the water would flow in a constant stream. Nollet began a series of experiments in which he measured the rate of water transpiration in plants (and as well, in animals) either in the presence, or in the absence of electricity, noting an increase in rate if the organism was electrified.

Nollet also carried out the first experiments in which what is now known as the principle of osmosis was discovered. He prepared a vessel containing alcohol ("spirits of wine") and enclosed the vessel within a piece of pig's bladder. After placing the covered vessel into a larger container filled with water, Nollet observed that only the water would transverse the bladder wall. In some experiments, the bladder would expand until it burst. In contrast, the alcohol did not transverse the bladder. This earliest known experiment demonstrating osmosis would have more immediate application in experimental physics. In addition to the principle of what would later be called osmosis, Nollet had demonstrated the "semipermeability" or "selective permeability" of the bladder wall, although the term "semipermeable" would not be applied for about 150 years.

Dutrochet and Cell Membranes

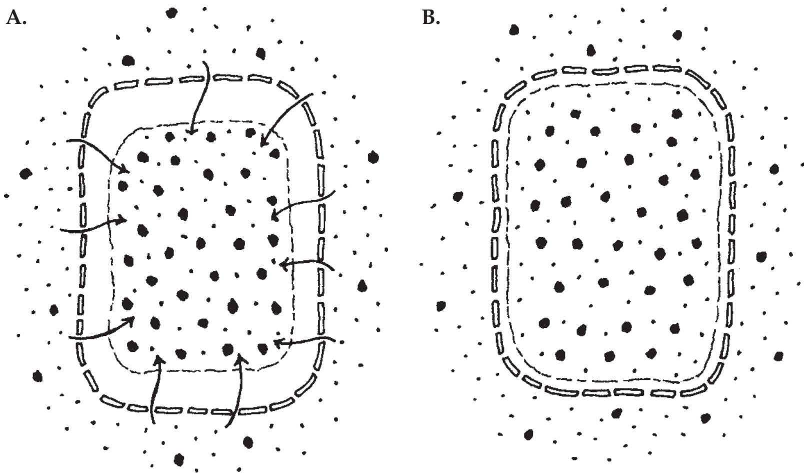
Although Nollet had utilized a biological membrane layer, the pig's bladder, the discovery would not be immediately applied to cell theory. In the early decades of the nineteenth century, Henri Dutrochet became aware of his countryman's earlier work and attempted to apply the same principle to movement of fluids across cell membranes. While studying both plant and animal cells with the microscope, Dutrochet observed the movement of (solvent) water through the cell membrane, a process he termed osmosis. Dutrochet further observed the direction of solvent flow was determined by the nature of the solvent, such as a function of the quantity of salt dissolved in the water, and was not determined by the nature of the membrane itself.

Dutrochet tested his ideas by building an osmometer, an instrument capable of measuring the movement of water across an artificial barrier. Dutrochet referred to the movement of water across the barrier as "endosmosis," while the reverse movement was termed "exosmosis."

IMPACT

Although the idea of the cell membrane as a barrier capable of regulating osmosis was a concept inimical to cell theory—and thus was beyond immediate application by Nollet—Nollet's discovery nevertheless represented one of the first in the developing area of experimental physics. Furthermore, once a similar process was found to occur in conjunction with biological membranes, applications in several scientific fields quickly developed. Wilhelm Pfeffer explained a role for osmotic pressure in the action of fluids within plant vessels.

THE PROCESS OF OSMOSIS



A. In the process of osmosis, water (small dots) outside the plant cell moves from a region of greater concentration, outside, across the cell wall and the cell membrane to a region of less concentration initially occupied by more solutes (large dots) inside the cell. B. The cell's uptake of water increases the volume of the cytoplasm and presses the cell membrane against the wall. (Kimberly L. Dawson Kurnizki)

JEAN-ANTOINE NOLLET: SPARE THE ROD

Jean-Antoine Nollet was born into a peasant family November 19, 1700, in Pimpré, Oise, France. After training for the priesthood, he was appointed to a deaconship (1728) and eventually served as abbot of the Grand Convent of the Carthusians in Paris. Although trained primarily in theology, Abbé Nollet was better known for his work in experimental physics. He was a member of both the Royal Society in London and the Paris Academy of Science, and he was appointed as a professor of experimental physics at the University of Paris. He worked for the Duke of Savoy in Turin, Italy, and was Physics Teacher to the Royal Children under King Louis XV of France.

Much of Nollet's work centered on the nature of electricity, which he viewed as a flow of matter taking place between charged bodies. In 1748, he invented the electrometer, an instrument capable of detecting and measuring electric charges. He also demonstrated the flow of electricity in a form of parlor trick: An electric charge was allowed to pass through a row of men, resulting in a simultaneous jump by the participants.

Nollet's religious views, as well as the questions dealing with the nature of electricity, became the basis for conflict with the American statesman and naturalist Benjamin Franklin. During the 1740's, Franklin began a series of experiments on the nature of electricity, culminating with recognition of the concept of "conservation of charge." During the summer of 1752, he conducted what posterity has called his "kite experiment," demonstrating that lightning represents a form of electricity. As a result, he invented the lightning rod, a device to protect buildings from fire resulting from lightning strikes.

Nollet, perhaps jealous of an "amateur's" discovery (or possibly zealously guarding his religious views), argued that the lightning rod was an "offense to God": Lightning originated from the heavens, so by "interfering with an instrument of God" Franklin was in effect acting against God. Although the lightning rod was quickly adopted through both Europe and the rest of the western world, the controversy resulted in harsh words between Franklin and Nollet. Ironically, Nollet's recognition of the importance of the presence points on the ends of electrical conductors led to the lightning rod's modern design.

Finally, the mathematics of osmosis and chemical equilibrium was worked out by Jacobus Henricus van't Hoff, the result of which was his being awarded the first Nobel Prize in Chemistry in 1901. Van't Hoff referred to the principle behind Nollet's bladder wall as "semipermeable," the first use of that term in conjunction with cellular membranes.

See also Cell Theory.

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—*Richard Adler*

OVA TRANSFER

THE SCIENCE: An obstetrical team transferred an embryo from one woman to another, who carried it to term and delivered a healthy baby boy.

THE SCIENTISTS:
John Edmond Buster (b. 1941) and
Maria Bustillo, American physicians

ARTIFICIAL IMPREGNATION

Artificial insemination and embryo transplantation have been practiced in the U.S. cattle industry and in other situations involving animals since the last decade of the nineteenth century. Such genetic engineering has enabled prize horses and bulls to sire literally thousands of offspring, thereby contributing their special genes to many more offspring than animals mating conventionally could ever produce.

Knowing the success of such animal experiments, physicians sought ways to make it possible for women who were infertile or whose mates were infertile to bear children. The best hope seemed to be through in vitro fertilization, a process that involves extracting eggs (ova) from the ovaries when the ova are ripe, carefully washing the tiny eggs (at that point, four thousandths of an inch across), and placing them in a sterile petri dish into which donor sperm in a nutrient solution is introduced. The petri dish is placed in an incubator at precisely the temperature of the human body. The dish remains in the incubator for twenty-four hours, at which time, if some of the eggs are fertilized, they will begin to divide, indicating a viable embryo. If this happens, the resulting embryo is implanted in the woman's uterus, where it may face rejection.

Baby X: Male

In August, 1983, John Edmond Buster, an obstetrician at the Harbor-UCLA Medical Center in Torrance, California, announced that the first experimental, nonsurgical ova transplants attempted by himself, Maria Bustillo, and a medical team of six others had been successful in two of eighteen such transfers attempted. Two women were pregnant with embryos produced from other women's ova and were carrying the fetuses thus produced.

Buster protected the privacy of these women, who remained anonymous even after the first delivered a healthy male infant at California's Long Beach Memorial Hospital in January, 1984. At a press conference held on February 3, 1984, Buster announced the birth of the first child ever produced by ova transfer, by a woman in her thirties with an eight-year history of infertility. Buster announced at his press conference that a second birth was imminent. On March 24, at a meeting of the Society for Gynecological Investigation in San Francisco, Buster revealed that a second ova transfer had resulted some ten days earlier in the birth of a healthy baby girl to a couple in their middle thirties, who were supplied with the egg by a married woman in her mid-twenties.

In both cases, the method employed to achieve pregnancy differed from in vitro fertilization in that a viable embryo was produced within one woman's uterus and, after five days, when it consisted of only eight or ten cells, was taken out of her uterus and tested for viability. When viability was established, the embryo was transferred to the recipient's uterus.

The entire procedure occurs quickly in a doctor's office, without anesthetic. If a fertilized ovum clings to the walls of the host uterus, it should continue to develop and—barring a miscarriage—result in the recipient's giving birth to a child that is not biologically hers.

In vitro fertilization enables a woman with blocked Fallopian tubes to receive her own egg, fertilized by her partner, and to give birth to her own offspring. The ova transplant, however, places one woman's embryo in another woman's body, where it grows to the moment of its delivery. The woman who delivers the child is not its biological mother, although her husband, as in both of these early cases, is usually its biological father.

The women most interested in this method of impregnation often have genetic defects they do not wish to transmit to their own offspring. Others have not been able to conceive because of hormonal problems or defective ovaries, which make it impossible for them to supply the egg that pregnancy requires. Such women wish to experience the carrying and bearing of a child. Biological circumstances, however, have made them incapable of conceiving. In other circumstances, a woman who can conceive but who, for any one of various biological or physiological reasons, cannot carry a child to term can have her fertilized ova transferred to a carrier who can deliver her child. Such a woman can claim that the child is biologically her own.

For ova transfers to work, the hormonal cycles of the recipient and donor must be carefully coordinated. Donors and recipients must also have the same blood type, Rh factor, and hair and eye color.

Impact

Ova transfer was controversial in 1984, and the controversy continues. The Roman Catholic Church has objected to the method because the fertilizing sperm is usually obtained through masturbation. In addition, some donor mothers have sought custody of or visiting rights to the children born from their eggs; courts have usually denied such demands if the conditions of the transfer have been clearly defined in a contract.

Other examples of ethical and legal concerns abound. In 1984, a well-to-do couple who had frozen some embryos were killed in an airplane crash. The question arose whether their embryos should be implanted in hosts and carried to term so that they could inherit the couple's considerable wealth. In another case, Mary Davis Stowe won custody of seven of her own embryos, which had been fertilized by her former husband, Junior Davis, before their divorce and her remarriage. A court awarded her custody of the embryos, which she planned to donate to infertile couples; her husband, however, appealed the decision to a higher court.

See also In Vitro Fertilization.

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—*R. Baird Shuman*

OXYGEN

THE SCIENCE: By heating a brick-red compound of mercury, Priestley produced a gas whose properties of enhanced support of combustion and animal respiration led him to believe that he had discovered an amazing new substance that he called "dephlogisticated air" (oxygen).

THE SCIENTISTS:

Joseph Priestley (1733-1804), English natural philosopher and Unitarian minister who was early modern chemistry's most prolific discoverer of new gases

Carl Wilhelm Scheele (1742-1786), Swedish chemist who, independently of Priestley, discovered oxygen (which he called "fire air")

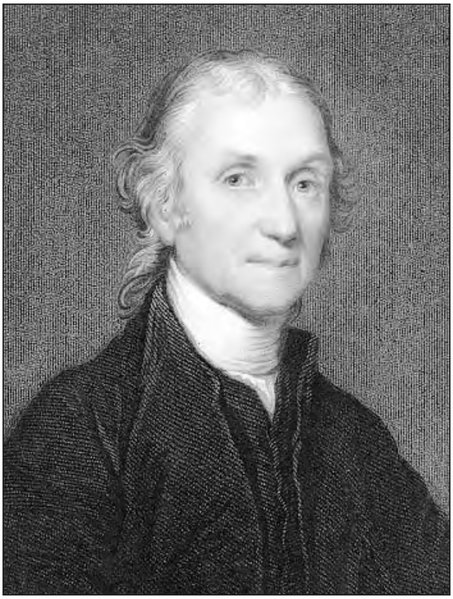
Henry Cavendish (1731-1810), English physicist and chemist who discovered "inflammable air" (hydrogen) and the composition of water

Antoine-Laurent Lavoisier (1743-1794), French chemist who made oxygen the central element of his new chemistry

STUDYING "AIRS"

Joseph Priestley came late to the study of gases (which he called "airs"), and he approached their study as an amateur rather than as a professional. After discovering that "fixed air" (carbon dioxide) formed, when dissolved in water, an effervescent liquid now known as soda water, he studied an "inflammable air" that Henry Cavendish had discovered, but Priestley confused it with other flammable airs.

Following a suggestion of Cavendish, Priestley began collecting other airs in a pneumatic trough over mercury rather than water, and he was thus able to isolate several new gases whose solubility in water had prevented previous chemists from seeing them. One of the first such gases he found was "nitrous air" (nitric oxide), which he prepared by combining "spirit of nitre" (nitric acid) with various metals. This substance provided him with a method for testing the "goodness" of common air for combustion and respiration. The quantitative measure of this goodness was the volume of a brown gas (nitrogen dioxide) that formed when he reacted nitrous air with the air in question.



Joseph Priestley. (Library of Congress)

After discovering an "acid air" (hydrogen chloride), Priestley delivered a paper in 1772 about his "Observations on Different Kinds of Airs." These discoveries, along with his liberal social and religious views, brought him to the attention of Lord Shelburne (later the first marquis of Landsdowne and England's prime minister), who offered him a position as his companion and librarian. The years Priestley spent in Shelburne's service proved to be the most productive of his life. He continued his studies of new gases at the lord's summer estate at Calne, near Bowood, in Wiltshire. Here he collected over mercury an "alkaline air" (ammonia) that he obtained by heating a mixture of sal ammoniac (ammonium chloride) and quicklime (calcium oxide).

Fire Air

During this early period in Lord Shelburne's employ, Priestley made the greatest discovery of his life, though, in retrospect, he realized that he had actually prepared the new gas earlier, in 1771 and 1772, but had not recognized it because he then believed that nothing was purer than ordinary air. Around the same time Carl Scheele in Sweden prepared a gas that he called "fire air" (oxygen), but his results were not published until 1777. In subsequent accounts Priestley claimed that his discovery of "dephlogisticated air" (oxygen) was the result of chance, not planning.

He had purchased a large magnifying lens and was using it to concentrate the Sun's heat on a variety of substances to see what gases were produced. A friend had given him an interesting brick-red substance, *mercurius calcinatus per se*, or "red calx of mercury" (mercuric oxide), and on August 1, 1774, Priestley focused sunlight on this red powder and observed that globules of liquid mercury and a colorless gas were generated. He collected this gas in an inverted vessel in a pneumatic trough filled with mercury and then studied its fascinating properties. It was not very soluble in water, but a candle flame burned faster and brighter in it than in common air. Intially he thought that the gas might be "dephlogisticated ni-

SOMETHING IN THE AIR: THE PHLOGISTON THEORY

In the seventeenth and eighteenth centuries, chemistry was dominated by the idea that air was a single element, one of the four Greek elements (the others being earth, water, and fire). British chemists from Robert Boyle through Stephen Hales and Joseph Black had made "pneumatic chemistry"—manipulating and measuring "air" in its various states of purity—practically a national specialty. Chemical research was also carried on around the organizing concept of the phlogiston theory put forward by the German Georg Stahl in 1723.

Phlogiston was believed to be the element of fire, or its principle, which caused inflammability when present in a body. It was considered central to most chemical reactions. Combustion was explained as a body releasing its phlogiston. In this dual context of pneumatic chemistry and phlogiston theory, Henry Cavendish presented his study of "factitious airs," or gases contained in bodies. Most important, he isolated and identified "inflammable air," now called hydrogen. Recognizing the explosive nature of "inflammable air," Cavendish went on to identify it as phlogiston itself. He cannot be said to have discovered hydrogen, as others had separated it before him, and he did not specifically claim its discovery.

Antoine-Laurent Lavoisier's anti-phlogiston explanation was indicative of a revolution in chemistry that he was leading on the Continent. Lavoisier had met Joseph Priestley during his trip to Paris and learned about oxygen. When Lavoisier weighed the product of calcination (oxidation in the new terminology), there was a weight gain in the calx. He offered the explanation that something was taken up in the process, rather than phlogiston being given off. This "something" he identified as oxygen—and thereby created a new chemistry. Cavendish recognized that Lavoisier's oxygen-based chemistry was essentially equivalent to a phlogiston-based chemistry, but he rejected the new ideas to the end of his life. "It seems," he wrote, "the phaenomena of nature might be explained very well on this principle, without the help of phlogiston; . . . but as the commonly received principle of phlogiston explains all phaenomena, at least as well as Mr Lavoisier's, I have adhered to that." In 1787, Lavoisier introduced his new chemistry in his *Nomenclature chimique*, and fully elaborated it in 1789 in *Traité élémentaire de chimie*. The phlogiston theory went up in smoke.

trous air" (nitrous oxide), a gas he had earlier studied, but additional research showed that it behaved far differently from this other gas.

In the fall of 1774, Priestley accompanied Lord Shelburne on a trip to continental Europe, including a stay in Paris, where he met Antoine-Laurent Lavoisier and told him about his experiments with the gas generated from red calx of mercury. This meeting proved to be fortuitous for Lavoisier and the future of chemistry: Lavoisier, now considered the father of modern chemistry, would eventually make this elemental gas, which he named oxygen, the centerpiece of his reform of chemistry.

Upon his return from this continental trip, Priestley discovered additional wonderful properties of dephlogisticated air, and some scholars date his effective discovery of oxygen to March, 1775, because it was then that he recognized it as much better than ordinary air. The test with two mice was particularly significant. He found that a mouse confined in two ounces of the new air lived twice as long as a mouse confined in two ounces of ordinary air. He even experimented on himself, experiencing a feeling of exhilaration when he breathed in the gas.

Because he was an ardent believer in the phlogiston theory, one of whose pivotal doctrines was that combustible substances contained a weightless material, phlogiston, Priestley named his new gas "dephlogisticated air," since he considered it to be common air that had been deprived of its phlogiston and thus able to readily absorb phlogiston escaping from burning materials.

During his later career, in England and America, Priestley continued to believe in the superiority of the phlogiston theory until his death in Pennsylvania in 1804. On August 1, 1874, Priestley's great-grandson and many American chemists gathered at his gravesite to commemorate the centennial of his discovery of oxygen. This meeting proved to be the beginning of what came to be called the American Chemical Society.

IMPACT

It is a central irony of Priestley's career that the discovery he hoped would buttress the phlogiston theory ended up, in the hands of Lavoisier, totally undermining it. Besides this ironic significance, his work on oxygen and several other gases contributed to solving one of the chief chemical problems of the time: the role of gases in combustion, calcination, the respiration of plants and animals, and the composition of common air. Because of his discoveries, some scholars have called him the father of pneumatic chemistry, the chemistry of gases. The test that he devised for the goodness of air has led to his designation as the father of eudiometry, the science of measuring air's purity. Medical doctors have honored him because he was prophetic in his suggestion that oxygen be investigated for its potential to heal diseased lungs.

Priestley's "discovery" of oxygen has not been without controversy, because Scheele actually prepared it prior to Priestley (though he did not publish his work until after Priestley), and because Lavoisier, who prepared it after Priestley, actually understood oxygen much better than either Priestley or Scheele. Furthermore, both Priestley and Scheele, as phlogistonists, interpreted their results in terms of a theory whose deficiencies had become obvious to Lavoisier and many others. Nevertheless, Priestley did bring an enlightened reason to a new intellectual territory, the realm of different kinds of gaseous substances, and in effect became the Columbus of this "new world" of chemistry.

See also Carbon Dioxide; Definite Proportions Law; Isotopes; Periodic Table of Elements; Photosynthesis; Water.

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—*Robert J. Paradowski*

OZONE HOLE

The Science: Despite efforts by scientists and the governments of 175 nations, the annual ozone hole covered a record 10.5 million square miles (27.3 million square kilometers).

THE SCIENTIST:

Jonathan Shanklin, senior scientific officer for the Meteorological and Ozone Monitoring Unit of the British Antarctic Survey

THE SURPRISE OF THE CENTURY

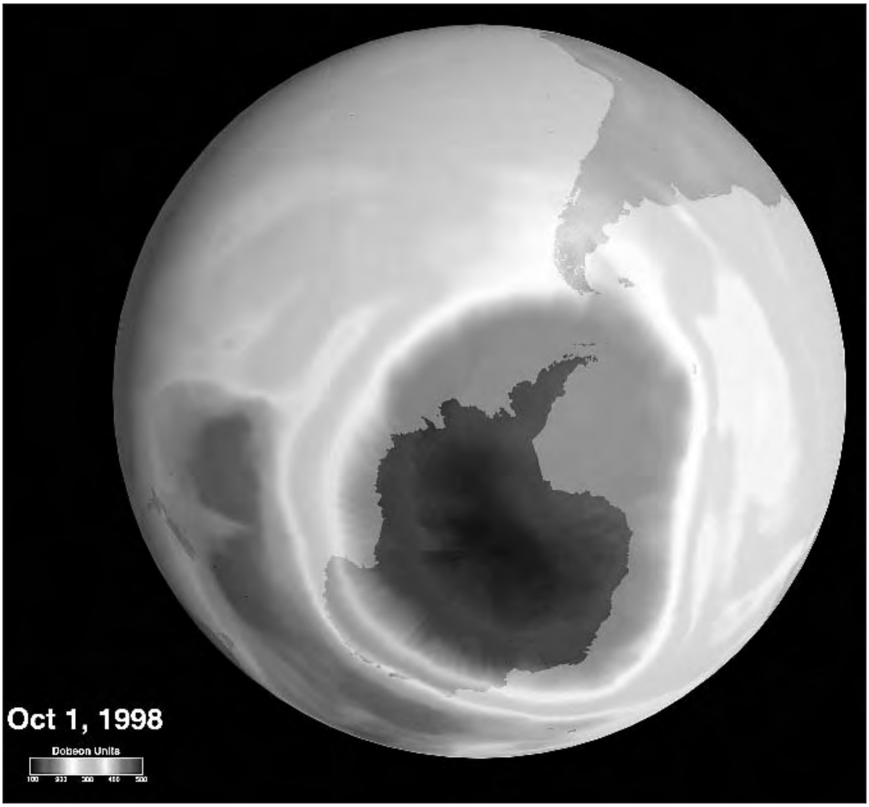
As disturbing as scientists found 1998's record-size ozone hole, they were far more alarmed by a 1985 paper published in the scholarly journal *Nature*. The British Antarctic Survey's team of scientists had noticed a regular springtime decline in ozone concentration since 1977, and the losses increased to 30 percent of the total by October, 1984. Three scientists from the team announced and defined the ozone hole for the scientific community. No mathematical models had predicted the magnitude of the changes their paper reported—not even for 50 to 100 years in the future. Michael H. Proffitt, the senior scientific officer for the World Meteorological Organization (WMO), stated, "That was the surprise of the century."

The ozone layer shields the Earth from dangerous ultraviolet (particularly UV-B) radiation. Problems caused when too much UV-B radiation reaches Earth's surface include increased levels of skin cancer, premature aging of the skin, cataracts, and weakening of the immune system. Phytoplankton are highly sensitive to UV-B radiation, and many species of crops show impaired growth and reproduction when subjected to high levels.

Scientists determined that the damage to the ozone layer was caused by chlorofluorocarbons (CFCs) and other ozone-depleting substances. CFCs were used as coolants in refrigerators and air conditioners (Freon), as a propellant in aerosol cans, and to produce foam for bedding and packaging. Other ozone-depleting substances include halons (used in firefighting equipment), methyl bromide (used in pesticides), and methyl chloride (a solvent used to clean electronic circuit boards and in dry cleaning). Use of CFCs in aerosol cans was banned in the United States in 1978. Following the 1985 discovery of the Antarctic ozone hole, much more serious action was taken. In 1987, a treaty called the Montreal Protocol on Substances that Deplete the Ozone Layer was adopted. Along with later amendments, it set dates for phasing out a total of 95 ozone-depleting substances.

BEAUTIFUL, LENS-SHAPED CLOUDS

A complex chemical process creates each year's Antarctic ozone hole. The ozone layer is located in the stratosphere between 6 miles (9.5 kilometers) and 18 miles (29 kilometers) above Earth's surface. Ozone is a compound consisting of three oxygen molecules. Measurements of total col-



The ozone hole over Antarctica in 1998, from satellite imagery. (NASA/GSFC)

umn ozone (the total amount above a point on Earth's surface) have been made from the ground using the Dobson spectrophotometer since the mid-1950's. In 1978, measurements were added from National Aeronautics and Space Administration (NASA) satellites using the Total Ozone Mapping Spectrometer (TOMS) system. Before ozone holes began appearing, the average ozone layer thickness was 300 to 350 Dobson units. An ozone hole (actually, a thinning) in the Antarctic is defined as an ozone column of 220 Dobson units or less. The Antarctic ozone hole is seasonal. Maximum depletions have usually been measured in late September, and the hole tends to disappear in late November or early December. During this period, monthly ozone column measurements will be 40 percent to 50 percent below pre-ozone hole (1970-1976) averages, with brief dips to 80 percent below. The 1998 record hole covered 10.5 million square miles (27.3 million square kilometers). The depth of the ozone depletion, 90 Dobson units, was the second lowest ever recorded. In addition, ozone loss was detected at the unusually high altitude of 79 miles (24 kilometers).

THE OZONE HOLE

Ozone is a molecule composed of three atoms of oxygen instead of two. At the earth's surface, it is one of the ingredients in smog. In the upper atmosphere, however, ozone forms a protective chemical shield against deadly cosmic radiation. In 1981 atmospheric scientists became alarmed when September and October (Antarctic springtime) ozone readings over an area of Antarctica the size of the continental United States registered 20 percent below normal. This drop in ozone coincided with the increased presence in the upper atmosphere of artificial chemicals called chlorofluorocarbons (CFCs), which contain chlorine, an element that destroys ozone. The chlorine is released when ultraviolet light strikes CFC molecules in the upper atmosphere. Each chlorine atom remains in the atmosphere an average of forty years, destroying tens of thousands of ozone molecules.

THE HOLE IN THE OZONE LAYER OVER ANTARCTICA, AS MEASURED IN 1987

The ozone hole began to develop over Antarctica because of the continent's extremely cold atmosphere. Polar stratospheric clouds, composed of ice particles containing water and nitrogen compounds, only occur when the air temperature drops below –112 degrees Fahrenheit (–80 degrees Celsius). These clouds occur during the Antarctic winter when the cold air circulates in a swirling pattern called the polar vortex at altitudes between 6 and 15 miles (10 to 24 km.). The clouds persist throughout the long winter without any influx of air from warmer areas. The surfaces of their ice crystals store chlorine compounds such as CFCs.

In the spring, the sun melts the ice crystals, freeing enormous amounts of chlorine to rapidly deplete the ozone layer, thus creating the ozone hole. In the summer, warm air breaks up the polar vortex and replenishes the ozone from other areas in the Southern Hemisphere. Bubbles of the ozone hole can break away, however, and drift north over populated areas. After 1987, CFC production decreased, but the ozone hole remained.

CFCs and other ozone-depleting substances are much heavier than air. It takes around two years for them to rise above Earth's surface and another three to five years to reach the ozone layer. In the winter in Antarctica, a strong westerly air circulation called the vortex allows the air inside it to become very cold, lower than minus 78° Celsius (minus 108° Fahrenheit). Only then can polar stratospheric clouds (PSCs) form. These beautiful, lens-shaped clouds—vibrant, iridescent blue and green, rimmed with pink—have a deadly side. When the Sun returns in the Antarctic spring, they provide the surface on which a chemical reaction takes place. The CFC molecules break down, releasing chlorine. One chlorine atom can break apart more than 100,000 ozone molecules before it is finally removed from the stratosphere.

Shortly after the announcement of 1998's record-size ozone hole, scientists predicted that the ozone layer would remain seriously depleted for ten to twenty years but then slowly begin to heal. By the year 2050, it would return to its pre-1970 condition. The recovery would be slower if nations did not comply with the Montreal Protocol's phase-out schedules or if climate change worsened the environment.

Impact

After the passage of the Montreal Protocol, and even after 1998's record-size ozone hole, the condition of the ozone layer remained complex and contradictory. By late 1999, CFC consumption had fallen 84 percent worldwide. However, in 2000, the ozone hole set a new record of 11.0 million square miles (28.4 million square kilometers). Shortly after this record was announced, Jonathan Shanklin, one of the three British scientists who wrote the *Nature* article announcing the ozone hole in 1985, predicted that in twenty years, the Arctic ozone hole could be as large as 2000's Antarctic hole. A hole of this size would extend over parts of Europe, North America, and Asia.

Ozone losses in the Arctic in the spring of 1995-1996, for the first time, were severe enough to be called ozone holes. Previously, ozone destruction in the Arctic had been less severe than in the Antarctic, partly because the northern stratosphere is not as cold. However, increases in greenhouse gases (such as carbon dioxide), which warm the surface of the Earth, make the stratosphere cooler so that PSCs can form and begin the ozone-destroying chemical reaction.

Another factor in the continuing depletion of the ozone layer is the increase in the level of bromine in the stratosphere. Ozone-depleting substances form bromine when they are broken apart in the stratosphere.

Bromine is fifty times deadlier to ozone than is chlorine. The Montreal Protocol requires developing countries to phase out methyl bromide. Other disturbing indicators of accelerated ozone depletion have been reported. In September, 2000, the Antarctic ozone hole stretched over Punta Arenas, Chile—the first time it had covered a city. A mini ozone hole was detected over Hokkaido, Japan, in 1996 and over the Weddell Sea, east of the Antarctic peninsula, in July, 2000. All these reports indicate that there is no room—and, more important, no time—for complacency in addressing the ozone layer problem.

See also Chlorofluorocarbons; Global Warming; Pesticide Toxicity.

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—*Glenn Ellen Starr Stilling*

PAVLOVIAN REINFORCEMENT

THE SCIENCE: The physiochemical explanation for learning was identified by Ivan Petrovich Pavlov, who investigated the phenomenon of reinforcement.

THE SCIENTIST:
Ivan Petrovich Pavlov (1849-1936), Russian physiologist

The Problem of Learning

In April, 1903, Ivan Petrovich Pavlov delivered a surprising address to an International Medical Conference in Madrid. It was thought that the noted Russian physiologist would discuss his research on digestion; instead, he described new investigations into the links between mental and physical processes. In particular, he focused on the experience that begins, maintains, or eliminates a given kind of behavior. While he did not formally name that concept until the following year, he was referring to "reinforcement," the key to understanding the physical aspects of the learning process.

Scientists interested in the concept of learning generally fell into two groups. One group, variously described as "mentalists," "vitalists," or "subjectivists," held the opinion that thoughts and emotions were not subject to physical laws and that experimental attempts to penetrate the boundary between mind and body were useless. Their opponents, generally called "monists," insisted that explanations of human behavior were to be found in the laws of physics and chemistry. Before Pavlov's work on reinforcement, however, monists lacked a clearly explainable theory and enough experimental evidence to back it up. They needed a clear approach to the problem of learning combined with ways to measure the physical reactions of healthy subjects. Pavlov provided both.

How Dogs Learn

The experimental technique Pavlov used to address learned behavior was an offshoot of his 1889 through 1897 investigations into the effect of the nervous system on digestion. In that project, which won for him the 1904 Nobel Prize in Physiology or Medicine, he diverted the duct of a dog's salivary gland (the parotid gland) to the outside of its muzzle so that the saliva could be collected from a funnel. This procedure became a major part of his research into reinforcement when he realized that the release of saliva was at least partly triggered by factors involving the brain. While doing research on the digestive system, he noticed an intriguing occurrence: When the presentation of food to a dog was regularly and closely preceded by an alerting signal such as approaching footsteps, the signal alone caused salivation. Pavlov directed preliminary investigations into that type of behavior (the conditioned reflexes) as early as 1897. Working in the well-equipped physiological laboratory of the St. Petersburg Institute of Experimental Medicine, he issued preliminary findings at Madrid in 1903 and presented formal results of his research in 1905.

IVAN PAVLOV, DOGS, AND DIGESTION

Ivan Pavlov had worked on the digestive tract before he worked on his theory of reinforcement. Pavlov perfected a surgical technique of creating a kind of separate stomach in dogs, which made it possible for investigators to monitor secretions and other activity of the digestive process. He was able to determine the function of nerves in controlling digestion. In 1888 he discovered the secretory nerves of the pancreas, and in 1889 he studied the functions of other gastric glands. His work on digestion, not reinforcement, earned him the Nobel Prize in Physiology or Medicine in 1904. It is his work on reinforcement, however, for which he is remembered.

At some point in the early 1900's, Pavlov became absorbed with the effects of the brain on learned behavior, focusing attention on what came to be known as his theory of conditioned reflexes. He realized through his digestive studies that dogs would secrete saliva and other digestive fluids *before* they actually received food—such as when the dogs heard the approach of laboratory assistants at feeding time. In one of the most famous scientific experiments ever conducted, Pavlov trained dogs to salivate at the sound of a bell, when they learned that the bell indicated that food was soon coming.

Some critics immediately dismissed his theory, claiming that Pavlov had simply given terminology to what every dog trainer already knew. Pavlov's accomplishment, however, was to demonstrate clearly that there is an explicit connection between physiological function and learned behavior. His experiment left more of a mark on psychology than it did on physiology. By showing that muscular reflexes of the nervous system could be expanded to include mental reflexes, he opened the question as to what extent human behavior is controlled by learned mental patterns and responses.


(The Nobel Foundation)

Beginning in 1918 and for several years thereafter, Pavlov studied the behavior patterns of several mentally ill patients in an attempt to treat them. He believed he could alter the behavior of the insane by removing the patient from physiological stimuli that might be considered harmful. Therefore, he treated insanity with quiet and solitude.

At the end of his career, Pavlov used his beliefs about conditioned reflexes to explore the differences between humankind and animals. He found that humans and animals shared some, but not all, reflexive responses; humans, he believed, were different from other creatures primarily because the brain and nervous system could accommodate more complicated, conditioned reflexes. He came to regard human language itself as the most advanced and complicated form of conditioned reflex.

Pavlov believed that all animals have an inborn neural capacity (the unconditioned reflex) to react to events necessary for survival (the unconditioned stimulus). For example, the sight of food normally produced a certain type and amount of salivation in a dog. As long as the dog was allowed to eat food presented to it, the unconditioned reflex endured. Eating the food reinforced the unconditioned reflex, because the act of eating maintained (excited) a neural association between the unconditioned stimulus and the unconditioned reflex. Yet, if a dog was repeatedly shown food it was not allowed to eat, salivation weakened and eventually disappeared. Pavlov interpreted this to mean that, on one hand, the association between the sight of food and salivation was actually a temporary neural connection that could be broken through lack of reinforcement. On the other hand, a broken connection could be reactivated by reestablishing the link between salivation and the sight of food. The link could also be redirected. If an unrelated stimulus (for example, the sound made by a bell) immediately preceded the delivery of food over a long enough period, it could provoke salivation. Moreover, a dog was able to discriminate between similar types of reinforced and unreinforced food. For example, it would stop salivating at the sight of white bread it was forbidden to eat but continued salivating at the sight of brown bread it was regularly fed.

Thus, reinforcement is the notion that holds that animals can associate any two occurrences if the first one is promptly and reliably followed by the second. Reinforcement has a clearly adaptive function, because it allows an animal to change its behavior in reaction to changes in its environment. Learning takes place because of the forging and breaking of neural connections in reaction to changing circumstances.

Impact

The importance of reinforcement was first recognized in Russia, where the monists and the subjectivists continued to debate the merits of Pavlov's new ideas. Yet although the state government (during the later years of the czar) backed subjectivism but opposed monism, private funding allowed Pavlov to expand his experiments.

The Revolutionary period disrupted Pavlov's work, but after 1921, the Soviet leadership vigorously supported his research. They did so for several reasons: Pavlov's emphasis on physical stimulation fit the materialistic orientation of the new Marxist regime, his doctrine of reinforcement strengthened the arguments of nurture over nature at a time when the government wanted to reeducate its citizenry, and his scientific triumphs made Soviet socialism look good to the rest of the world. With state sponsorship, Pavlov and his successors directed large research projects on complex aspects of association through reinforcement.

Largely because of the language barrier, non-Russians were unable to absorb Pavlov's concept of reinforcement until the 1920's. European reaction was unenthusiastic, and in the United States it was often confused with the idea of rewards and punishments. Generally, Americans and Western Europeans admire Pavlov's exacting investigations and associate his original concept with a specific kind of simple learning (classical, or passive, learning). Some aspects of Pavlovian reinforcement have been incorporated into theories of language formation and information processing. Nevertheless, it is only one of many influences affecting theories of human behavior.

See also Manic Depression; Neurons; Psychoanalysis; REM Sleep; Split-Brain Experiments.

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—*Michael J. Fontenot*

PEKING MAN

THE SCIENCE: The discovery of a fossilized tooth provided the first evidence that Homo erectus had existed outside the Indonesian island of Java.

THE SCIENTISTS:

Otto Zdansky, Austrian paleontologist who discovered Peking man

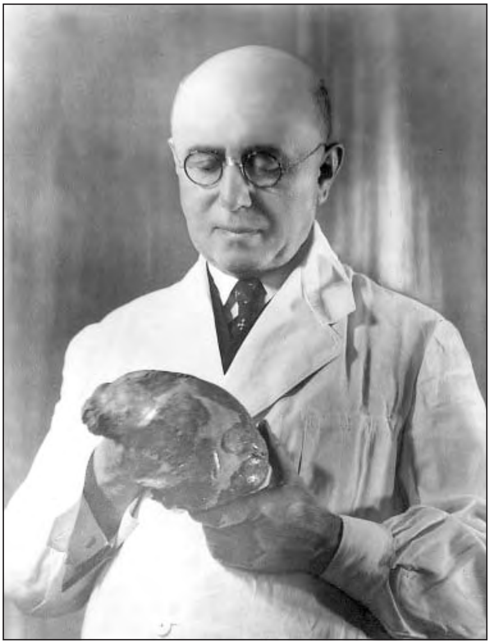
Johan Gunnar Andersson (1874-1960), Swedish mining expert who was the original excavator at Zhoukoudian

Franz Weidenreich (1873-1948), anthropologist from the University of Chicago who directed excavations and described finds

Weng Zhong Bei (Weng Chung Pei; b. 1904), Chinese paleontologist who discovered the first Peking man skull in 1929

DRUGSTORE ARCHAEOLOGY

The story of the discovery (and loss) of Peking man began in 1899, when K. A. Haberer, a German physician in China's capital city of Beijing (then known in the West as Peking) found his movements seriously restricted by the Boxer Rebellion. As a result of the violence surrounding Beijing, he wisely restricted his hobby of hunting fossils to urban drugstores; it had long been traditional in China to grind up fossils and use them for medicine. Haberer soon had a large collection, which he sent in several shipments to Munich. His friend Max Schlosser described them in a monograph, *Die fossilen Säugethiere Chinas* (1903; *Fossil Primates of China*, 1924). All the fossils in the collection were mammalian—there were no fossils of reptiles or birds—and included a tooth that seemed to be either apelike or human. Eventually, the tooth proved to be that of a prehistoric ape, but the collection aroused interest throughout the West, in large part because Schlosser predicted that some new form of prehistoric fossil would soon be found.



Franz Weidenreich with the skull of Peking man. (American Museum of Natural History)

Nothing further took place, however, until 1918, when Johan Gunnar Andersson turned to professional fossil collecting in China on behalf of Swedish institutions. When Andersson's discoveries proved to be not only abundant but also interesting, Otto Zdansky, a professionally trained paleontologist, was sent to China by the Swedish Paleontological Institute of Uppsala to improve the scientific quality of Andersson's work.

Arriving in the summer of 1921, Zdansky began operations of his own at an abandoned limestone quarry some 48 kilometers southwest of Beijing, near a village called Zhoukoudian. Andersson had recommended the site to Zdansky two years before. Locally, the site was known as Chicken Bone Hill. After excavations began, Zdansky was told by his workmen of a richer site, Dragon Bone Hill, next to another abandoned quarry on the other side of the village.

HOMO ERECTUS

In 1923, Zdansky found a single molar tooth at Dragon Bone Hill, the first fossil evidence of Peking man. Curiously enough, however, he made no mention of it in his publications until 1926, when he had returned to Sweden. By this time, Crown Prince Gustav Adolf, chairman of the Swedish China Research Committee and Zdansky's longtime patron, was scheduled to visit China. Asked to contribute finds, Zdansky informed Andersson of the two teeth he had earlier discovered (a second example having turned up before he left China). At a reception for the prince in Beijing on October 22, 1926, Andersson, in turn, informed Gustav Adolf and the world. The news caused a sensation everywhere in the educated world, as the fossil find now called "Peking man" was thought to represent the oldest form of humanity known.

Despite extensive efforts, further excavations yielded nothing of fundamental importance until December, 1929, when Weng Zhong Bei, who was assisting at the dig, found an almost complete skull of Peking man partially embedded in a cave. A comparison of the skull with fragments discovered by Eugène Dubois in Java (known as Java man) showed them to be so nearly identical that separate designations for the two finds seemed inappropriate. The name *Homo erectus* was used to apply to both examples.

Between 1934 and 1937, when military conditions forced a halt, continuing excavations at Zhoukoudian revealed a wonderful collection of further skulls, jaws, teeth, and even some limb bones. Franz Weidenreich, an anthropologist from the University of Chicago, then studied, described, and made cases of these specimens in a series of admirably competent monographs. In April, 1941, he brought the casts, photographs, and notes he had made of them with him to the United States. In December, 1941, an attempt was made to evacuate the fossils from Beijing to a waiting American ship.

Unfortunately, war between Japan and the United States broke out, forcing the interruption of the shipment, and the precious fossils disappeared.

IMPACT

The most immediate consequence of the discovery of Peking man was to reinforce—with, for the first time, fossil evidence—the contemporary belief that humankind had originated in Asia. Earlier work in archaeology (the discovery of the Sumerians by Sir Leonard Woolley in particular) had already established Asia as the home of human civilization; it thus seemed logical to assume that Asia had also been the original habitat for uncivilized humankind. It is now generally believed, however, that humankind originated in Africa, as Charles Darwin had predicted. The first significant fossil evidence in support of an African origin was the discovery of *Australopithecus* (the Taung child) by Raymond Arthur Dart in 1925. The more obviously human *Homo erectus* distracted attention away from *Australopithecus* and the African origin hypothesis, thereby delaying its acceptance. Eventually, though, discoveries by the Leakeys and others would put *Homo erectus* closer to the end of human evolution than to the beginning.

Discoveries in the cave and quarry deposits of Zhoukoudian were revolutionary in that they offered more information regarding the daily living of human ancestors than previous fossil evidence had done. Peking man, for example, had used fire, but perhaps without knowing how to make it. He was, moreover, a cannibal and primitive toolmaker. Many speculations followed as to what life in the caves must have been like. Peking man was the first opportunity given reputable scientists to study not only early humans but also the society that they created.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Qafzeh Hominids; *Zinjanthropus*.

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—Dennis R. Dean

PENDULUM

THE SCIENCE: In *The Pendulum Clock*, Christiaan Huygens explained how his accurate pendulum clock was first built in 1656, the mathematics behind its accuracy, the important properties of pendula, centrifugal force, and the acceleration of gravity.

THE SCIENTISTS:
Christiaan Huygens (1629-1695), Dutch mathematician and physicist
Marin Mersenne (1588-1648), French philosopher, mathematician, and scientist
Galileo Galilei (1564-1642), Italian astronomer and physicist
Sir Isaac Newton (1642-1727), English physicist and mathematician

BODIES IN FREE FALL

When Christiaan Huygens was only seventeen years old, he developed a proof showing that the distance a freely falling body covered increased with the square of the time it had fallen. His proud father passed this on to his friend, Marin Mersenne, one of the foremost scientists of the time. Delighted and impressed, Meresenne encouraged the young Huygens to continue his scientific studies and suggested that he work on properties of the pendulum and also on measuring the distance a freely falling body fell in the first second after being released (this is equivalent in modern terms to measuring the acceleration of gravity).

Huygens worked on these problems over the years, and he reported his results in his most important book, *Horologium oscillatorium sive de mortu pendulorum ad horologia aptato demonstrationes geometricae* (1673; *The Pendulum Clock*, 1986). To measure the acceleration of gravity, *g*, Huygens improved an experiment of Mersenne in which a ball was dropped simultaneously with the release of a pendulum of known period. At its lowest point, the pendulum struck a vertical board making a sound. The initial height of the ball was adjusted until the sound of its striking the floor was simultaneous with that of the pendulum striking the board, thereby accurately measuring the time it took for the ball to fall. Huygens found a value equivalent to the modern value of g correct to within 0.1 percent.

During these investigations, Huygens also related the speed with which a suspended object swings to the tension in the cord holding it and to the centrifugal force. He arrived at the correct result that the centrifugal force is proportional to the square of the velocity and inversely proportional to the radius of the circular path.

The Pendulum Clock

One of the great technological problems of Huygens's day was how to determine the position of a ship exactly when it was far out at sea. Good star maps already existed, so that in principle, a navigator could measure how far above the horizon a few bright stars were and then calculate where on Earth one had to be to have that view of the sky. Because the stars wheel across the sky each night, the navigator also needed to know at what time the measurements were made. Unfortunately, mechanical clocks were accurate only to within about 15 minutes per day, which could produce navigational errors of 250 miles.

Mechanical clocks driven by a spring tended to run fast or slow depending upon how tightly the spring was wound. Huygens was a keen follower of Galileo, who had suggested that the steady swinging of a pendulum might be used to regulate a clock, but Huygens was the first to construct such a clock successfully. Like Isaac Newton, Huygens was gifted in both mathematics and in constructing mechanical models. He combined these talents to construct a pendulum clock in 1656. As it swung back and forth, the pendulum mechanism allowed a gear to advance only one tooth at the end of each pendulum swing, producing the characteristic ticktock sound. The mechanism also gave the pendulum a slight nudge to keep it in motion. This clock was accurate to within about one minute per day.

How Pendulums Work

Huygens continued to analyze and refine his clocks, finally publishing his results in *The Pendulum Clock* in 1673. A simple pendulum consists of a light string or rod extending downward from a pivot and having a weight, called a bob, on the lower end. Huygens found that a lens-shaped bob had less air resistance that a spherical bob, so it made the clock more accurate. He also discovered that the period of a pendulum depends upon the square root of the length of the pendulum's string; that is, if one pendulum's string was twice as long as another pendulum's string, its period of oscillation was not twice as long as the first pendulum's, but only 1.41 (the square root of 2) times as long.

If the mass of the string or rod cannot be ignored compared with the mass of the bob, the pendulum is no longer "simple." Such a pendulum whose mass is not concentrated in a small bob is called a "compound" or a "physical" pendulum. Huygens showed that a compound pendulum acted mathematically like a simple pendulum with all of its mass concentrated at a point, called the center of oscillation. This allowed Huygens to predict the effect of adding small masses above the bob to adjust the pendulum's period. Analyzing the physical pendulum also required Huygens to develop the concept of rotational moment of inertia, the effect that a mass distribution has on the ease with which it can be made to rotate about an axis.

Suitable for Sea

Huygens discovered that the period of a pendulum is constant only if the amplitude of its swing is small, a condition that could not be maintained on a rocking ship at sea. He used clever mathematical analysis to show that the pendulum would be isochronous; that is, its period would remain constant regardless of the swing's amplitude if the path of the bob were a cycloid. A cycloid is the shape traced out by a point fixed on the rim of a wheel as the wheel rolls along the ground. A cycloid can be pictured as a wire that is first bent into the shape of a semicircle, and then the ends are pulled a bit farther apart, making the curve flatter.

Huygens made the bob follow a cycloidal path by suspending the pendulum between a pair of guide plates shaped like a portion of a cycloid and by using a ribbon for the upper part of the pendulum that was between the guide plates. In action, near the end of the pendulum's swing, the ribbon swung up against a guide plate and matched its contour. This shortened the pendulum's length and made the period nearly independent of the amplitude of the swing.

He made his ship's clocks in pairs so that if one stopped or needed repair, the other would keep on running. In practice, he hung them side by side from a wooden beam and was astounded to find that regardless of how they were started, after about thirty minutes the pendula were exactly 180° out of phase. (When one pendulum was at the extreme right end of its swing, the other was at the extreme left end of its swing.) He correctly concluded that otherwise imperceptible vibrations were traveling along the

CHRISTIAAN HUYGENS: IMPROVING ON GALILEO

Christiaan Huygens's first plunge into scientific research took place in 1655, when he and his brother began to build improved telescopes, grinding their own lenses. With these instruments, Huygens found Saturn's moon Titan and discovered that Mars has a varied surface. He gradually discerned a ring around Saturn that nowhere touched the planet, thus improving on Galileo's more primitive observation. In order to protect the priority of this discovery while continuing his viewing, he announced by the publication of a coded message that he had found the ring. At about this time Huygens published his work on hyperbolas, ellipses, and circles, and in 1657 he published the world's first formal treatise on probability.

In addition to building the pendulum clock—his greatest original invention—Huygens enjoyed membership in France's Royal Academy of Sciences, residing in Paris from 1666 until 1681. Still, when Huygens left Paris in 1681 for a third trip to the Netherlands, he never returned. His patron, Louis XIV's chief minister Jean-Baptiste Colbert, died in 1683, and anti-Protestant sentiment was growing in France, making Huygens's position difficult, as he was nominally a Calvinist.

(Library of Congress)

Huygens's philosophy of science was intermediate between those of the two giants of his day: René Descartes in France and Sir Isaac Newton in England. Descartes attempted to explain all phenomena by use of deductive logic alone. Newton, on the contrary, relied on observations and experiments as the bases for his laws. Huygens grew up a Cartesian but broke with his mentor over the latter's extreme devotion to the mathematical, or deductive, approach to science; his basic approach to the universe was mechanistic. He did prefer, however, Descartes's supposedly more tangible "vortices" of "subtle matter" to Newton's "gravity" in explaining the movements of heavenly bodies. In the matter of relativity, however, Huygens was in advance of Newton and anticipated Einstein. For Huygens, all motion in the universe was relative. Huygens also bested Newton in his understanding of light: Newton held to the corpuscular (particle) theory of light, whereas Huygens propounded a wave theory of light; modern quantum theory combines the two, but in Huygens's day the corpuscular theory was dominant.

Huygens remained in communication with Newton, although his relations with London's Royal Society dwindled after 1678. He visited England again in 1689, conversing with Newton and addressing the Royal Society on his non-Newtonian theory of gravity. Huygens's last years were spent in The Hague, where he died in 1695.

support beam from one clock to the other, a condition known as "weak coupling between the pendula." Huygens believed that this effect would help keep his clocks accurate, and in fact they were accurate to within about 10 seconds per day.

IMPACT

Christiaan Huygens's expression for centrifugal force when combined with Johannes Kepler's third law of planetary motion (which relates the time it takes a planet to go around the Sun and its distance from the Sun) immediately implies that the gravitational force between the Sun and the planets becomes stronger or weaker in inverse proportion to the square of the distance between the planet and the Sun. This, in turn, led Newton to his law of gravity.

See also Longitude; Speed of Light.

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—*Charles W. Rogers*

PENICILLIN

THE SCIENCE: The first successful and widely used antibiotic drug, penicillin has been called the twentieth century's greatest "wonder drug."

THE SCIENTISTS:

Sir Alexander Fleming (1881-1955), Scottish bacteriologist, cowinner of the 1945 Nobel Prize in Physiology or Medicine

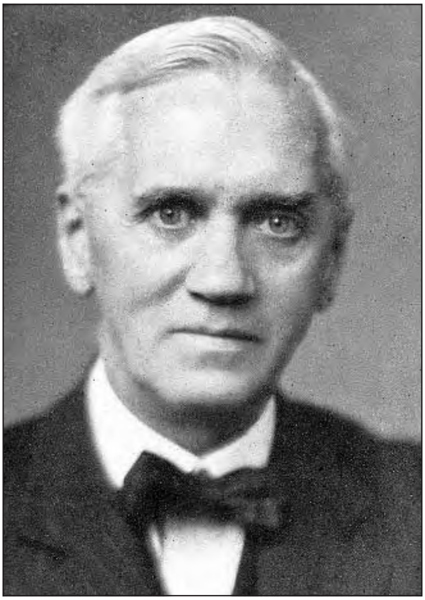
Baron Florey (1898-1968), Australian pathologist, cowinner of the 1945 Nobel Prize in Physiology or Medicine

Ernst Boris Chain (1906-1979), émigré German biochemist, cowinner of the 1945 Nobel Prize in Physiology or Medicine

ANTIBIOTICS

During the early twentieth century, scientists were aware of antibacterial substances but did not know how to make full use of them in the treatment of diseases. Sir Alexander Fleming discovered penicillin in 1928, but he was unable to duplicate his laboratory results of its antibiotic properties in clinical tests. As a result, he did not recognize the medical potential of penicillin.

Between 1935 and 1940, penicillin was purified, concentrated, and clinically tested by pathologist Baron Florey, biochemist Ernst Boris Chain, and members of their Oxford research group. Their achievement has since been regarded as one of the greatest medical discoveries of the twentieth century. Florey was a professor at Oxford University in charge of the Sir William Dunn School of Pathology. Chain had worked for two years at Cambridge University in the laboratory of Frederick Gowland Hopkins, an eminent chemist and discoverer of vitamins. Hopkins recommended Chain to Florey, who was searching for a candidate to lead a new biochemical unit in the Dunn School of Pathology.



Sir Alexander Fleming. (The Nobel Foundation)

In 1938, Florey and Chain formed

a research group to investigate the phenomenon of antibiosis, or the antagonistic association between different forms of life. The union of Florey's medical knowledge and Chain's biochemical expertise proved to be an ideal combination for exploring the antibiosis potential of penicillin. Florey and Chain began their investigation with a literature search in which Chain came across Fleming's work and added penicillin to their list of potential antibiotics.

Their first task was to isolate pure penicillin from a crude liquid extract. A culture of Fleming's original *Penicillium notatum* was maintained at Oxford and was used by the Oxford group for penicillin production. Extracting large quantities of penicillin from the medium was a painstaking task, as the solution contained only one part of the antibiotic in ten million. When enough of the raw juice was collected, the Oxford group focused on eliminating impurities and concentrating the penicillin. The concentrated liquid was then freeze-dried, leaving a soluble brown powder.

Tests and Results

In May, 1940, Florey's clinical tests of the crude penicillin proved its value as an antibiotic. Following extensive controlled experiments with mice, the Oxford group concluded that they had discovered an antibiotic that was nontoxic and far more effective against pathogenic bacteria than any of the known sulfa drugs. Furthermore, penicillin was not inactivated after injection into the bloodstream but was excreted unchanged in the urine. Continued tests showed that penicillin did not interfere with white blood cells and had no adverse effect on living cells. Bacteria susceptible to the antibiotic included those responsible for gas gangrene, pneumonia, meningitis, diphtheria, and gonorrhea. American researchers later proved that penicillin was also effective against syphilis.

In January, 1941, Florey injected a volunteer with penicillin and found that there were no side effects to treatment with the antibiotic. In February, the group began treatment of Albert Alexander, a forty-three-year-old policeman with a serious staphylococci and streptococci infection that was resisting massive doses of sulfa drugs. Alexander had been hospitalized for two months after an infection in the corner of his mouth had spread to his face, shoulder, and lungs. After receiving an injection of 200 milligrams of penicillin, Alexander showed remarkable progress, and for the next ten days his condition improved. Unfortunately, the Oxford production facility was unable to generate enough penicillin to overcome Alexander's advanced infection completely, and he died on March 15.

A later case involving a fourteen-year-old boy with staphylococcal sep-

TEAM "WONDER DRUG"

Penicillin was a bacteriological curiosity when Sir Alexander Fleming isolated it in 1928—at best a possible local antiseptic. No one realized that this chemical would become a potent, systemic antibacterial "wonder drug."

It would be more than a decade before the monumental applications of penicillin were investigated by Baron Florey and Ernest Chain, marked by the exciting observation that its injection into mice killed disease-causing staphylcocci and gangrene-causing bacteria. In these experiments, all the untreated mice injected with the disease bacteria died, whereas virtually all the penicillin-treated animals survived. Florey began to direct the great scientific resources of Oxford's School of Pathology toward full-scale study of the drug. By virtue of much work, carried out by numerous gifted Oxford scientists, the basic project proceeded quickly. First, the wide range of microbes killed by penicillin was identified. Then the pharmacology and the toxicology of the drug were delineated in animals and in humans.

A major initial stumbling block to human studies was the fact that successful treatment of a single human being required administration of the entire "yield" of penicillin, isolated from hundreds of gallons of culture medium. The efforts of another of Florey's colleagues, Norman Heatley, led to development of the laboratory equipment that allowed the production of enough penicillin for wider human testing. Production of penicillin was soon increased enough to allow successful treatment of ten cases of human bacterial infection.

Exciting though this was, Britain—in the throes of World War II—did not have the resources to produce enough penicillin for widespread use. Therefore, Florey traveled to the United States and convinced the American Office of Scientific Research to fund the effort. Thanks to this massive American funding and the collaborative efforts by American industry, enough penicillin was produced to allow its widespread use in treatment of war casualties after the 1944 Normandy invasion. With large-scale production of penicillin now well in hand, Florey next identified the best methods for testing the efficacy of the drug and effecting the most appropriate ways to administer it to patients. In 1945, Florey, Chain, and Fleming shared the Nobel Prize in Physiology or Medicine "for the discovery of penicillin and its curative effect in various infectious diseases."

ticemia and osteomyelitis had a more spectacular result: The patient made a complete recovery in two months. In all the early clinical treatments, patients showed vast improvement, and most recovered completely from infections that resisted all other treatment.

IMPACT

Penicillin is among the greatest medical discoveries of the twentieth century. Florey and Chain's chemical and clinical research brought about a revolution in the treatment of infectious disease. Almost every organ in the body is vulnerable to bacteria. Before penicillin, the only antimicrobial drugs available were quinine, arsenic, and sulfa drugs. Of these, only the sulfa drugs were useful for treatment of bacterial infection, but their high toxicity often limited their use. With this small arsenal, doctors were helpless to treat thousands of patients with bacterial infections.

The work of Florey and Chain achieved particular attention because of World War II and the need for treatments of such scourges as gas gangrene, which had infected the wounds of numerous World War I soldiers. With the help of Florey and Chain's Oxford group, scientists at the U.S. Department of Agriculture's Northern Regional Research Laboratory developed a highly efficient method for producing penicillin using fermentation. After an extended search, scientists were also able to isolate a more productive penicillin strain, *Penicillium chrysogenum*. By 1945, a strain was developed that produced five hundred times more penicillin than Fleming's original mold had.

Penicillin, the first of the "wonder drugs," remains one of the most powerful antibiotics in existence. Diseases such as pneumonia, meningitis, and syphilis are still treated with penicillin. Penicillin and other antibiotics also had a broad impact on other fields of medicine, as major operations such as heart surgery, organ transplants, and management of severe burns became possible once the threat of bacterial infection was minimized.

Florey and Chain received numerous awards for their achievement, the greatest of which was the 1945 Nobel Prize in Physiology or Medicine, which they shared with Fleming for his original discovery. Florey was among the most effective medical scientists of his generation, and Chain earned similar accolades in the science of biochemistry. This combination of outstanding medical and chemical expertise made possible one of the greatest discoveries in human history.

See also Anesthesia; Antisepsis; Aspirin; Contagion; Diphtheria Vaccine; Germ Theory; Hybridomas; Immunology; Polio Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Streptomycin; Vitamin C; Vitamin D; Yellow Fever Vaccine.

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—*Peter Neushul*

Periodic Table of Elements

The Science: Building on his experiences in writing a textbook, Dmitri Mendeleyev formulated a law about the recurrent reliance of each element's properties on its atomic weight, and he devised a periodic table that enabled him to predict the characteristics of unknown elements.

The Scientists:

Dmitri Ivanovich Mendeleyev (1834-1907), Russian chemist who discovered the periodic law

Julius Lothar Meyer (1830-1895), German chemist who independently discovered the periodic law

Johann Wolfgang Döbereiner (1780-1849), German chemist who noticed the gradation of properties in such elemental groups as chlorine, bromine, and iodine (the "law of triads")

John Alexander Reina Newlands (1837-1898), English chemist who discovered that properties repeat after seven elements (the "law of octaves")

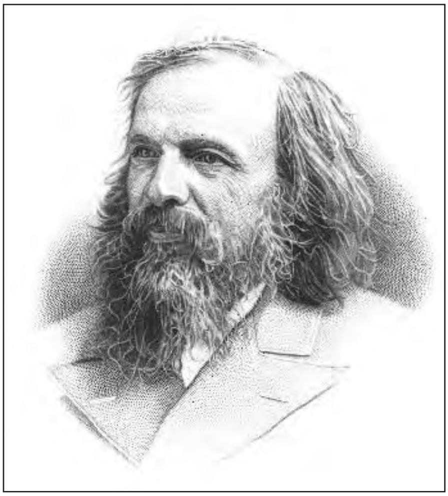
The Concept of Chemical Elements

For more than two thousand years, most natural philosophers believed that only four elements—earth, air, fire, and water—existed, and they attempted to fit all newly discovered substances into this quadripartite scheme. During the eighteenth century Antoine-Laurent Lavoisier, who helped create modern chemistry, listed thirty-three substances as provisionally elemental, and by 1830 chemists recognized fifty-five substances as genuinely elemental. This was an embarrassment of riches, because these elements varied widely in properties and no system existed for making sense of them. As more elements were added to the list, questions arose about how many actually existed and what principles regulated their properties and interrelationships.

The first person to discover some order among these elements was Johann Döbereiner, who, in the years 1816 to 1829, noticed that strontium had an atomic weight halfway between calcium and barium and that the newly discovered element bromine had properties intermediate between those of chlorine and iodine. He discovered other triads that exhibited similar gradations of properties, and over the next twenty-five years other chemists expanded Döbereiner's scheme to include further triads and some four- and five-membered families of elements. In the 1860's the English chemist John Newlands found that, when he arranged the elements in order of their increasing atomic weights, similar physical and chemical properties appeared after seven elements, but members of the Chemical Society ridiculed his "law of octaves" for its implied analogy to music. It took twenty-three years for English scientists to honor Newlands for his prescient ideas on the periodic law.

ATOMIC WEIGHTS

The actual periodic system of the elements was discovered independently in Russia by Dmitri Mendeleyev and Julius Lothar Meyer in Germany. In the late 1860's both Mendeleyev and Meyer were preparing textbooks of chemistry. Meyer based his on the atomic theory and the systematization of elemental properties. Mendeleyev, skeptical of atomism, initially organized his *Principles of Chemistry* around chemical practice rather than any theories of the classification of elements. It was not until early in 1869, when he was writing the second volume of his textbook, that he realized that he needed a better way of organizing the fifty-five elements he had not yet discussed.



Dmitri Mendeleyev. (Library of Congress)

During the first few weeks of

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February, 1869, while he was writing his second volume's first two chapters on the alkali metals, he listed sodium and potassium along with the recently discovered rubidium and cesium in order of their increasing "elemental" (his preferred term), or atomic, weights. He compared this arrangement with a similar one for the halogens (fluorine, chlorine, bromine, and iodine) and for the alkaline earths (magnesium, calcium, strontium, and barium).

Precisely how Mendeleyev arrived at his recognition of the importance of atomic weight as a classificatory tool is controversial; the paucity of contemporary documents leaves room for various interpretations. In some accounts, a dream played a role. Some scholars claim that Mendeleyev put the elements and their properties on cards, arranged them in rows according to increasing atomic weights, and then noticed regular repetitions of physical and chemical properties. Other scholars believe that he grouped elements into natural families, such as the halogens, and then noticed their dependence on atomic weight. Still other scholars hold that me made his discovery as a pedagogue who was looking for a method of discovery rather than a system of classification. However he arrived at his breakthrough, his account of it, "The Relation of the Properties to the Atomic Weights of the Elements," was made public when a friend presented this paper for him at a meeting of the Russian Chemical Society on March 6, 1869, and it was soon published both in Russian and a précis in German.

Corrections and Improvements

Over the next three years Mendeleyev gradually realized the deficiencies of his early formulations of the periodic law and table, and he grasped how to remove many of these defects while increasing the power of his systematization of the elements to make useful predictions. When arranged strictly in order of increasing atomic weights, some elements appeared to be out of place, and Mendeleyev assumed that erroneous atomic weights were responsible for these anomalies. Some of his adjusted atomic weights proved helpful, but others were simply wrong (three atomic weight inversions exist in the modern periodic table, which is based on atomic number rather than atomic weight).

By November of 1870, Mendeleyev had heard of Meyer's work, published eight months earlier, in which Meyer had arranged fifty-six elements in vertical columns according to their increasing atomic weights. Meyer's horizontal families clearly showed their periodic recurrence of properties. In the same paper he presented a graphical illustration of periodicity by plotting atomic volumes (the space occupied by atoms) versus atomic weights, in which the analogous relationships of properties occurred as waves, with the alkali metals at the peaks of each curve.

Mendeleyev became so convinced of the lawlike nature of his system that he published a periodic table with empty spaces for unknown elements, and because his law of periodicity brought out the dependence of properties on atomic weight, he was able to characterize these unknown elements with precision. For example, he reasoned that the unknown element in the empty space following calcium should be related to boron, and he gave this unknown element the provisional name "eka-boron" (after the Sanskrit "eka, " meaning "first"). He also predicted the properties of two other unknown elements, eka-aluminum and eka-silicon.

When, late in 1871, Mendeleyev published an improved and expanded periodic table, he was convinced that he had discovered a new law of chemistry. This table, which had twelve horizontal rows and eight vertical columns, showed that most of the elements' properties had a periodic dependence on their atomic weights. Nevertheless, perplexing problems remained. For example, Mendeleyev failed to understand the few rare-earth elements that were then known, since these actually abundant metals have closely similar properties (and, once all fourteen were discovered, they needed a separate section in the periodic table). However, when Lecoq de

Boisbaudran found eka-aluminum in 1875 and named it gallium, the power of Mendeleyev's formulation of his periodic table and law began to generate admirers, including Meyer. With the discovery of scandium (eka-boron) in 1879 and germanium (eka-silicon) in 1886, both of which had properties that Mendeleyev had predicted, chemists became satisfied that Mendeleyev's periodic table was much more than the simple teaching tool that he had initially envisioned. It was a new way of making sense of chemistry's rich past and of creating a fertile future.

IMPACT

Although it took time for the periodic table to assume its modern form, it provided throughout its history a way for physicists and chemists to understand accumulated information about the elements. It also helped teachers to communicate to students the nature and properties of the basic building blocks of matter, and it enabled researchers to make discoveries of new elements. A good early example of its value as a research tool was the discovery by William Ramsay and Lord Rayleigh of the inert gases helium, neon, argon, krypton, and xenon. A good later example is the discovery by Glenn Seaborg and others of such transuranic elements as plutonium, curium, and americium.

New discoveries, such as atomic number by Henry Moseley, helped scientists to reorganize the periodic table. When scientists discovered the spin of the electron and the shared-electron-pair bond, these new ideas helped to deepen their understanding of the periodic law. Mendeleyev himself gave his estimate of the significance of his discovery by emphasizing the table's ability to elucidate unexplained phenomena and to make verifiable predictions. Therefore, the periodic law's value to modern scientists has proved flexible and expandable, increasing with our understanding of the nature of the atom through quantum mechanics. What was once a ridiculed idea in the nineteenth century has become a foundation stone of modern science.

See also Atomic Structure; Atomic Theory of Matter; Carbon Dioxide; Definite Proportions Law; Isotopes; Periodic Table of Elements; Photosynthesis; Water; X-Ray Fluorescence.

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—*Robert J. Paradowski*

PERSONAL COMPUTERS

THE SCIENCE: The first commercially available, preassembled personal computer, the Apple II helped move computers out of the workplace and into the home.

THE SCIENTISTS:
Stephen Wozniak (b. 1950), cofounder of Apple and designer of the Apple II computer
Steven Jobs (b. 1955), cofounder of Apple
Regis McKenna (b. 1939), owner of the Silicon Valley public relations and advertising company that handled the Apple account
Chris Espinosa (b. 1961), the high school student who wrote the BASIC program shipped with the Apple II
Randy Wigginton (b. 1960), high school student and Apple software programmer

INVENTING THE APPLE

As late as the 1960's, not many people in the computer industry believed that a small computer could be useful to the average person. It was through the effort of two friends from the Silicon Valley (between San Francisco and San Jose) that the personal computer revolution was started.

Both Steven Jobs and Stephen Wozniak had attended Homestead High School in Los Altos, California, and both developed early interests in technology, especially computers. In 1971, Wozniak built his first computer from spare parts. Shortly afterward, he was introduced to Jobs. Jobs had already developed an interest in electronics—he once telephoned William Hewlett, cofounder of Hewlett-Packard, to ask for parts—and he and

Wozniak became friends. Their first business together was the construction and sale of "blue boxes," illegal devices that allowed the user to make long-distance telephone calls for free.

After attending college, the two took jobs within the electronics industry. Wozniak began working at Hewlett-Packard, where he studied calculator design, and Jobs took a job at Atari, the video-game company. The friendship paid off again when Wozniak, at Jobs's request, designed the game "Breakout" for Atari, and the pair was paid seven hundred dollars.

In 1975, the Altair computer, a personal computer in kit form, was introduced by Micro Instrumentation and Telemetry Systems (MITS). Shortly thereafter, the first personal computer club, the Homebrew Computer Club, began meeting in Menlo Park, near Stanford University. Wozniak and Jobs began attending the meeting regularly. Wozniak eagerly examined the Altairs that others brought. He thought that the design could be improved. In only a few more weeks, he produced a circuit board and interfaces that connected it to a keyboard and a video monitor. He showed the machine at a Homebrew meeting and distributed photocopies of the design.

In this new machine, which he named an "Apple," Jobs saw a big opportunity. He talked Wozniak into forming a partnership to develop personal computers. Jobs sold his car, and Wozniak sold his two Hewlett-Packard calculators; with the money, they ordered printed circuit boards

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made. Their break came when Paul Terrell, a retailer, was so impressed that he ordered fifty fully assembled Apples. Within thirty days, the computers were completed, and they sold for a fairly high price: $666.66.

During the summer of 1976, Wozniak kept improving the Apple. The new computer would come with a keyboard, an internal power supply, a built-in computer language called the Beginner's All-Purpose Symbolic Instruction Code (BASIC), hookups for adding printers and other devices, and color graphics, all enclosed in a plastic case. The output would be seen on a television screen. The machine would sell for twelve hundred dollars.

Selling the Apple

Regis McKenna was the head of the Regis McKenna Public Relations agency, the best of the public relations firms that served the high-technology industries of the valley, which Jobs wanted to handle the Apple account. At first, McKenna rejected the offer, but Jobs's constant pleading finally convinced him. The agency's first contributions to Apple were the colorful striped Apple logo and a color ad in *Playboy* magazine.

In February, 1977, the first Apple Computer office was opened in Cupertino, California. By this time, two of Wozniak's friends from Homebrew, Randy Wigginton and Chris Espinosa—both high school students—had joined the company. Their specialty was writing software. Espinosa worked through his Christmas vacation so that BASIC (the built-in computer language) could ship with the computer.

The team pushed ahead to complete the new Apple in time to display it at the First West Coast Computer Faire in April, 1977. At this time, the name Apple II was chosen for the new model. The Apple II computer debuted at the convention and included many innovations. The "motherboard" was far simpler and more elegantly designed than that of any previous computer, and the ease of connecting the Apple II to a television screen made it that much more attractive to consumers.

Consequences

The introduction of the Apple II computer launched what was to be a wave of new computers aimed at the home and small-business markets. Within a few months of the Apple II's introduction, Commodore introduced its PET computer and Tandy Corporation/Radio Shack brought out its TRS-80. Apple continued to increase the types of things that its computers could do and worked out a distribution deal with the new ComputerLand chain of stores.

In December, 1977, Wozniak began work on creating a floppy disk system for the Apple II. (A floppy disk is a small, flexible plastic disk coated with magnetic material. The magnetized surface enables computer data to be stored on the disk.) The cassette tape storage on which all personal comput-

The Wizard of Woz

Stephen Wozniak was born on August 11, 1950, and became interested in electronics at a young age: By the time he was in the sixth grade, he had earned his ham radio license. He and fellow Apple founder Steven Jobs attended the same high school in Los Altos, California, although they did not meet until the early 1970's, when they formed a business to build and sell "blue boxes"—illegal devices that generated phone pulses, allowing users to access long-distance telephone service for free.

In 1975 he dropped out of the University of California, Berkeley, to devote full time to computers. By 1976, Wozniak was working for the premier electronics company of the time, Hewlett-Packard, which had recently begun to market some of the earliest handheld electronic calculators for personal use. There, he designed computer chips. Jobs, in the meantime, was working for the video game company Atari. The earliest computers were then being constructed from kits, and the two were active in a computer club devoted to this interest.

On April 1, 1976, Jobs and Wozniak founded Apple Computer. They developed the improved Apple II, which could display color graphics, in 1977, and by 1980 the company had gone public. Wozniak and Jobs were building and marketing thousands of Apples—the first complete personal computer—and they were rich.

After overcoming short-term memory loss after a February, 1981, plane accident, Wozniak was married and returned to college to earn his undergraduate degree. His interdisciplinary interests led to his sponsoring the "US Festival," which celebrated the interactions of music, television, computers, and people. He returned to Apple for a few years as an engineer and then left to found Cloud 9, a company that marketed the first universal remote control in 1987.

Wozniak next turned his attention to education: He taught fifth-graders and supported events and institutions focused on education, including San Jose Children's Museum and California's Los Gatos school district. He received the National Medal of Technology from President Ronald Reagan in 1985, was named a Fellow of the Computer History Museum in 1997, was inducted into the National Inventors Hall of Fame in 2000, and received an honorary doctorate in science from North Carolina State University in 2004. His company Wheels Of Zeus (WOZ), founded in 2001, builds wireless GPS devices to "help everyday people find everyday things."

ers then depended was slow and unreliable. Floppy disks, which had been introduced for larger computers by the International Business Machines (IBM) Corporation in 1970, were fast and reliable. As he did with everything that interested him, Wozniak spent almost all of his time learning about and designing a floppy disk drive. When the final drive shipped in June, 1978, it made possible development of more powerful software for the computer.

By 1980, Apple had sold 130,000 Apple II's. That year, the company went public, and Jobs and Wozniak, among others, became wealthy. Three years later, Apple became the youngest company to make the Fortune 500 list of the largest industrial companies. By then, IBM had entered the personal computer field and had begun to dominate it, but the Apple II's earlier success ensured that personal computers would not be a market fad. By the end of the 1980's, 35 million personal computers would be in use.

See also Artificial Intelligence; Electron Tunneling; Internet.

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—*George R. Ehrhardt*

Pesticide Toxicity

The Science: Rachel Carson warned of the dangers of chemical pesticides, triggering a wave of public protest that marked the beginning of the modern environmental movement.

The Scientists:

Rachel Carson (1907-1964), biologist and the author of *Silent Spring*

Clarence Cottam (1899-1974), biologist and the assistant director of the U.S. Fish and Wildlife Service

A New Poison


Rachel Carson. (Library of Congress)

The publication of *Silent Spring* in 1962 is often considered to mark the beginning of the modern environmental movement. The book was written with a rare combination of scientific training, dedicated research, and literary skill. Through her subject—the threat to the Earth and its ecology through the unrestricted use of chemical pesticides—Rachel Carson captured international attention as she turned a debate mostly held among scientists into a public political issue.

Carson was working for the U.S. Fish and Wildlife Service. She decided to write a book after receiving a letter from a friend, Olga Huckins of Duxbury, Massachusetts. In the summer of 1957, a state-hired airplane had crisscrossed Huckins's two-acre wooded lot, spraying dichloro-diphenyl-trichloroethane (DDT) for mosquito control. The following day, Huckins found seven dead songbirds in her yard. With another round of spraying scheduled for the next summer, Huckins wrote to Carson, asking whether she knew of anyone in Washington who could help. It was while Carson was looking for someone who could help her friend that she became alarmed at how serious the pesticide problem had become.

DDT is extremely poisonous to many different kinds of insects and does not degrade quickly in the environment. Although first made in 1874, DDT was not found to be an effective insecticide until 1939, in time to be used during World War II (1939-1945) to dust the clothing of soldiers for protection against typhus (which is spread by lice) and malaria (which is spread by mosquitoes).

Carson began her book with a fable, a description of spring in a pleasant rural town where birdsongs, as well as the usual sounds of other animals, were missing. The residents, it turned out, had brought this "silent spring" upon themselves, through their use of chemical pesticides. Although this town was imaginary, Carson explained that similar tragedies had actually occurred in different places throughout the United States. The rest of her book provided scientific evidence to show how serious was the threat of pesticides such as DDT. She described how hundreds of chemicals had been created to kill pests and how the "fittest" insects had built up tolerances to these chemicals, forcing the creation of even more lethal compounds to kill the insects that survived. Carson also argued that chemical pesticides often caused severe damage to wildlife and had long-term effects on human health.

Clear Lake

One example made famous by Carson's book was from Clear Lake, California, a popular fishing spot about 145 kilometers north of San Francisco. To get rid of a small gnat that had become a nuisance to both tourists and residents, local officials there treated the lake in 1949 with dichlorodiphenyl-dichloroethane (DDD), an insecticide very similar to DDT. The chemical seemed to work well, killing most of the gnat larvae and providing effective gnat control for years. Then, in 1954, another treatment became necessary. The first sign of trouble came the following winter when more than one hundred of the lake's western grebes (swimming and diving birds) were found dead. More grebes died after a third application of the insecticide in 1957. According to Carson, the chemical had been absorbed by plankton, which were then eaten by fish. Western grebes ate the fish. Scientists had found an increase in the concentration of DDD with each step up the food chain. The chemical did not break down and disappear in the environment.

Carson called attention also to examples of reckless use of insecticides by the United States Department of Agriculture (USDA). The gypsy moth had plagued New England states with occasional serious infestations for nearly a century. In 1956, the USDA began an attempt to eliminate the pest by spraying nearly one million acres with DDT. Citizens on Long Island were unable to get a court ruling to stop the spraying. After the treatment, fish, songbirds, and beneficial insects such as bees were found dead, leaf crops were badly damaged, vegetables were coated with spray residue, and milk was contaminated by pesticide residues on the grass eaten by dairy cattle.

Another example was the fire ant, which had come into the United States from South America after World War II. At worst, the fire ant had become a minor nuisance in Southern states, occasionally stinging people and building large mounds that sometimes got in the way of farm machinery. In 1957, however, through press releases, newspaper stories, and films, the fire ant began to seem like a major pest, dangerous to livestock, wildlife, and people. Ignoring the protests of state conservation agencies, the USDA launched a spraying program that treated one million acres in 1958 with heptachlor and dieldrin, two of the most poisonous insecticides. The effects were beginning to sound familiar: Songbirds, game birds, pets, poultry, cows, and other livestock and wildlife were killed, and milk was contaminated.

Impact

After the publication of *Silent Spring*, President John F. Kennedy requested a study of the pesticide issue. A panel was formed from the President's Science Advisory Committee; in 1963, the committee released its

"A Fable for Tomorrow"

In 1962, Rachel Carson's Silent Spring *painted a bleak picture of a not-too-distant future in which unrestricted use of chemical pesticides had upset the balance of nature, resulting in a sterile, dead landscape:*

> There was once a town in the heart of America where all life seemed to live in harmony with its surroundings. The town lay in the midst of a checkerboard of prosperous farms, with fields of grain and hillsides of orchards.
>
> Along the roads laurel, viburnum and alder, great ferns and wildflowers delighted the traveller's eye through much of the year. Even in winter the roadsides were places of beauty, where countless birds came to feed on the berries and on the seed heads of the dried weeds rising above the snow. The streams flowed clear and cold out of the hills and contained shady pools where trout lay.
>
> Then a strange blight crept over the area and everything began to change. . . . Everywhere was a shadow of death. . . .
>
> There was a strange stillness. The birds, for example—where had they gone? Many people spoke of them, puzzled and disturbed. The feeding stations in the backyards were deserted. The few birds seen anywhere were moribund; they trembled violently and could not fly. It was a spring without voices. . . . The apple trees were coming into bloom but no bees droned among the blossoms, so there was no pollination and there would be no fruit. . . . Even the streams were now lifeless. Anglers no longer visited them, for all the fish had died.
>
> In the gutters under the eaves and between the shingles of the roofs, a white granular powder still showed a few patches: some weeks before it had fallen like snow upon the roofs and the lawns, the fields and the streams.
>
> No witchcraft, no enemy action had silenced the rebirth of new life in this stricken world. The people had done it themselves.

Source: Excerpted from Rachel Carson, "A Fable for Tomorrow," chapter 1 in *Silent Spring* (Boston: Houghton Mifflin, 1962).

findings in a report, *Use of Pesticides*. The report credited Carson with having alerted the public to the problem. It recommended that the government inform people of the hazards as well as the benefits of pesticides. The report supported Carson's argument that pesticides should be tested for safety before they are allowed to be used. The report also criticized government insect elimination programs.

Carson's warning about the impact of human activity on the environment became the central theme of the new environmental movement. After reading Carson's book, Senator Abraham A. Ribicoff established Senate committee hearings to study all federal programs related to environmental pollution, including pesticides. When Carson testified before the Ribicoff Committee, she explained how chemicals from aerial spraying could attach to particles of dust and drift for long distances. DDT residues were found even in Antarctica, where the pesticide had never been used. The committee's 1964 report, *Pesticides and Public Policy*, urged federal support for research on the environmental and human health effects of pesticides.

Carson also tried to call attention to the potential for long-term health effects, such as the risk of cancer. In 1969, the National Cancer Institute released a study showing that continuous exposure to low levels of DDT could produce cancer in laboratory animals. This study caused officials to regard DDT as "potentially" carcinogenic to humans, an important part of the decision to ban the chemical.

Carson's book prompted calls for a complete overhaul of the nation's environmental policies. In 1969, Congress officially recognized the importance of environmental quality when it passed the National Environmental Policy Act.

See also Chlorofluorocarbons; Global Warming; Ozone Hole.

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—*Robert Lovely*

PHOTOELECTRIC EFFECT

THE SCIENCE: Albert Einstein explained how a metal surface releases electrons after exposure to light.

THE SCIENTISTS:

Albert Einstein (1879-1955), German-born American physicist who described the photoelectric effect
Max Planck (1858-1947), German physicist
Heinrich Hertz (1857-1894), German physicist who discovered the photoelectric effect
Sir Joseph John Thomson (1856-1940), English physicist who discovered the electron

PUZZLING EFFECTS

The photoelectric effect is the process by which electrons are ejected from a metal surface when light is shined on that surface. Since it requires energy to remove an electron from a metal, it is clear that this energy comes from the incident light (that is, the light that falls upon, or strikes, the surface). In 1887, Heinrich Hertz discovered that light striking a metal surface can produce visible sparks if that surface is in the presence of an electric field.

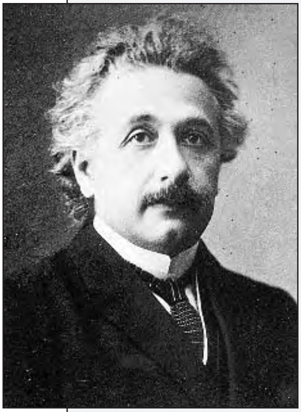
In 1888, the German physicist Wilhelm Hallwachs showed that shining light on a surface can cause an uncharged body to become positively charged (that is, to lose electrons). In 1899, Sir Joseph John Thomson, who had discovered the electron two years earlier, stated that the photoelectric effect involved the emission of electrons from the surface of the metal. This explained Hertz's observation (the sparks were created by electrons that were accelerated by the electric field) and also explained Hallwachs's results (the emitted electrons were carrying negative charge away from the metal body, thus leaving it with a net positive charge).

In 1902, the German physicist Philipp P. Lenard showed that the energy of the ejected electrons—or, equivalently, their speed—did not depend on the intensity, or brightness, of the incident light. It was shown in 1904 that the energy of the ejected electrons depended on the frequency, or color, of the light: The higher the frequency of the incident light, the greater the speed of the escaping electrons.

These two discoveries contradicted the classical theories of physics, which held that light was an electromagnetic wave that carried energy based on its intensity. When this energy struck a certain surface, the electrons on the surface would gain energy gradually, or "heat up," until even-

YOUNG EINSTEIN

When Albert Einstein described the photoelectric effect in 1905, he was a young man in his mid-twenties. In 1902, he had been hired as a technical expert in the Swiss patent office in Berne, where he was to remain for seven years; in 1903, he had married Mileva Maric, a friend from his student days in Zurich; and in 1904 the first of their two sons was born.


(The Nobel Foundation)

In 1905, Einstein published three major papers, any one of which would have established his place in the history of science. The first, which was to bring him the Nobel Prize in Physics for 1921, explained the photoelectric effect and formed the basis for much of quantum mechanics. It also led to the development of television. The second concerned statistical mechanics and explained the phenomenon known as Brownian motion, the erratic movement of pollen grains when immersed in water. Einstein's calculations gave convincing evidence for the existence of atoms.

It was the third paper, however, containing the special theory of relativity, that was to revolutionize our understanding of the nature of the physical world. The theory stated that the speed of light is the same for all observers and is not dependent on the speed of the source of the light, or of the observer, and that the laws of nature (both the Newtonian laws of mechanics and Maxwell's equations for the electromagnetic field) remain the same for all uniformly moving systems. This theory meant that the concept of absolute space and time had to be abandoned because it did not remain valid for speeds approaching those of light. Events that happen at the same time for one observer do not do so for another observer moving at high speed in respect to the first. Einstein also demonstrated that a moving clock would appear to run slow compared with an identical clock at rest with respect to the observer, and a measuring rod would vary in length according to the velocity of the frame of reference in which it was measured.

In another paper published in 1905, Einstein stated, by the famous equation $E = mc^2$, that mass and energy are equivalent. Each can be transferred into the other because mass is a form of concentrated energy. This equation suggested to others the possibility of the development of immensely powerful explosives.

Such was Einstein's achievement at the age of twenty-six. There had not been a year like it since Sir Isaac Newton had published his *Principia* in 1687. The scientific world quickly recognized Einstein as a creative genius—yet his most important work, on general relativity, still lay before him.

tually they became energetic enough to escape from the surface. If the light was very bright, or intense, the electrons should escape with a large supply of energy—in contradiction to the findings of Lenard. Scientists began to look for a solution to the problem.

The Light-Quanta Hypothesis

In 1905, Albert Einstein published three revolutionary papers. The most famous was on relativity, one was on Brownian motion as evidence for the existence of atoms, and the third was on the photoelectric effect. Einstein suggested that the photoelectric effect could be understood by discarding certain key concepts from classical physics and replacing them with radical new ideas—ideas that would form the basis of modern physics. One of these radical ideas was the concept of light "quanta" (parcels), which had been proposed by Max Planck in 1900.

As an aid to understanding, Einstein suggested that the incident light of the photoelectric effect should not be viewed as a classical wave but rather as a collection of particles—light quanta, later to be renamed "photons." The amount of energy that these photons carry depends on their frequency, not their intensity.

By viewing the incident light as a collection of photons, Einstein was able to explain the photoelectric effect as follows: When a photon strikes a metal surface, there is a strong chance that it will encounter "free electrons," which are electrons that are detached from atoms and can move from atom to atom, conducting electricity or heat. When a photon encounters an electron, it will usually transfer all of its energy to the electron. In general, an electron can absorb only one photon, but it will always absorb this photon in its entirety. After the absorption, the electron, which had very little energy before it absorbed the photon, has the added energy of the photon. If this energy is high enough, the electron will be able to escape from the surface of the metal.

Einstein was able to make several predictions: that the energy of a photoejected electron can never exceed the energy of the photon, and that if the photon's energy is less than the energy needed for the electron to escape, no electrons will be ejected no matter how bright the incident light.

Einstein's explanation for the photoelectric effect came at a time when classical ideas were still strong and the notion of light quanta seemed radical and mysterious. Even Planck and Einstein had reservations about the concepts they had put forward, but they believed that the concepts were helpful in describing what they observed and useful in predicting the outcome of future observations. It would be nearly two decades before these important ideas were universally accepted.

IMPACT

The light-quanta hypothesis became an important part of several larger theories. In 1911, the Danish physicist Niels Bohr began to use the idea of light quanta to account for the emission spectra of atoms. It was known that atoms, when excited, gave off light with certain characteristic frequencies that differed from one atom to the next. The famous "Bohr model" of the atom stated that these frequencies could be understood as the frequency of the light quantum, or photon, emitted by an atom when an electron jumped from a large orbit to a smaller one. Since electrons generally are limited to specific orbits within an atom, the frequency of the emitted photon would depend on the difference in energy levels between the two orbits.

Later, the French physicist Louis de Broglie recognized that light, which had been demonstrated to behave like a wave, also behaved like a particle at times. If light indeed had a "dual character," should not electrons, which had always been understood as behaving like particles, also behave like waves? De Broglie then proposed his famous theory of wave-particle duality, which stated that light and matter had both wave and particle characteristics. These radical notions would have been unthinkable without the concept of photons.

See also Black Holes; Compton Effect; Electrons; Electroweak Theory; Grand Unified Theory; Gravitation: Einstein; Gravitation: Newton; Heisenberg's Uncertainty Principle; Mössbauer Effect; Quantum Mechanics; Relativity; Schrödinger's Wave Equation; Speed of Light; String Theory; Wave-Particle Duality of Light.

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—*Karl W. Giberson*

PHOTOSYNTHESIS

THE SCIENCE: By studying the relationship between green plants, oxygen, carbon dioxide, and light, Jan Ingenhousz discovered all of the major externally observable components of the process of photosynthesis. It would remain for later scientists to understand the internal chemical reactions at the heart of the process.

THE SCIENTISTS:
Jan Ingenhousz (1730-1799), Dutch-born English physician and chemist
Joseph Priestley (1733-1804), English clergyman and chemist
Jean Senebier (1742-1809), Swiss clergyman and naturalist
Antoine-Laurent Lavoisier (1743-1794), French chemist
Nicolas de Saussure (1709-1790), French agriculturist
Melvin Calvin (1911-1997), American chemist and biochemist who identified how carbon dioxide was assimilated by plants

PLANT FOOD

The understanding that green plants synthesize their own food is relatively recent, as is an appreciation of the importance of this process. In photosynthesis, a plant uses two simple, inorganic raw materials, water and carbon dioxide, and, in the presence of light, produces carbohydrate (which constitutes plant food), releasing oxygen gas as a waste product. Light provides the energy for this process. At the time of Jan Ingenhousz's discoveries, photosynthesis was only beginning to be understood.

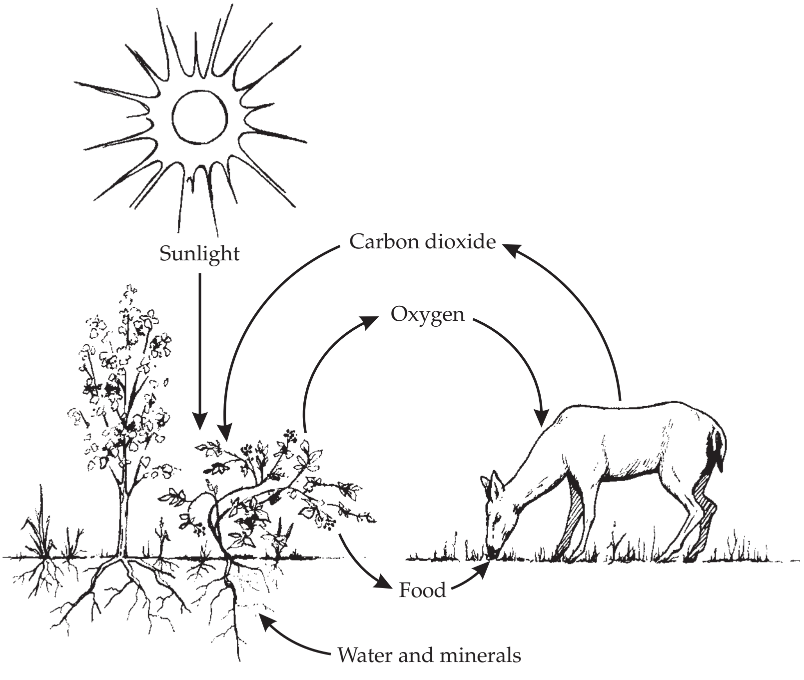
Aristotle and other ancient Greeks had believed that plants obtain all of their nutrition from the soil, analogously to the way animals ingest their food. This belief persisted until the Enlightenment, in the seventeenth and eighteenth centuries, when intensive experimentation and discoveries led to a series of insights into photosynthesis. In the early seventeenth century, Jan van Helmont concluded from an experiment that water rather than soil was the source of the gain in dry weight by growing plants. He was correct that water played a role but incorrect in concluding that water was the sole factor. In the early eighteenth century, Stephen Hales correctly surmised that some of a plant's nutrition was derived from "air."

PLANTS AND "IMPURE AIR"

Ingenhousz's discoveries came later in the eighteenth century, as scientists were making great advances in the understanding of chemistry, especially the composition of air. Chemists of the time, such as Joseph Priestley and Antoine-Laurent Lavoisier, were replacing old ideas with new concepts and terminology. Their chemical dissection of the air revealed that it was composed of various gases, including carbon dioxide, oxygen, hydrogen, and nitrogen. These gases were as yet imprecisely understood, however, and they were given names such as "pure air," "dephlogisticated air," or "vital air" (oxygen) and "impure air," "vitiated air," and "fixed air" (carbon dioxide). Advances in the understanding of photosynthesis both benefited from, and contributed to, the growing knowledge of gases and their roles in chemical reactions.

Ingenhousz's research on plants was inspired by experiments conducted by Priestley. In 1771, Priestley had discovered that air that had been made "impure" (oxygen-poor, in modern terms) by the burning of a candle or the respiration of a mouse could be "restored" by a sprig of mint so that it was again capable of supporting combustion and respiration. By show-

The Photosynthetic Cycle



The processes of photosynthesis and cellular respiration are complementary: Oxygen released into the atmosphere, a by-product of photosynthesis, is breathed in by animals, which in turn breathe out carbon dioxide, the gas that is essential for photosynthesis. (Kimberly L. Dawson Kurnizki) ing that animals inhale "pure air" and plants release it, Priestley had discovered the interdependence of plants and animals, mediated by gases. Priestley was troubled by inconsistency in his results, however.

During the summer of 1779, Ingenhousz conducted more than five hundred experiments on plants. He repeated and extended the work of Priestley, performing many trials on detached leaves immersed in water. Substitution of leaves for the whole plants used by Priestley allowed Ingenhousz to draw conclusions that would have been elusive using whole plants, which are composed of both green and nongreen parts. Ingenhousz analyzed the gas composition of the bubbles that collected on the surfaces of the submerged leaves to determine whether they were "pure air" (oxygen) or "impure air" (carbon dioxide).

Ingenhousz confirmed Priestley's observations and demonstrated, in addition, that light is required for plants to produce oxygen. Ingenhousz showed that, under brilliant illumination, plants could restore "impure air" within several hours, rather than the several days that Priestley had often found. Ingenhousz attributed Priestley's inconsistent results to variation in the degree of illumination of Priestley's plants from experiment to experiment. Ingenhousz also identified leaves as the portion of plants affected by light and showed that the part of the Sun's radiation that affects them is visible light, not heat.

Plants and Light

In addition, Ingenhousz discovered that, although the green parts of plants give off oxygen in sunlight, they emit carbon dioxide in shade and at night and that the nongreen parts of plants emit carbon dioxide in both dark and light conditions. Thus, he provided evidence that plants, like animals, perform respiration. (In a modern, cellular sense, respiration is the process whereby plants, animals, and some other organisms use oxygen to break down organic compounds in order to obtain energy and molecular building blocks. In the process, they release carbon dioxide, the raw material for photosynthesis, and thus they complete what is now known as the "oxygen cycle.") Ingenhousz showed that, overall, the amount of oxygen taken up by green plants in respiration is far smaller than the amount released through photosynthesis.

Ingenhousz immediately published the results of his summer's work in *Experiments upon Vegetables: Discovering Their Great Power of Purifying the Common Air in the Sunshine and of Injuring It in the Shade and at Night* (1779). Subsequently, Priestley claimed that he had discovered the light requirement before Ingenhousz had. Thus began a long-running quarrel between the two men over the priority of their claims. Most scholars, however, credit Ingenhousz with the breakthrough.

Plants and Carbon

Working at about the same time as Ingenhousz, Swiss naturalist Jean Senebier repeated and extended Ingenhousz's experiments. Senebier showed that plants must have access to carbon dioxide in order to liberate oxygen and that the amount of oxygen liberated is related to the amount of carbon dioxide available to the plant. Using Senebier's findings, Ingenhousz subsequently established that plants retain weight from the carbon in the carbon dioxide they absorb. Ingenhousz thereby disproved the idea that the carbon in plants is absorbed through the roots, from humus in the soil. His finding explained the disappearance of carbon dioxide during photosynthesis. He published these research results in the second of his two works on photosynthesis, *An Essay on the Food of Plants and the Renovation of Soils* (1796).

Impact

Ingenhousz's work laid the groundwork for further research on photosynthesis. In 1804, Nicolas de Saussure discovered that a growing plant gains more in dry weight than just the weight of the carbon dioxide it absorbs. De Saussure correctly reasoned—in a throwback to van Helmont—that water also contributes to the increase in dry matter of the plant during photosynthesis.

Although Ingenhousz discovered the requirement for light, he did not determine the function of light in photosynthesis. Robert Mayer, a physicist, demonstrated in the mid-nineteenth century that the amount of energy that is liberated by the combustion of the organic matter produced in photosynthesis is equivalent to the amount of light energy that the plant has absorbed. This finding showed that photosynthesis is a mechanism for converting the radiant energy of the Sun into a stored, chemical form of energy. The organic molecules produced in photosynthesis are used for energy and as building blocks for other organic molecules, both plants and by the animals that eat them. The oxygen released by photosynthesis is essential to plant and animal respiration. Photosynthesis is one of the most important processes on Earth.

Late in the nineteenth century, the overall chemical equation for photosynthesis was formulated, stating that carbon dioxide and water, in the presence of light, yield glucose and oxygen. The early twentieth century brought the insight that the oxygen released in photosynthesis is derived from the splitting of water, not from carbon dioxide as Ingenhousz had thought. In the late 1950's, Melvin Calvin was the first to trace the complex chemical path of photosynthesis in plants through a series of intermediate

MELVIN CALVIN ON THE PHOTOSYNTHETIC PATH

Although photosynthesis is one of the fundamental processes of nature, without which no life could exist, its intermediate chemical steps were long considered a complete mystery. There had been no way to learn what happened between the intake of the necessary materials and the formation of the finished product.

Using the green alga *Chlorella pyrenoidosa* in a suspension of water over which a constant light glowed, Melvin Calvin introduced carbon dioxide containing a known amount of radioactive carbon 14. He then traced these irradiated carbon atoms from the moment the carbon dioxide entered the plant through its conversion into the different substances the plant produced. He observed the chemical steps by making extracts of the plant at different stages of its growth; he then measured the radioactivity and examined its contents. Calvin was able to identify eleven intermediate compounds created in the plant, step by step, between the intake of the simple ingredients and the formation of energy compounds.

The problem remained, however, as to how the Sun's energy is converted to the form required to operate the intermediate chemical cycle. Calvin learned that chlorophyll was phosphorescent: It could give off a lingering emission of light after exposure to radiant energy. This ability to hold on to energy in the form of light lasts long enough—approximately one-tenth of a second—for the energy to be transformed into sugars and other substances. The conversion process can be carried out even in the dark.

In the late 1950's, Calvin identified the key "primary product" of the assimilation: phosphoglyceric acid. This led to his finding that photosynthesis and carbohydrate metabolism are closely connected. He then created methods of tracing the path of photosynthetic process from phosphoglyceric acid to the end products, carbohydrates, showing how light and oxygen work in this pathway. Later experiments in Calvin's laboratory proved that chlorophyll, arranged in flat, disclike plates, captures light energy by a layer-to-layer method, operating very much like electronic solar batteries.

For his work "on the carbon dioxide assimilation in plants," Calvin won the 1961 Nobel Prize in Chemistry. In making its presentation, the Nobel Foundation commended Calvin for shedding light on a field of biochemistry "which was, until recently, veiled in obscurity."

Source: Quotations from *Nobel Lectures, Chemistry 1942-1962*. Amsterdam: Elsevier Publishing Company, 1964.

compounds to its carbohydrate end products. As of the early twenty-first century, at least fifty intermediate steps in photosynthesis had been identified, and the discovery of many more was fully anticipated.

See also Amino Acids; Carbon Dioxide; Citric Acid Cycle; Hydrothermal Vents; Mass Extinctions; Oxygen; Spontaneous Generation; Water.

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—Jane F. Hill

PLANETARY FORMATION

THE SCIENCE: Carl Friedrich von Weizsäcker devised a theory of planetary formation based on contemporary theories of high-temperature turbulence and star formation.

THE SCIENTISTS:

Pierre-Simon Laplace (1749-1827), French astronomer and mathematician
René Descartes (1596-1650), French philosopher, physicist, and mathematician
Immanuel Kant (1724-1804), German philosopher and theoretical physicist
T. C. Chamberlin (1843-1928), American geologist
F. R. Moulton (1872-1952), astronomer
Sir James Jeans (1877-1946), English physicist
Sir Harold Jeffreys (1891-1989), English geophysicist
Carl Friedrich von Weizsäcker (b. 1912), German nuclear astrophysicist

EARLY THEORIES

The earliest scientific hypotheses of planetary formation were those of René Descartes (1644), Immanuel Kant (1755), and Pierre-Simon Laplace (1796). All of them proposed nebular (gas cloud) theories of the formation of the solar system: These stated that the universe (then not known beyond the Sun and five planets) was filled with gas and dustlike particles of matter. Descartes, the French mathematician and philosopher, imagined a large primary gas vortex of circular shape, surrounded by still smaller eddies, from which, respectively, the Sun, major planets, and their satellites were to have formed as the result of turbulent collision and condensation.

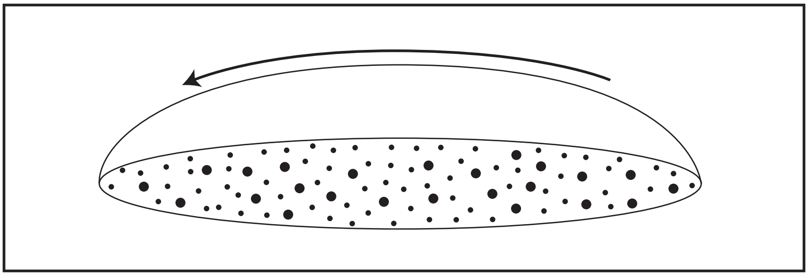
Likewise, the German philosopher Kant, in his *Allgemeine Naturgeschichte und Theorie des Himmels* (1755; *Universal Natural History and Theories of the Heavens*, 1900), proposed a large nebula of rotating gas and dust, which increased speed and flattened, becoming a disk, as it contracted because of gravitational attraction. From this disk, the remaining matter was supposed to have condensed to form the Sun and planets.

Laplace, the French astronomer and mathematician, modified Kant's theory by assuming that as the disk-shaped cloud's rotation increased, centrifugal force at its edge also increased until it exceeded gravity forces acting toward the center, thereafter separating into concentric rings, each subsequently condensing to form a planet.

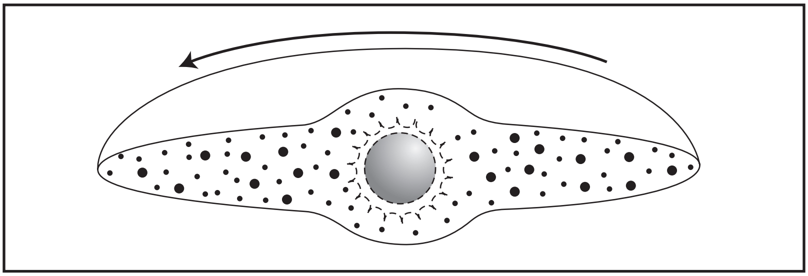
PLANETESIMAL MODELS

A major problem with these nebular hypotheses became apparent after the 1870's, when scientists began to make further observations of stars and stellar nebulae: If the solar system's nebula increased rotational speed as it

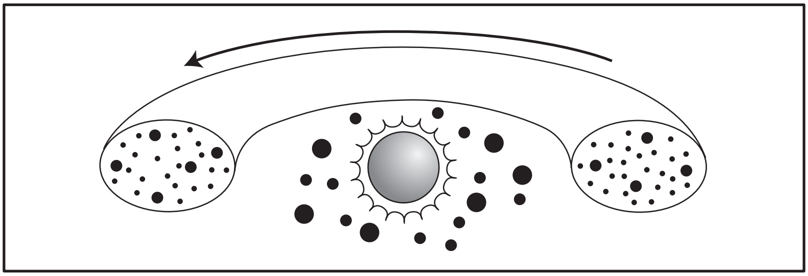
Formation of the Solar System



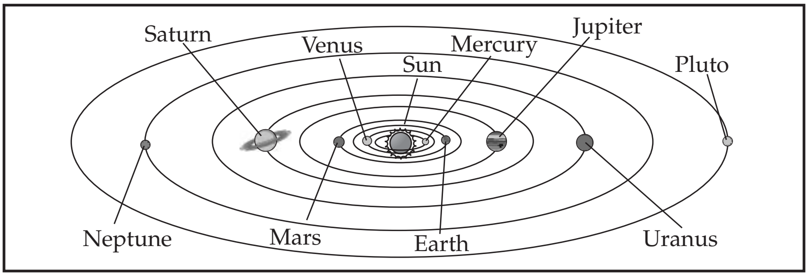
1. The solar system began as a cloud of rotating interstellar gas and dust.



2. Gravity pulled some gases toward the center.



3. Rotation accelerated, and centrifugal force pushed icy, rocky material away from the proto-Sun. Small planetesimals rotate around the Sun in interior orbits.



4. The interior, rocky material formed Mercury, Venus, Earth, and Mars. The outer, gaseous material formed Jupiter, Saturn, Uranus, Neptune, and Pluto.

contracted, the Sun should be rotating much faster than the planets. Its rotational speed should include the bulk of the solar system's angular momentum (speed of rotation); the actual rate, however, was equal to only 2 percent of the solar system's total. James Clerk Maxwell further argued that Laplace's rings would not coalesce directly into planets but would first have to be collected into rings of smaller planetoids, or planetesimals.

In a series of papers published around 1900, American geologist T. C. Chamberlin and astronomer F. R. Moulton argued strenuously against the nebular hypothesis, revived the comte de Buffon's 1745 idea of a catastrophic star-Sun encounter, and presented a tidal-collisional planetesimal model. They proposed that the solar system developed from material ejected by huge solar tides raised in a glancing collision of another star or comet. English physicist Sir James Jeans and geophysicist Sir Harold Jeffreys later proposed a similar theory, in which a close encounter withdrew solar gas filaments that coalesced into beadlike strings of protoplanets.

Within two decades, however, several problems arose with collision accounts of planetary origins. For example, the statistical frequency of interstellar encounters was far too low to make this a probable mechanism. Also, no collision hypothesis could explain the current angular momentum distribution. In 1939, the American astrophysicist Lyman Spitzer showed that gases torn from the Sun or a passing star or comet would disperse before being able to cool sufficiently for condensation.

Lenticular Rings

In mid-1943, at the University of Strassburg in Germany, nuclear astrophysicist Carl Friedrich von Weizsäcker was completing a nebular theory paper titled "On the Formation of Planetary Systems." After initially summarizing the history of earlier nebular hypotheses, he addressed the question of how the Sun's original mass was distributed within the boundaries of the present solar system. This raised the old question about the Sun's low angular momentum.

Weizsäcker assumed that, obeying the laws of momentum and energy conservation, a portion of the original gas nebula would fall into the cloud's center, liberating energy that would carry off most of the Sun's angular momentum. Weizsäcker next discussed whether and how it was possible for particles in the rotating disk to form stable and predictable patterns. He concluded that this would be possible if the primary force at work was gravity. The next stage, his theory's core, derived a set of five concentric lenticular (lens-shaped) rings around the Sun.

The corresponding diagram of this system was eventually reprinted in many textbooks and publications. This nebula figure, which was ingeniously derived from particle dynamics, revealed a ratio of orbital distances that accorded with the well-known Bode-Titius law of 1772, which predicted how far from the Sun each planet should orbit. This provided a major consistency and validity check for the whole theory.

Impact

Although most immediate discussions of Weizsäcker's theory were delayed by World War II, almost all initial published reactions were positive. In the spring of 1945, the noted nuclear physicist George Gamow and the cosmologist J. A. Hynek published a short review, "A New Theory by C. F. von Weizsäcker on the Origin of the Planetary System," in the *Astrophysical Journal*. In their opinion, the theory "allowed an interpretation of the Bode-Titius law of planetary distances" and explained "all the principal features of the solar system"—particularly the fact that all the planets orbit along the same plane and in the same direction—and why larger planets have lower densities.

The theory received further attention in 1946, when the noted astrophysicist Subrahmanyan Chandrasekhar published a favorable review in the *Reviews of Modern Physics*. Nevertheless, German astronomer Friedrich Nölke and Dutch astrophysicist D. ter Haar in 1948 independently published criticisms of Weizsäcker's theory, based on rigorous and extensive hydrodynamic considerations of nebular eddies. Nölke showed that serious difficulties remained in the angular momentum problem. According to ter Haar, there was still a thousandfold difference between the actual and the predicted solar mass. Dutch American astronomer Gerhard Peter Kuiper also rejected Weizsäcker's theory of planetary formation, but he redeveloped the nebular theory, proposing a more random formation.

Later theories incorporated the ideas of turbulence, magnetic fields, and planetesimals, maintaining that supersonically turbulent nebular clouds break up into chaotic swarms, or "floccules," that continually disperse and reform according to certain statistical laws. Despite advances in empirical and theoretical astrophysics, Weizsäcker's theory of planetary formation remains, among some scientists, a partial source and model for theories of solar system formation.

See also Cassini-Huygens Mission; Copernican Revolution; Extrasolar Planets; Galileo Mission; Gravitation: Newton; Halley's Comet; Heliocentric Universe; Herschel's Telescope; Jupiter's Great Red Spot; Kepler's

Laws of Planetary Motion; Nebular Hypothesis; Oort Cloud; Saturn's Rings; Solar Wind; Speed of Light; Stellar Evolution; Voyager Missions.

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—Gerardo G. Tango

PLATE TECTONICS

THE SCIENCE: Plate tectonics—the most important concept of geologic change to emerge during the twentieth century—is the theory that Earth's crust is composed of six major rigid plates as well as many minor plates, which move in response to the convection of the asthenosphere. The interactions of these plates are responsible for the Earth's surficial features and have also had an impact on the evolution of life and ecological systems.

THE SCIENTISTS:

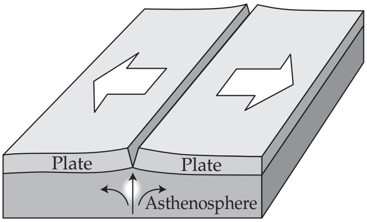
Alfred Lothar Wegener (1880-1930), German scientist-explorer
Arthur Holmes (1890-1965), British geologist
Harry Hammond Hess (1906-1969), American geologist

EARTH'S ARMOR

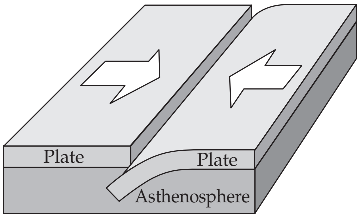
Plate tectonics is the theory that the Earth's crust is composed of six major rigid plates and numerous minor plates with three types of boundaries. The divergent plate boundary is a tensional boundary in which basaltic magma is formed so that the plate grows larger along this boundary. The rigid plate, or lithosphere (the crust and part of the upper mantle, averaging about 100 kilometers thick) moves in conveyer-belt fashion in both directions away from a divergent boundary across the ocean floor at rates of up to 18 centimeters per year. The lithosphere seems to slide over an underlying plastic layer of rock and magma called the asthenosphere.

Eventually, the lithosphere meets a second type of plate boundary, called a convergent plate margin. If lithosphere-containing oceanic crust collides with another lithospheric plate containing either oceanic or continental crust, then the oceanic lithospheric plate is thrust, or subducted, below the second plate. If both intersecting lithospheric plates contain continental crust, they crumple and form large mountain ranges, such as the Himalaya or the Alps. Much magma is also produced along convergent boundaries.

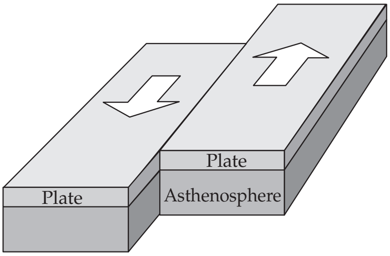
PLATE BOUNDARIES



Divergent Boundary



Convergent Boundary



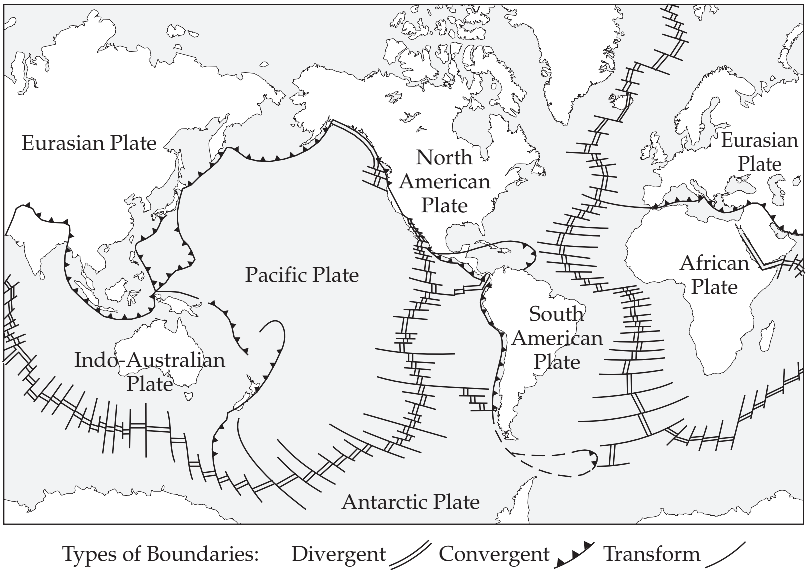
Transform Fault Boundary

A third type of boundary, called a transform fault, may develop along divergent or compressional plate margins. Transform faults develop as fractures transverse to the sinuous margins of plates, in which they move horizontally so that the plate margins may be displaced many tens or even hundreds of kilometers.

The geodynamics occurring in the wake of these movements have created the major features of the Earth's surface, from mountain ranges to volcanoes to islands and deep-sea trenches. Plate tectonics is therefor a major, unifying theory that clarifies many large-scale processes on the Earth.

PIECES OF THE PUZZLE

The major concepts to support the theory were put together only in the late 1950's and the 1960's. Yet, many of the keys to develop-



EARTH'S TECTONIC PLATES AND MID-OCEAN RIDGES

ing the theory had been known for many years. Beginning in the seventeenth century, a number of people noticed the remarkable "fit" in the shape of the continents on opposing sides of the Atlantic Ocean and suggested that the continents could have been joined at one time.

It was not until the early twentieth century that Alfred Wegener put many pieces of this puzzle together. Wegener noticed the remarkable similarity of geological structures, rocks, and especially fossils that were currently located on opposite sides of the Atlantic Ocean. Most notably, land plants and animals that predated the hypothesized time of the breakup of the continents, at about 200 million years before the present, were remarkably similar on all continents. Subsequently, their evolution in North and South America was quite different from their development in Europe and Africa. Climates could also be matched across the continents. For example, when the maps of the continents were reassembled into their predrift positions, the glacial deposits in southern Africa, southern South America, Antarctica, and Australia could be explained as having originated as one large continental glacier in the southern polar region.

One of the biggest problems with the concept of continental drift at that time was the lack of understanding of a driving force to explain how the continents could have drifted away from one another. Then, in 1928, Arthur Holmes proposed a mechanism that foreshadowed the explanation geologists later adopted. He suggested that the mantle material upwelled under the continents and pulled them apart as it spread out laterally and produced tension. The basaltic oceanic crust would then carry the continents out away from one another much like rafts. When the mantle material cooled, Holmes believed, it descended back into the mantle and produced belts along these areas.

From the 1920's to the early 1960's, however, continental drift theories had no currency, for there was no real evidence for driving forces that might move the continents. It was not until the ocean floors began to be mapped that evidence was found to support a plate tectonic model. The topography of the ocean floor was surveyed, and large mountain ranges, such as the Mid-Atlantic Ridge with its rift valleys, and the deep ocean trenches were discovered.

Harry Hess suggested in the early 1960's that the oceanic ridges were areas where mantle material upwelled, melted, and spread laterally. Evidence for this seafloor spreading hypothesis came from the mirror-image pattern of the periodically reversed magnetic bands found in basalts on either side of the ridges. The symmetrical magnetic bands could be explained only by the theory that they were originally produced at the ridges, as the Earth's magnetic field periodically reversed, and then were spread laterally in both directions at the same rate.

IMPACT

Plate tectonics is the most important geological theory to emerge in the twetieth century and is now accepted by virtually all earth scientists. After Hess's observations of seafloor spreading, supporting evidence for plate tectonics began to accumulate: Further magnetic pattern surveys on ocean floors confirmed that the symmetrical pattern of matching magnetic bands could be found everywhere around ridges. Also, earthquake, volcanic rock, and heat-flow patterns were discovered to be consistent with the concept of magma upwelling along rises and seafloor material being subducted along oceanic trenches. Oceanic and lithospheric plates could then be defined, and the details of the interaction of the plate boundaries could be understood. With this overwhelming evidence, most geologists became convinced that the plate tectonic model was valid.

See also Continental Drift; Earth's Core; Earth's Structure; Geomagnetic Reversals; Hydrothermal Vents; Mid-Atlantic Ridge; Radiometric Dating; Seafloor Spreading.

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—*Robert L. Cullers*

PLUTO

THE SCIENCE: In 1930, amateur astronomer Clyde William Tombaugh discovered Pluto, the most distant planet known in the solar system at the time.

THE SCIENTISTS:

Clyde William Tombaugh (1906-1997), American amateur astronomer

Percival Lowell (1855-1916), American astronomer and founder of the Lowell Observatory

POPULAR ASTRONOMY

In 1920, Clyde William Tombaugh purchased a 5.7-centimeter telescope through the mail from the Sears-Roebuck Company and taught himself astronomy by reading everything he could on the subject. In 1924, he was impressed with Latimer Wilson's article "The Drift of Jupiter's Markings" in *Popular Astronomy*. Wilson's drawings were made from observing the planet with a homemade telescope. Tombaugh learned how to make telescopes through correspondence with Wilson. When Tombaugh built his telescope, he observed Jupiter and Mars and in 1928 recorded these observations in drawings. Fascinated with drawings of Mars released by the Lowell Observatory in Flagstaff, Arizona, and published in *Popular Astronomy*, Tombaugh sent his 1928 drawings to its director, Vesto Melvin Slipher, for some advice.

The Lowell Observatory was founded by Percival Lowell in Flagstaff in 1894. Lowell was fascinated with the maps of the "canals" of Mars made popular by the Italian astronomer Giovanni Schiaparelli in 1877 to 1888. Lowell's observations extended the few dozen canals mapped by Schiaparelli to several hundred. He later popularized his speculations of Mars and alien civilizations in *Mars* (1895), *Mars and Its Canals* (1906), *The Evolution of Worlds* (1909), and *Mars as the Abode of Life* (1908). Although Lowell's theories excited the public and inspired science-fiction writers, astronomers were not convinced. In an attempt to improve his credibility, Lowell initiated the search for a ninth planet.

Planet X

Neptune, the eighth planet, had been discovered in 1846, based on the gravitational effect it was having on the orbit of its neighbor, Uranus. In the same way, the orbit of Neptune was different from what had been predicted, and this led astronomers Lowell and William Pickering to suspect a yet more distant planet. Lowell called this object "Planet X," Pickering "Planet O." Lowell reasoned that if he could predict the orbit of a ninth planet beyond Neptune and find it, the discovery would enhance his professional status and thereby provide respect for his theory of Martian canals.

Lowell began searching with a special camera in 1905, confident of the planet's location and brightness. In 1911, Lowell obtained a new research tool, a Zeiss blink-microscope comparator, to examine the photographic plates. With this device, two photographic plates of the same star region taken at different times are alternately seen or "blinked" in the viewer. Stellar objects, at their great distances, do not appear to move in the time between exposures. Closer objects, such as planets or asteroids, shift on the photographic plate and appear to "blink."

After ten years of searching, Lowell became discouraged. Ironically, Planet X appeared on two separate photographic plates taken before his death in 1916. The planet was camouflaged by the Milky Way background between the constellations Taurus and Gemini. In 1919, Pickering, at the Mount Wilson Observatory, captured the planet on four different photographic plates yet failed to identify it.

Plate Blinking

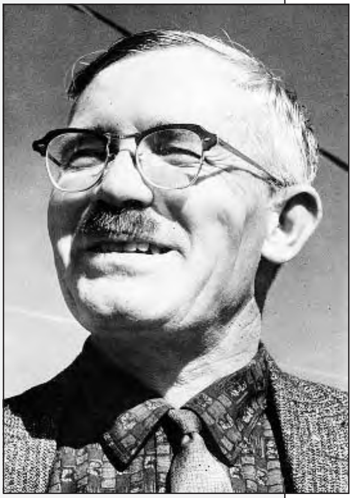
In February, 1929, the Lowell Observatory resumed the quest for Planet X with the completion of a 33-centimeter telescope-camera. Tombaugh's letter and drawings of 1928 could not have arrived at a better time. His observations and drawings caught the attention of Slipher, who was looking for a talented amateur to operate the new photographic telescope. When Slipher offered Tombaugh a job, he accepted.

Initially, Slipher told Tombaugh to search the Gemini region. It took about a week for Slipher and his brother, Edward, to blink the Gemini plates, without result. Disappointed, Slipher directed the research eastward through the zodiac and in June of 1929 asked Tombaugh to take over the task of plate blinking. Tombaugh found plate blinking tedious and was often distracted by other objects in the photographs.

Frustrated with this Herculean task, Tombaugh devised a technique for photographing a region of the zodiac when it was at "opposition" (on the side of the Earth opposite the Sun). Having done so, he noticed several

Clyde Tombaugh: Searching for Planet X

In many ways, Clyde Tombaugh was like his astronomer hero William Herschel, who discovered Uranus unexpectedly during a routine sky survey in 1781. Both were dedicated amateur astronomers and skilled telescope makers who devoted hours to tedious observations. Tombaugh, however, was only twenty-four years old when he discovered Pluto, while Herschel was in his early forties. Furthermore, Tombaugh's yearlong search for Planet X lasted much longer than that of either Herschel or Johann Galle, who discovered Neptune in 1846 on the first night he looked for it, lying less than 1 degree from its predicted position.


(National Archives)

The search for Pluto was complicated by the fact that its orbit is highly eccentric—sometimes even passing inside the orbit of Neptune—and has a large inclination of about 17 degrees from the mean plane of the other planets. It is now known that Percival Lowell's predictions for the position of Pluto were based on faulty calculations, and its discovery within 6 degrees of the predicted location was only a coincidence. Fortunately, Tombaugh did not limit his observations to the predicted area of the sky or to the region close to the mean orbital plane of the planets.

When James Christy discovered Pluto's moon, Charon, in 1978, it was conclusively demonstrated that the mass of Pluto was far too small to cause observable deviations in the orbits of Uranus and Neptune; thus the two larger planets' orbits could not be used to predict Pluto's position. In the 1990's, several icy objects much smaller than Pluto were discovered just beyond its orbit in the Kuiper comet belt with periods of about three hundred years, compared with Pluto's 248-year period.

things. At opposition, asteroids shifted about seven millimeters per day. Neptune, being farther from the Earth and from the asteroid belt, shifted less, about two millimeters per day. He then reasoned that any undiscovered planet beyond Neptune ought to shift less than Neptune. If he could find such a planet, it would truly be Planet X.

In early 1930, Tombaugh resumed plate blinking, but the proximity to the Milky Way slowed his progress. It was then that Tombaugh realized that the Sliphers had blinked through the 1929 Gemini plates in only about a week. He suspected that the Sliphers, in rushing the job, had missed something. Therefore, on the basis of his earlier theory, he decided to rephotograph the region, this time near opposition. The first exposure of the Gemini region on January 21, 1930, was disturbed by wind gusts, which shook the observatory, shaking the telescope and blurring the image. He rephotographed this region on January 23 and 29 and began the tedious blink procedure.

Tombaugh retrieved the poor January 21 plate, compared it with the January 23 plate, and found Planet X exactly where it should be. Using a hand magnifier, he then compared the plates with another taken by a smaller camera. The object was in the same corresponding position on all three plates. Tombaugh then called C. O. Lampland and Slipher to the blink comparator to confirm his find. Both agreed that the object could be Planet X, and Slipher asked Tombaugh to rephotograph the region as soon as possible. Based on photographs shot on February 18, 1930, Lampland, Slipher, and Tombaugh were able to confirm the presence of Planet X.

Impact

Slipher was aware of the impact of the discovery and carefully prepared for the public announcement and the questions that would result. The observatory's reputation was in question over the Martian canal research, and they had to be very sure not only of their data but also of the protocol involved in the announcement.

Thousands of letters arrived suggesting names for the planet. Because planets were usually named after mythological deities, three names headed the list: Minerva, Pluto, and Cronus. The first person to propose the name Pluto outside the Lowell group seems to have been Miss Venetia Burney, eleven years old, of Oxford, England. Pickering, who had predicted a trans-Neptunian planet in 1908, also suggested Pluto after the Greek god of darkness, who was able at times to render himself invisible. Without doubt, all involved in the search would agree this quality of invisibility was appropriate for the new planet.

The Lowell group proposed the name Pluto to the American Astronomical Society and the Royal Society. It was accepted unanimously by both societies in 1930. In 1931, the Associated Press voted the discovery of the planet Pluto one of the top news stories in the world for 1930.

See also Cassini-Huygens Mission; Extrasolar Planets; Galileo Mission; Halley's Comet; Kepler's Laws of Planetary Motion; Nebular Hypothesis; Oort Cloud; Planetary Formation; Saturn's Rings; Solar Wind; Stellar Evolution; Voyager Missions.

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—*Richard C. Jones*

PLUTONIUM

THE SCIENCE: Edwin Mattison McMillan and Glenn Theodore Seaborg discovered the first of the "transuranic" elements (elements heavier than uranium), the most important of which is plutonium.

THE SCIENTISTS:

Edwin Mattison McMillan (1907-1991), American nuclear physicist, cowinner of the 1951 Nobel Prize in Chemistry

Glenn Theodore Seaborg (1912-1999), American chemist, cowinner of the 1951 Nobel Prize in Chemistry

Philip Abelson (1913-1004), American physical chemist

Nuclear Fission and Transuranic Elements

In nuclear physics, fission is defined as the splitting of an atomic nucleus into two parts, especially after that nucleus has been bombarded by a neutron. When the nuclei of the heavier atomic elements, such as uranium and plutonium, are split, tremendous amounts of energy are released.

Plutonium's story has fission at its beginning and at its end. The discovery of fission in 1938 was the stimulus for scientists such as Edwin M. McMillan and Glenn T. Seaborg to discover the transuranic elements neptunium and plutonium, and the discovery of a fissionable isotope of plutonium led to the atomic bomb, dropped on Hiroshima and Nagasaki, Japan, in 1945.

Ironically, the discovery of nuclear fission by the German chemists Otto Hahn and Fritz Strassmann was secondary to their search for a transuranic element—an element with a heavier atomic weight than uranium, which until then was the heaviest element. They had not intended to split the uranium nucleus; they were simply trying to add a neutron to this element to make it heavier. The splitting of the nucleus into such smaller nuclei to form the elements barium and lanthanum came as a surprise, as did the production of large amounts of energy.

The news of the discovery of fission in January, 1939, excited McMillan tremendously. He had worked with the American physicist Ernest O. Lawrence on the development of the cyclotron (a machine that accelerates atomic particles), and this new discovery stimulated him to think of various experiments that could be done with the cyclotron to investigate this new phenomenon.

Element 93

After the discovery of fission, McMillan quickly began to investigate the range that the fission fragments would have. To study this, he put a thin coating of uranium oxide on a cigarette paper and then exposed it to a neutron beam formed by a cyclotron in order to produce fissions in the uranium. He noticed, however, that after the neutron bombardment, the original uranium oxide had a new radioactivity. McMillan suspected that this activity might be from a new element, element 93. According to then-current chemical theories, the new element should have had properties similar to those of the element rhenium. Tests, however, showed that the new element did not behave like rhenium.

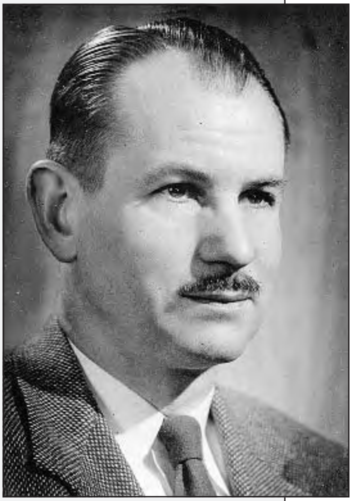
McMillan remained puzzled by this enigma and a year later decided to try the investigation once more with a colleague, Philip Abelson. The hy-

EDWIN MCMILLAN AND PHASE STABILITY

In addition to his work with plutonium, Edwin McMillan made another major contribution to physics through his principle of phase stability. After the war, he worked to improve prewar cyclotrons, or "atom smashers," which produced particles whose energies were limited to 100 million electron volts. The special theory of relativity requires that as a particle increases its velocity, it also increases its mass. Therefore, during the particle's acceleration in the cyclotron, it fell out of synchronism with the radio frequency field and eventually failed to gain energy from it.

McMillan showed theoretically that if one used a new principle of phase stability, the relativistic limitation could be overcome. This was done by changing either the magnetic field holding the particles in orbit or the frequency of the accelerating electric field in such a way that if a particle were too slow compared to the electric field, it was speeded up, or slowed down if it were too fast. In this manner, a particle was "stable" as it was accelerated and remained in synchronization with the accelerating electric field, thereby continually gaining energy.

McMillan's concept of phase stability was immediately put to the test in an electron synchrotron (as he named it), which was constructed at the Berkeley laboratory. It performed as the theory predicted: Electrons were accelerated to 335 million electron volts—more than six hundred times their rest mass—a clear proof that the relativistic limitation had been removed.


(The Nobel Foundation)

The principle of phase stability was soon applied to increase the energy available from cyclotrons. The first such application was to the 184-inch cyclotron at the Berkeley laboratory. Soon a number of "synchrocyclotrons" were built at nuclear laboratories throughout the world. For example, the Bevatron was constructed at Berkeley to accelerate protons to six billion electron volts. With this energy available, antimatter consisting of antiprotons and antineutrons was subsequently discovered.

It is remarkable, but not an uncommon coincidence in scientific history, that the principle of phase stability was discovered independently by another scientist, the Russian Vladimir I. Vexler, working in isolation in the Soviet Union during World War II. For their joint discovery McMillan and Vexler shared the prestigious Atoms for Peace Award in 1963.

pothesis this time was that the new observed radioactivity came from element 93, despite its different chemical properties. This proved correct after exhaustive chemical tests. Before this discovery, there were only 92 known elements. With the discovery of element 93 in 1940, McMillan had opened a new field of transuranic elements. McMillan named the new element neptunium, after the planet Neptune, because the new element followed after uranium, which was named after the planet Uranus.

ELEMENT 94

McMillan immediately started experiments directed at finding element 94, using deuterons from a Berkeley, California, cyclotron. He found new patterns of radioactivity, but before he could complete the work he was called away to the East Coast in 1940 to help develop radar for the U.S. War Department. With McMillan's permission and notes, Seaborg and a team of colleagues took up the research and obtained definitive proof that a second new element had indeed been made in the cyclotron.

In February, 1941, by bombarding uranium with deuterons in a cyclotron, they discovered element 94, plutonium, in the form of plutonium 238. This element was named "plutonium" for the next planet in the solar system after Neptune, which is Pluto. After more experimentation, they discovered plutonium 239, which proved to be a fissionable isotope that might serve as the explosive ingredient in a nuclear bomb and as a nuclear fuel. In 1942, Seaborg and another team of scientists created and identified a second major source of nuclear energy, the isotope uranium 233, which is the key to the use of the abundant element thorium as a nuclear fuel.

IMPACT

In the spring of 1942, Seaborg went to join the operation to make material for an atomic bomb. He moved to the University of Chicago to continue research on plutonium 239. He led a team whose goal was to develop chemical techniques that could be used to manufacture massive quantities of plutonium from uranium.

In the course of its work, Seaborg's team developed new techniques for handling minuscule amounts of radioactive material, transforming such common apparatus as test tubes, flasks, and balances into devices that could handle tiny quantities of material. These techniques enabled his group to work out the chemistry of plutonium. In an important early experiment, they succeeded, on September 10, 1942, in weighing the first visible amount of plutonium 239 (about one-ten-millionth of an ounce).

The successful solutions to the problems of the chemical separation of plutonium led to the construction, in Hanford, Washington, of large plutonium-producing nuclear reactors and a massive plant designed for the chemical separation of plutonium. As is well known, the labors of these and many other scientists and technicians eventually were marshalled by the Manhattan Project at Los Alamos, New Mexico, to produce enough pure plutonium for use in the atom bomb. The world's first detonation of an atomic bomb occurred at Alamogordo, New Mexico, on July 16, 1945. The next detonation would occur over Japan in August, 1945.

See also Alpha Decay; Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Isotopes; Nuclear Fission; Radioactive Elements.

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—*Robert J. Paradowski*

POLIO VACCINE: SABIN

THE SCIENCE: Albert Bruce Sabin's vaccine was the first to stimulate long-lasting immunity against polio without the risk of causing paralytic disease.

THE SCIENTISTS:

Albert Bruce Sabin (1906-1993), Russian-born American virologist

Jonas Edward Salk (1914-1995), American physician, immunologist, and virologist

Renato Dulbecco (b. 1914), Italian-born American virologist

A PARALYZING DISEASE

In the early twentieth century, the first major poliomyelitis (polio) epidemic was recorded. Thereafter, epidemics of increasing frequency and severity struck the industrialized world. By the 1950's, as many as sixteen thousand individuals, most of them children, were being paralyzed by the disease each year.

Poliovirus enters the body through ingestion by the mouth. It replicates in the throat and the intestines and establishes an infection that normally is harmless. From there, the virus can enter the bloodstream. In some individuals it makes its way to the nervous system, where it attacks and destroys nerve cells crucial for muscle movement. The presence of antibodies in the bloodstream will prevent the virus from reaching the nervous system and causing paralysis. Thus, the goal of vaccination is to administer poliovirus that has been altered so that it cannot cause disease but nevertheless will stimulate the production of antibodies to fight the disease.

EARLY VACCINE

Albert Bruce Sabin received his medical degree from New York University College of Medicine in 1931. Polio was epidemic in 1931, and for Sabin polio research became a lifelong interest. In 1936, while working at the Rockefeller Institute, Sabin and Peter Olinsky successfully grew poliovirus using tissues cultured in vitro. Tissue culture proved to be an excellent source of virus. Jonas Edward Salk soon developed an inactive polio vaccine consisting of virus grown from tissue culture that had been inactivated (killed) by chemical treatment. This vaccine became available for general use in 1955, almost fifty years after poliovirus had first been identified.

SEEKING PERMANENT PROTECTION

Sabin, however, was not convinced that an inactivated virus vaccine was adequate. He believed that it would provide only temporary protection and that individuals would have to be vaccinated repeatedly in order to maintain protective levels of antibodies. Knowing that natural infection

Image Not Available

with poliovirus induced lifelong immunity, Sabin believed that a vaccine consisting of a living virus was necessary to produce long-lasting immunity. Also, unlike the inactive vaccine, which is injected, a living virus (weakened so that it would not cause disease) could be taken orally and would invade the body and replicate of its own accord.

Sabin was not alone in his beliefs. Hilary Koprowski and Harold Cox also favored a living virus vaccine and had, in fact, begun searching for weakened strains of poliovirus as early as 1946 by repeatedly growing the virus in rodents. When Sabin began his search for weakened virus strains in 1953, a fiercely competitive contest ensued to achieve an acceptable live virus vaccine.

Tests on Monkeys

Sabin's approach was based on the principle that, as viruses acquire the ability to replicate in a foreign species or tissue (for example, in mice), they become less able to replicate in humans and thus less able to cause disease. Sabin used tissue culture techniques to isolate those polioviruses that grew most rapidly in monkey kidney cells. He then employed a technique developed by Renato Dulbecco that allowed him to recover individual virus particles. The recovered viruses were injected directly into the brains or spinal cords of monkeys in order to identify those viruses that did not damage the nervous system. These meticulously performed experiments, which involved approximately nine thousand monkeys and more than one hundred chimpanzees, finally enabled Sabin to isolate rare mutant polioviruses that would replicate in the intestinal tract but not in the nervous systems of chimpanzees or, it was hoped, of humans. In addition, the weakened virus strains were shown to stimulate antibodies when they were fed to chimpanzees; this was a critical attribute for a vaccine strain.

By 1957, Sabin had identified three strains of attenuated viruses that were ready for small experimental trials in humans. A small group of volunteers, including Sabin's own wife and children, were fed the vaccine with promising results. Sabin then gave his vaccine to virologists in the Soviet Union, Eastern Europe, Mexico, and Holland for further testing. Combined with smaller studies in the United States, these trials established the effectiveness and safety of his oral vaccine.

During this period, the strains developed by Cox and by Koprowski were being tested also in millions of persons in field trials around the world. In 1958, two laboratories independently compared the vaccine strains and concluded that the Sabin strains were superior. In 1962, after four years of deliberation by the U.S. Public Health Service, all three of Sabin's vaccine strains were licensed for general use.

Impact

The development of polio vaccines ranks as one of the triumphs of modern medicine. In the early 1950's, paralytic polio struck 13,500 out of every 100 million Americans. The use of the Salk vaccine greatly reduced the incidence of polio, but outbreaks of paralytic disease continued to occur: Fifty-seven hundred cases were reported in 1959 and twenty-five hundred cases in 1960. In 1962, the oral Sabin vaccine became the vaccine of choice in the United States. Since its widespread use, the number of paralytic cases in the United States has dropped precipitously, eventually averaging fewer than ten per year. Worldwide, the oral vaccine prevented an estimated 5 million cases of paralytic poliomyelitis between 1970 and 1990.

The oral vaccine is not without problems. Occasionally, the living virus mutates to a disease-causing (virulent) form as it multiplies in the vaccinated person. When this occurs, the person may develop paralytic poliomyelitis. The inactive vaccine, in contrast, cannot mutate to a virulent form. Ironically, nearly every incidence of polio in the United States is caused by the vaccine itself.

In the developing countries of the world, the issue of vaccination is more pressing. Millions receive neither form of polio vaccine; as a result, at least 250,000 individuals are paralyzed or die each year. The World Health Organization and other health providers continue to work toward the very practical goal of completely eradicating this disease.

See also Anesthesia; Antisepsis; Aspirin; Contagion; Diphtheria Vaccine; Germ Theory; Hybridomas; Immunology; Penicillin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Streptomycin; Viruses; Yellow Fever Vaccine.

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—*Robin S. Treichel*

POLIO VACCINE: SALK

THE SCIENCE: Jonas Salk's vaccine was the first that prevented polio, resulting in the virtual eradication of crippling polio epidemics.

THE SCIENTISTS:

Jonas Edward Salk (1914-1995), American physician, immunologist, and virologist

Thomas Francis, Jr. (1900-1969), American microbiologist

HISTORY OF POLIO

Poliomyelitis (polio) is an infectious disease that can adversely affect the central nervous system, causing paralysis and great muscle wasting due to the destruction of motor neurons (nerve cells) in the spinal cord. Epidemiologists believe that polio has existed since ancient times, and evidence of its presence in Egypt, around 1400 B.C.E., has been presented. Fortunately, the Salk vaccine and the later vaccine developed by the American virologist Albert Bruce Sabin can prevent the disease. Consequently, except in underdeveloped nations, polio is rare. Moreover, although once a person develops polio there is still no cure for it, a large number of polio cases end without paralysis or any observable effect.

Polio is often called "infantile paralysis." This results from the fact that it is seen most often in children. It is caused by a virus and begins with body aches, a stiff neck, and other symptoms that are very similar to those of a severe case of influenza. In some cases, within two weeks after its onset, the course of polio begins to lead to muscle wasting and paralysis.

The First Vaccine

On April 12, 1955, the world was thrilled with the announcement that Jonas Edward Salk's poliomyelitis vaccine could prevent the disease. It was reported that schools were closed in celebration of this event. Salk, the son of a New York City garment worker, has since become one of the most well-known and publicly venerated medical scientists in the world.

Vaccination is a method of disease prevention by immunization, whereby a small amount of virus is injected into the body to prevent a viral disease. The process depends on the production of antibodies (body proteins that are specifically coded to prevent the disease spread by the virus) in response to the vaccination. Vaccines are made of weakened or killed virus preparations.

Image Not Available

Electrifying Results

The Salk vaccine was produced in two steps. First, polio viruses were grown in monkey kidney tissue cultures. These polio viruses were then killed by treatment with the right amount of formaldehyde to produce an effective vaccine. The killed-virus polio vaccine was found to be safe and to cause the production of antibodies against the disease, a sign that it should prevent polio.

In early 1952, Salk tested a prototype vaccine against Type I polio virus on children who were afflicted with the disease and were thus deemed safe from reinfection. This test showed that the vaccination greatly elevated the concentration of polio antibodies in these children. On July 2, 1952, encouraged by these results, Salk vaccinated forty-three children who had never had polio with vaccines against each of the three virus types (Type I, Type II, and Type III). All inoculated children produced high levels of polio antibodies, and none of them developed the disease. Consequently, the vaccine appeared to be both safe in humans and likely to become an effective public health tool.

In 1953, Salk reported these findings in the *Journal of the American Medical Association*. In April, 1954, nationwide testing of the Salk vaccine began, via the mass vaccination of American schoolchildren. The results of the trial were electrifying. The vaccine was safe, and it greatly reduced the incidence of the disease. In fact, it was estimated that Salk's vaccine gave schoolchildren 60 to 90 percent protection against polio.

Salk was instantly praised. Then, however, several cases of polio occurred as a consequence of the vaccine. Its use was immediately suspended by the U.S. surgeon general, pending a complete examination. Soon, it was evident that all the cases of vaccine-derived polio were attributable to faulty batches of vaccine made by one pharmaceutical company. Salk and his associates were in no way responsible for the problem. Appropriate steps were taken to ensure that such an error would not be repeated, and the Salk vaccine was again released for use by the public.

Impact

The first reports on the polio epidemic in the United States had occurred on June 27, 1916, when one hundred residents of Brooklyn, New York, were afflicted. Soon, the disease had spread. By August, twenty-seven thousand people had developed polio. Nearly seven thousand afflicted people died, and many survivors of the epidemic were permanently paralyzed to varying extents. In New York City alone, nine thousand people developed polio and two thousand died. Chaos reigned as large numbers of terrified people attempted to leave and were turned back by police. Smaller polio epidemics occurred throughout the nation in the years that followed (for example, the Catawba County, North Carolina, epidemic of

1944). A particularly horrible aspect of polio was the fact that more than 70 percent of polio victims were small children. Adults caught it too; the most famous of these adult polio victims was U.S. President Franklin D. Roosevelt. There was no cure for the disease. The best available treatment was physical therapy.

As of August, 1955, more than four million polio vaccines had been given. The Salk vaccine appeared to work very well. There were only half as many reported cases of polio in 1956 as there had been in 1955. It appeared that polio was being conquered. By 1957, the number of cases reported nationwide had fallen below six thousand. Thus, in two years, its incidence had dropped by about 80 percent.

This was very exciting, and soon other countries clamored for the vaccine. By 1959, ninety other countries had been supplied with the Salk vaccine. Worldwide, the disease was being eradicated. The introduction of an oral polio vaccine by Albert Bruce Sabin supported this progress.

Salk received many honors, including honorary degrees from American and foreign universities, the Lasker Award, a Congressional Medal for Distinguished Civilian Service, and membership in the French Legion of Honor, yet he received neither the Nobel Prize nor membership in the American National Academy of Sciences. It is believed by many that this neglect was a result of the personal antagonism of some of the members of the scientific community who strongly disagreed with his theories of viral inactivation.

See also Anesthesia; Antisepsis; Aspirin; Contagion; Diphtheria Vaccine; Germ Theory; Hybridomas; Immunology; Penicillin; Polio Vaccine: Sabin; Schick Test; Smallpox Vaccination; Streptomycin; Viruses; Yellow Fever Vaccine.

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—*Sanford S. Singer*

POLYNOMIALS

THE SCIENCE: In the late eighteenth century, the mathematician Adrien-Marie Legendre found, in the course of trying to solve a differential equation, a family of polynomials that satisfied the same kind of properties that ordinary polynomials did. This suggested the use of those polynomials for representing all functions that had a certain features, and similar families have been studied by mathematicians and physicists ever since.

THE SCIENTISTS:
Adrien-Marie Legendre (1752-1833), French mathematician and textbook-writer
Pierre-Simon Laplace (1749-1827), French mathematician and astronomer, colleague of Legendre
Leonhard Euler (1707-1783), Swiss mathematician and authority on infinite series
Joseph Fourier (1768-1830), French mathematician and physicist

EARLY USE OF POLYNOMIALS

Polynomials have been known in mathematics for centuries. They are expressions involving combinations of whole-number powers of the variable, and the solution of general equations involving polynomials of the third and fourth degree had been part of the renaissance of mathematics in the sixteenth century. One of the central features of polynomials that made them crucial in algebra was the principle of undetermined coefficients. This principle states that if two polynomials are equal for all values of the variable, then the coefficients of like powers of the variable have to be equal. This was taken for granted in the seventeenth century and investigated more rigorously in the eighteenth.

CALCULUS AND DIFFERENTIAL EQUATIONS

The calculus was introduced by Sir Isaac Newton and Gottfried Wilhelm Leibniz in the early seventeenth century. In view of the centrality of polynomials in algebra, they played an important role in the calculus as well. The field of differential equations involves taking a mathematical statement about the rate at which a quantity is changing and trying to figure out an expression for the original quantity. If it was possible to get the original quantity as a simple polynomial, then the solver could use everything that was known about polynomials to analyze the solution. The earliest differential equations, however, already involved functions that were more complicated than polynomials, such as the trigonometric and exponential functions. It seemed as though the background from polynomials was not going to be useful in analyzing such solutions.

Leonhard Euler made an immense contribution to understanding the analysis of such solutions by treating even complicated functions as a kind of polynomial with no limit to the highest power of the term. Such a polynomial of "infinite" degree is called an infinite series, and Euler was a master of manipulating infinite series for many kinds of functions. Once Euler could demonstrate that a function could be represented uniquely as an infinite series, he was able to put information about polynomials to use in talking about complicated functions, although subsequent generations have sometimes found a lack of rigor in his treatment. Nevertheless, his intuition sufficed to get remarkable formulae connecting the solutions of differential equations.

Legendre's Orthogonal Polynomials

Adrien-Marie Legendre managed to carry the work of Euler further with the help of his colleague Pierre-Simon Laplace. Both were interested in the question of how to simplify the problem of gravitational attraction by a body that was spread over space, and the work of the founders of calculus, Newton and Leibniz, indicated that the attraction could be expressed as a differential equation. Solving such differential equations was quite difficult, especially if it was not clear what form the solution was going to take. It was clear that the result was not going to be a simple function, but the problem facing Legendre was to figure out some kind of expression.

Legendre came up with the idea of representing the solution of the differential equation in which he was interested as a series involving powers of the cosine of the angle made at the center of the solid he was studying by two lines connecting the center with the surface. Each of the coefficients of the series would be a polynomial, and from that he could obtain an expression that could be evaluated. If it were possible to determine properties of the polynomials in question, then the solutions for a whole family of differential equations could be evaluated.

In his 1784 paper on celestial mechanics (the application of calculus to the motion of the planets), Legendre generated a number of results about the polynomials that he had derived in the course of working on the solution to the differential equation. In particular, he could derive properties of the polynomials without having to write down their explicit forms (which could be quite complicated). He could figure out how the polynomials interacted with one another. Most important, he was able to show that functions of certain kinds could be represented in only one way as expressions involving his polynomials.

This combination of knowing how the Legendre polynomials (as they came to be known) interacted with one another and that representation of certain kinds of functions was unique by series involving such polynomials led to the study of similar classes of polynomials called “orthogonal.” The evaluation of the expressions that arose in Legendre’s paper required the help of Laplace, and Legendre polynomials are sometimes also called Laplace coefficients. Legendre did not himself develop the study of such polynomials in detail, as he continued to move about in branches of mathematics like geometry and number theory in addition to differential equations. Nevertheless, the use of orthogonal polynomials as a kind of series offered a solution technique for differential equations that would attract engineers as well as mathematicians and physicists. Even when it might be hard to justify the application of techniques on rigorous grounds, the ability to compute a solution as needed enabled defects in rigor to be overlooked.

IMPACT

One of the major subjects for study in physics in the early nineteenth century was the behavior of waves. Regular trigonometric functions like the sine function had simple graphs, but observation found plenty of more complicated curves. Trying to analyze them in terms of ordinary trigonometric functions did not seem helpful but they also did not fit in with standard polynomials.

The mathematician Joseph Fourier recognized that the waves could be analyzed by using a series of trigonometric functions, using the same kind of approach that Legendre had with his polynomials. These Fourier series enabled mathematical physicists to represent the waves uniquely, and the coefficients could be calculated on the basis of the experimental data. Without Legendre’s study of the earlier kind of orthogonal polynomials, Fourier’s results (which were still regarded with suspicion by members of the mathematical community with a concern for rigor) would have been even harder to swallow.

The importance of orthogonal series continued to be demonstrated in the twentieth century. One way of interpreting the results of quantum mechanics is in terms of a certain kind of infinite-dimensional space. While this is clearly beyond what Legendre would have envisaged, the notion that one could still be using the properties of polynomials even in such a remote setting was a guide for those who sought to analyze mathematically the behavior of waves in nature.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Probability Theory; Russell's Paradox; Speed of Light.

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—*Thomas Drucker*

POMPEII

THE SCIENCE: The excavation of the intact ancient Roman city of Pompeii, which had been buried under layers of volcanic ash for more than sixteen centuries, caused a sensation among intellectuals and amateurs alike and brought about a revival of interest in the values and styles of the Roman world.

THE SCIENTISTS:

Carl Jacob Weber (1712-1764), Swiss architect and engineer
Roque Joachim de Alcubierre (fl. mid-eighteenth century), Spanish excavator in charge of uncovering Herculaneum and Pompeii
Johann Joachim Winckelmann (1717-1768), German art historian and archaeologist

A Sleeping Giant

For millennia, the rich volcanic soil of Mount Vesuvius had produced abundant crops for the ancient peoples living in the area of the Bay of Naples. In an ironic twist of fate, that same Mount Vesuvius, which had long been inactive, reawakened on the morning of August 24, 79 C.E., burying the region and its inhabitants under thick layers of volcanic ash and lava. The thriving towns of Pompeii, Herculaneum, and Stabiae were suddenly and completely engulfed in the volcano's eruption.

The eruption of Mount Vesuvius changed the course of rivers and altered entire coastlines, filling in areas of the bay with volcanic rock and ash. When the upheaval finally ceased, residents of Pompeii who returned in hopes of gathering their belongings had difficulty locating their city: Not only was it buried deep under meters of volcanic ash, but it was also no longer on the coast. After a short period of vain attempts to rescue what they could, the inhabitants of the former city moved away, and Pompeii was almost entirely forgotten. The area above the former city came to be known as Civitas, or the City, even though no city was ever again built on the site. Ancient Herculaneum, which now rested below meters of hardened mud, was later built over with a new city, Resina-Ercolano.

Ruthless Excavation

It was not until the late sixteenth century that either ancient city came to light again. Even then, the importance of the discovery went unrecognized: In the 1590's, several ancient remains were exposed during construction projects, but the artifacts were ignored. Nearly a century later, in 1689, engineers found a stone inscribed "Decurio Pompeiis." Thinking it was a reference to Pompeii, a statesman from the era of Republican Rome, the engineers ignored it as well.

Then, in 1709, while digging a well in Resina-Ercolano, workers brought up pieces of marble statuary. The prince d'Elbeuf, a member of the Austrian court that occupied Italy at the time, ordered the excavations to be extended, and he used the recovered treasures to decorate his nearby villa. By 1738, the excavations at Herculaneum drew the attention of Charles IV, the Austrian Bourbon king of the Two Sicilies (Naples and Sicily), who appointed Roque Joachim de Alcubierre director of excavations. Alcubierre was charged with tunneling through the ancient city to find additional treasures. The resulting destruction was enormous. No records were kept of where items were found. Tunnels were drilled and then refilled as soon as all valuable items were removed in order to prevent houses from collapsing in the city above.

All items of value that Alcubierre discovered were taken to the king's palace in Naples (now the Museo Archeologico Nazionale di Napoli).

By 1748, Herculaneum appeared to have given up most of its valuable artworks, and the king ordered excavation to begin at Civitas, which, at that time, was thought to be the site of ancient Stabiae. Herculaneum had been buried under meters of rock-hard volcanic material that required arduous tunneling, but at Civitas, Pompeii was buried under layers of much lighter volcanic ash. For Alcubierre, this meant that work could go even more quickly.

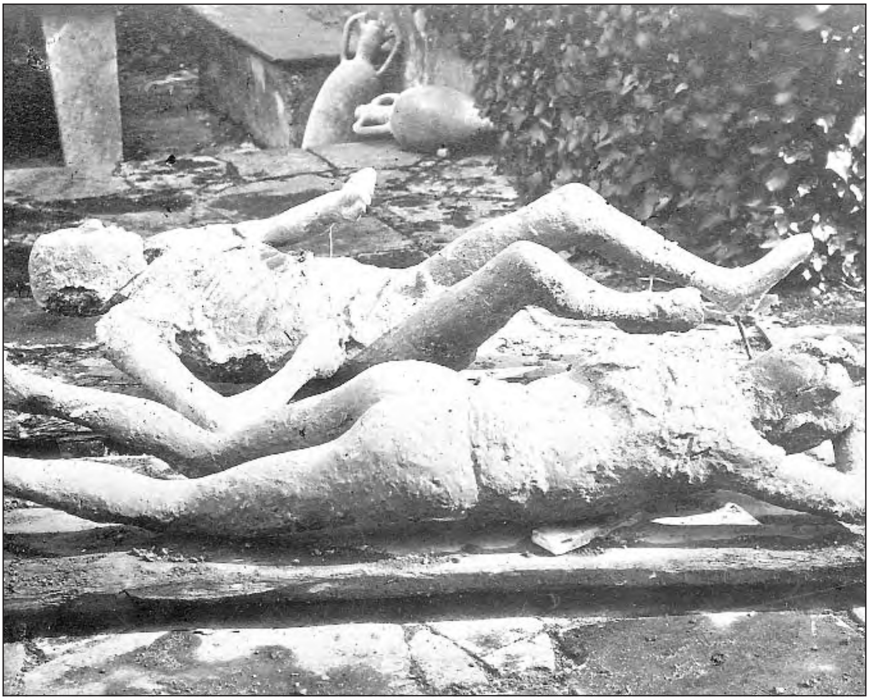
Fortunately, the Swiss architect and engineer Carl Jacob Weber joined the team of excavators in 1750. Weber introduced new archaeological methodologies, including recording the locations of finds, saving "insignificant" objects, such as ordinary household items, and publishing finds for review by the academic community. Weber's time-consuming and laborious techniques infuriated the impatient Alcubierre, and for the remainder of their time together, Alcubierre and Weber quarreled over how to run the excavations.

In 1762, when the famed art historian Johann Joachim Wincklemann visited the site, he was so appalled at Alcubierre's ramrod approach to excavation that Wincklemann wrote an open letter to all European scholars attacking Alcubierre and his mismanagement of the ancient sites. Wincklemann's letter served to awaken international interest in the excavations.

Pompeii Found

In 1763, excavators found an inscription verifying that Civitas was, in fact, the ancient city of Pompeii. For the first time, an entire ancient Roman city had been found intact. Unlike the remains of other ancient cities, such as the Rome itself, which had been exposed to the elements for centuries, Pompeii was completely preserved under layers of ash that protected it from the ravages of time. Pompeii retained the vivid, bright colors of its wall paintings and the minute details of daily life, such as foodstuffs and clothing. Even the exact locations and positions of the citizens who succumbed to the toxic fumes and extreme heat of the volcanic eruption could be recovered by filling the voids where the bodies had decomposed with plaster of Paris. Through this process, it was estimated that two thousand citizens of Pompeii perished during the eruption of Vesuvius.

The excavations at Pompeii revealed a town of about twenty thousand inhabitants as it appeared on that fateful day in August of 79 C.E. Its straight streets were lined with raised sidewalks, along which were located shops, bakeries, small restaurants, taverns, bathhouses, public latrines, laundries, apartments, and houses. At the center of town was a forum,



Plaster casts of two victims of the eruption of Mount Vesuvius in 79 C.E. (Library of Congress)

along with temples and a large food market. The town had a covered theater and an open-air amphitheater with seating for twenty thousand people. On the outskirts of town were the lavish villas of Roman aristocrats who preferred to escape the heat and crowds of the city of Rome for the fresh air of Pompeii's seaside location. Protected for centuries by volcanic ash, the excavations revealed intact wall paintings, furniture, and mosaics, as well as perfectly preserved bronze and marble statuary.

As news about the finds at Pompeii and Herculaneum traveled across Europe, interested scholars and tourists flocked to Pompeii on their Grand Tours to experience firsthand the feeling of walking through an ancient Roman city. Block by block, the excavations continued across Pompeii, until it was realized that the exposed excavated areas were succumbing to the elements and to poorly administered tourism and even looting. It was not until the mid-nineteenth century that any truly scientific or systematic excavations were carried out at the sites. The excavations then continued with greater supervision, and archeological methods continuously improved. Today, one-third of the city of Pompeii and two-thirds of the city of Herculaneum remain unexcavated, reserved for future generations and more advanced archaeological methods.

IMPACT

The excavation of Pompeii opened the ancient Roman world to greater scrutiny than ever before. This glimpse into another world fired the imaginations of many Europeans and American colonists who were chaffing under the excesses and despotism of despised monarchies. Scholars and statesmen began looking to the ancient world for solutions to their own contemporary problems, finding in ancient Rome an ideal of republican values, patriotism, and reason. The desire to overthrow tyrannical monarchies and to reestablish Roman republican forms of government served as a stimulus for the revolutions in both America (1776) and France (1789).

The excavations at Pompeii also had great cultural influences in both Europe and America. The discoveries of entire ancient buildings, complete with rooms, furniture, and artifacts from everyday life, helped to initiate the neoclassical movement in art and architecture and inspired the Empire style in dress and furniture. The revival of classical aesthetics served as a statement of protest against the extravagances of the ornately decorative Baroque and rococo styles popular with the monarchs of Europe. Neoclassical artists, such as Jacques-Louis David, painted moralizing works depicting noble Romans making personal sacrifices for the good of the state. Architects, such as Robert Adams and James Adams, designed rooms inspired by Roman originals, complete with historically accurate bright colors, such as "Pompeii red." The writer Madame de Staël wrote the novel *Corrine: Ou, L'Italie* (1807; *Corrine: Or, Italy*, 1807) based on Pompeii and the composer Giovanni Pacini wrote the opera *L'Ultimo giorno di Pompei* (pr. 1825, pb. c. 1826; the last days of Pompeii), complete with an erupting Mount Vesuvius at the ending.

The discovery of Pompeii also brought to the public's attention the importance of accurately recording and preserving evidence of the past. The excavations were initiated in a random treasure hunt to fill the palaces of Europe with precious artworks, but through time they evolved into a precise scientific endeavor to recapture and preserve not only the artworks but also the details of the everyday lives of those who lived long ago.

See also Dead Sea Scrolls; Rosetta Stone; Stonehenge; Troy.

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—*Sonia Sorrell*

POPULATION GENETICS

THE SCIENCE: Godfrey Hardy and Wilhelm Weinberg independently presented the first model for evaluating changes in gene frequency within a population and gave birth to the field of population genetics.

THE SCIENTISTS:

Wilhelm Weinberg (1862-1937), German physician, geneticist, and medical statistician

Godfrey Harold Hardy (1877-1947), professor of mathematics at Trinity College and Oxford University, and a leading mathematician

Gregor Johann Mendel (1822-1884), Austrian botanist

Charles Darwin (1809-1882), English naturalist

DARWIN AND MENDEL

Within a few decades following the publication of *On the Origin of Species by Means of Natural Selection* (1859) by Charles Darwin, the theory of natural selection had gained considerable approval in the scientific community and had revolutionized the way biologists viewed the natural world. This work provided a comprehensive explanation for both the origin and the maintenance of the seemingly endless variation of life in nature.

Despite its almost immediate acceptance, however, the theory was incomplete in that it failed to explain how individual characteristics are inherited and how the process of inheritance could translate into the kinds of changes in populations and species that originally were predicted in Darwin's theory.

The first of these problems was overcome in 1900, when the work of Gregor Johann Mendel, which had gone almost unnoticed for more than three decades, was rediscovered independently by several researchers. In his series of breeding experiments on garden peas, Mendel had demonstrated that many inherited traits are determined by factors known now as genes. Genes are the molecular units by which hereditary characteristics are passed from one organism to another. From the frequency of traits in his populations of pea plants, Mendel reasoned that an organism receives one gene from each parent for all such heritable traits. In addition, he argued that alleles (alternate forms of the same gene) separate independently and randomly from one another when gametes (egg and sperm) form but combine again during fertilization.

Almost immediately following the rediscovery of Mendel's laws of inheritance, several scientists began to realize the implications for the study of population genetics and evolutionary change. The first observations were noted by the American zoologist W. E. Castle in 1903. More complete analyses were presented independently in 1908 by the English mathematician Godfrey Harold Hardy and the German physician Wilhelm Weinberg. These later works came to be known collectively as the Hardy-Weinberg law and eventually became the foundation for the study of population genetics.

THE HARDY-WEINBERG LAW

The Hardy-Weinberg law states that, given simple patterns of Mendelian inheritance, the frequency of alleles in a population will remain constant from generation to generation, if certain ideal conditions are met. In other words, if these conditions hold true, allelic frequencies will not change, the genetic structure of the population will remain constant over time, and evolutionary change will not occur.

These ideal conditions are as follows. First, the population must be a large, randomly breeding population. In other words, all individuals in the population must have equal reproductive success. If this condition is not met, and certain individuals experience greater reproductive success than others, or if nonran-

Godfrey Harold Hardy.

GENOME FREQUENCIES

Genotype	*Number*	*Genotype frequency*
AA	36	36/100 = **0.36**
AB	48	48/100 = **0.48**
BB	16	16/100 = **0.16**
Total	100	1.00

dom breeding occurs as a result of small population size, then certain genes will be overrepresented in the next generation and the population's gene frequencies will change. Second, the population must be closed; that is, there must be no immigration or emigration of individuals in or out of the population. Third, there must be no spontaneous changes in alleles (mutations). Finally, all alleles must share equal probability of transmission to the next generation. For example, if some individuals possess alleles or combinations of alleles that, under certain environmental conditions, enhance their chances of survival and subsequent reproduction, then their genes will be represented more than those of others in the next generation, gene and allelic frequencies will change, and the population will adapt to environmental conditions. This is the essence of Darwin's theory of natural selection and the primary mechanism by which evolutionary changes proceed.

Given these conditions, the Hardy-Weinberg law asserts that changes in gene frequency in a population (evolution) will not occur. When any one or more of these conditions are violated, however, gene frequencies will be altered and evolution will take place. Thus, by demonstrating the conditions necessary for evolution *not* to occur, Hardy and Weinberg were able to illustrate those factors that actually contribute to evolutionary change.

A SYNTHESIS OF EVOLUTION AND GENETICS

The Hardy-Weinberg law was a critical breakthrough in evolutionary biology that effectively linked Mendel's laws of inheritance with Darwin's theory of natural selection. It demonstrated clearly how cellular mechanisms of inheritance can translate into the microevolutionary changes that Darwin had predicted.

The synthesis of Mendel's and Darwin's work resulted in renewed interest in evolutionary biology and gave birth to the new field of population genetics. This field was advanced greatly during the 1920's, and it continues to be one of the major fields of biological research.

IMPACT

In addition to its impact on basic research, the Hardy-Weinberg law has had several practical applications. Perhaps the most important of these is its use as a conceptual teaching model. The Hardy-Weinberg model is employed in nearly every college-level biology text as a starting point for discussions on evolution, adaptation, and population genetics.

A second important application derived from the model concerns the manner and degree to which harmful alleles manifest themselves within a population. The Hardy-Weinberg model shows how lethal alleles, such as those that code for fatal genetic diseases, can be maintained in a population at low frequencies.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Recombinant DNA Technology; Ribozymes; Stem Cells; Viruses.

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—*Michael A. Steele*

PROBABILITY THEORY

THE SCIENCE: Two mathematicians, Blaise Pascal and Pierre de Fermat, laid the foundations for probability theory when they responded to an inquiry about how to split the stakes from a game. Shortly thereafter, the first textbook on the subject was written by Dutch mathematician Christiaan Huygens.

THE SCIENTISTS:
Blaise Pascal (1623-1662), mathematician, theologian, and philosopher
Pierre de Fermat (1601-1665), mathematician and jurist
Christiaan Huygens (1629-1695), mathematician and physicist

CASTING THE DICE

Probability is the branch of mathematics that assesses how likely certain outcomes are when an experiment is performed. It entered the mathematical literature in the form of questions about games of dice, especially in the work of Gerolamo Cardano (1501-1576). These questions did not seem to have attracted much attention elsewhere, and Cardano's own work suffered from errors. It was not clear at the time how best to define even the basic notions on the basis of which to perform calculations involving events of chance.

Antoine Gombaud, the chevalier de Méré (1607-1684), was a French nobleman who was also a gambler, had investigated two problems. One was that of how to divide up the stakes in a game of dice when the game had to be broken off before it was finished. The other involved the likelihood of throwing a certain number of sixes in a certain number of throws of dice. De Méré knew how many tosses it would take to reach a 50 percent chance of at least one six landing face-up. He assumed that if he multiplied that number by six, he would have the number of tosses it would take for the likelihood of at least two sixes showing up to be more than 50 percent.

Experience showed that this was incorrect (and it had been the view of Cardano, although de Méré was unfamiliar with his work). Recognizing that he was out of his depth, de Méré turned to the eminent French mathematician Blaise Pascal. Pascal recognized the interest of the problems that had been proposed and initiated a correspondence in 1654 with perhaps the most accomplished mathematician of the period, Pierre de Fermat. Two of the world's greatest mathematicians thus turned their attention to a problem raised in the context of gambling. Both Pascal and Fermat were able to recognize the mathematical issues underlying the problem, and between them they created the theory of probability.

RECURSION

The nature of their arguments involved a precise analysis of the collection of possible outcomes at each stage of the games being played. Starting with a small number of principles, they could tackle both of the problems raised by de Méré by the use of a process now known as recursion. Recursion involves recognizing at certain stages of the game that the situation is exactly the same as it was at a previous turn and deriving from that recognition an algebraic equation that can be solved easily. Both Pascal and Fermat felt satisfied with the solutions that they obtained, although the absence of some of their correspondence does not provide a consistent basis for judging the generalizability of their arguments.

PASCAL'S TRIANGLE

One of the key ingredients to Pascal's solution was the triangle that bears his name. The triangle starts with a 1 at its apex, has two 1's in the next row, and continues with 1's at the ends of each row and interior elements obtained by adding up the two numbers immediately adjacent to it in the previous row. This particular triangle had been known for many years and went back at least to medieval Arabic mathematicians. What Pascal recognized was the way in which the numbers in a given row corresponded to the coefficients in expansions of a binomial expression, such as raising $(a + b)$ to the nth power. The amount of mathematical ingenuity that Pascal lavished on the triangle was impressive, but more surprising was the extent to which it enabled him to answer questions about probability.

Fermat's method of proceeding is less well documented, as is frequently the case with Fermat's work. His inclination was seldom to produce more than the details asked for in a problem rather than the method of proof. His willingness to calculate at length to enumerate all the possible outcomes of an experiment was the basis for his results, which agreed with those of Pascal.

Pascal had a religious conversion shortly after his correspondence with Fermat and gave up mathematics to a large extent. He made one further contribution to probability, however, which suggested the wider applications of their work. He framed an argument for belief in God that he suggested would be useful in arguing with those who needed to see everything put in terms of games and gambling. The argument used the idea of expectation and has remained an important contribution to philosophy.

HUYGENS'S THEOREMS

The idea of "expectation" is connected with that of "average," and the rise of probability in the seventeenth century was perhaps connected with the availability of large quantities of data coming from national governments and other large bodies, such as municipalities. This notion provided the basis for the treatise on probability put together by the Dutch mathematician Christiaan Huygens (*Libellus de ratiociniis in ludo aleae*, 1657; *The Value of All Chances in Games of Fortune*, 1714). It is not clear how familiar he was with Fermat's and Pascal's work, but he did write the first systematic treatise on the rudiments of probability.

From a simple axiom he derived three theorems, and on the strength of those he explained the solutions to a sequence of problems, relying on the same sort of technique that had been used by Pascal. Where Pascal had used the combinatorial ideas embodied in his triangle, however, Huygens just lumbered through long computations. In a way, Huygens's work was a step back, but his casting the ideas of probability in a systematic form helped the subject to get something of a foothold among mathematicians.

IMPACT

Until the time of Pascal and Fermat, there was a tendency to appeal to arguments from inspiration and authority in many spheres. By the middle of the seventeenth century, the continued hostilities between Catholic and Protestant forces had cooled down to confrontations rather than conflict. In such a setting there was a call for the kind of argument that depended on something that could be accepted by both sides. Mathematics provided such a setting, and so there was a call for the ideas of probability in both Protestant and Catholic Europe.

Although the correspondence of Pascal and Fermat was not immediately available to subsequent mathematicians, the treatise by Huygens provided some impetus for further research. By the end of the century, there was an explosion of interest in probability, and a number of treatments of the basis of the subject took the place of Huygens's original work. Even in the middle of the eighteenth century, however, the leading authority on probability could look back on the subject as having been the creation of Pascal and Fermat. They had not been the first mathematicians to consider questions arising from games of chance, but they were the first to apply enough mathematical systematization to the subject to make sure that they did not fall into the traps that had bedeviled their predecessors and continue to afflict those who assess questions of probability without mathematics.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Russell's Paradox; Speed of Light.

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—*Thomas Drucker*

PSYCHOANALYSIS

THE SCIENCE: The foundations for psychoanalysis were laid by Sigmund Freud's *The Interpretation of Dreams*, in which he used dream analysis to introduce his influential theory that unconscious motives, molded from relationships in childhood, are basic to adult personality.

THE SCIENTISTS:

Sigmund Freud (1856-1939), Austrian neurologist who founded psychoanalysis

Josef Breuer (1842-1925), Austrian physician who worked with Freud on hysteria

Erik Erikson (1902-1994), psychoanalyst who modified Freud's ideas

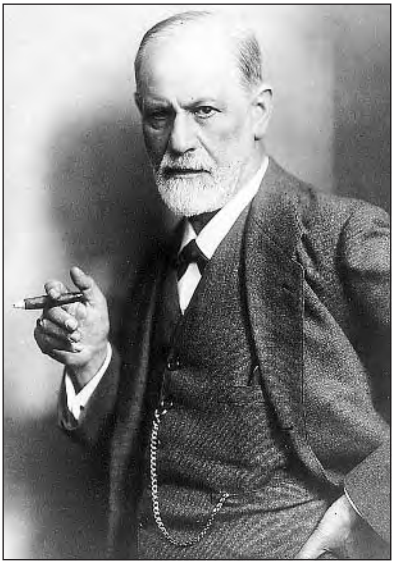
Hypnotism and Hysteria

Die Traumdeutung (1900; *The Interpretation of Dreams*, 1913) is widely considered to be the greatest work of Sigmund Freud. This work is important because it introduced the core ideas of psychoanalysis. Although today the use of psychoanalysis as a therapy in mental health has changed significantly, Freud's theory—that hidden, unconscious feelings and motives determine both the symptoms of mental patients and the normal thoughts and deeds of everyday life—laid the foundations for modern psychiatry and psychological therapies.

Even before he began his study of dreams, Freud, an Austrian neurologist, had already proved himself a capable medical researcher and produced several significant papers on neurological conditions. About 1885, he was introduced to the study of hypnotism, and in the 1890's he worked with Josef Breuer to develop a theory of hysteria. Breuer had called to the attention of Freud the case of a young girl who suffered from apparent paralysis and psychic confusion. He noticed that if the girl were allowed to give verbal expression to her fantasies, the symptoms tended to disappear. Breuer also observed that, whereas the girl could not account for her symptoms in a conscious state, under hypnosis she well understood the connection between her symptoms and past experiences. From this case, Breuer and Freud developed their theory: that hysteria is a condition that imitates a physical or neurological disorder but for which no physical or neurological causes can be discovered. According to the theory, hysteria springs from the repression of desired acts and can be cured only by a kind of catharsis in which unconscious desires are rendered conscious and meaningful.

The Unconscious and the Unintentional

These studies in hysteria contained one basic idea that Freud was later to develop in his theory of psychoanalysis: that a significant aspect of mental life was "unconscious." Inexpressible in words, the unconscious had indirect and sometimes perverse effects upon daily activity. In the 1890's, Freud began to appreciate the general significance of his discovery. He began to analyze his own dreams and unintentional behavior. The unconscious, he realized, could be revealed in many ways other than hypnosis and its significance was not limited to mental patients. *The Interpretation of*



Sigmund Freud. (Library of Congress)

Dreams was significant in that it introduced psychoanalysis not only as a treatment for hysteria but also as a comprehensive theory of human motivation and development.

Freud's work was distinguished both by the methodology he used to investigate dreams and by the meaning he assigned to dreams. He argued that the meaning of a dream is not to be discovered by some hidden external logic, but rather through a process of free association—by getting the *dreamer* to uncover its meaning. According to Freud, dreams are the protectors of sleep; they both express and censor unconscious desires, which are allowed free play once conscious mental activity is suspended. Thus the "manifest" dream—the dream that is remembered in a conscious state—is not the same as the "latent" dream-thought or desire, because this desire is often of such a nature (often sexual) that it conflicts with the requirements of society and the moral code that the individual self-imposes. The manifest dream partly censors this unconscious desire and at the same time expresses it in symbolic form.

Decoding Dreams

The decoding of such symbolism is the entrance into the complexes which, if not understood and rationally addressed, would lead to mental disorder. Several core themes of Freud's "dream book" became further elaborated in his later writings. The centrality of forbidden wishes (the "id") as modified and deflected by a "censor" remained one such continuing theme. This censor was in later work subdivided into the realistic controls of the conscious self: the "ego" as well as the less rational, moralistic restraints and demands of an internalized parental image, the "superego."

One core theme, the eroticized love for one's parent of the opposite sex and jealousy of one's same-sex parental rival, recurred in many dreams. This, later labeled the Oedipus complex, was considered by Freud to be basic to adult sexual identity and to neurosis. The mechanism of displaced symbolization which disguises forbidden dream wishes was later elaborated into Freud's many "mechanisms of defense."

MODIFICATIONS OF FREUDIAN THEORY

Not all of Freud's assumptions in 1900 have withstood the test of time. Freud's theory of motivation rested upon a hydraulic, tension-reducing analogy where such motives as sex and aggression would build up a sort of pressure that would demand some sort of release. The thrust of more recent psychology gives far more attention than did Freud to the joys of seeking out self-enhancing activities that often involve increased tension and excitement.

Major twentieth century psychoanalysts such as Erik Erikson give more emphasis than did Freud to the social interactions between parent and child quite apart from the sexual overtones of such relationships. Moreover, Freud's writings suffer in several ways from male biases characteristic of views of women prevalent in his time. Freud's account of little girls' family affections and jealousies was heavily flavored by an assumption of the biologically rooted inadequacy of females—an assumption that finds few defenders a century later. It has been charged that Freud too readily dismissed as fantasies reports by female patients of sexual abuse by trusted males.

FREUD ON SCIENCE

The work of Sigmund Freud has been the object of criticism for its now seemingly naive, as well as politically incorrect, approach to the human mind and personality. Many have condemned Freudian psychology, if not psychoanalysis as a whole, as "pseudoscience." No one, however, was more aware of the basis for this criticism than Freud himself, as he made clear in 1932:

In no other field of scientific work would it be necessary to insist upon the modesty of one's claims. In every other subject this is taken for granted; the public expect nothing else. No reader of a work on astronomy would feel disappointed and contemptuous of that science, if he were shown the point at which our knowledge of the universe melts into obscurity. Only in psychology is it otherwise; here the constitutional incapacity of men for scientific research comes into full view. It looks as though people did not expect from psychology progress in knowledge, but some other kind of satisfaction; every unsolved problem, every acknowledged uncertainty is turned into a ground of complaint against it.

Anyone who loves the science of the mind must accept these hardships. . . .

Source: Sigmund Freud, preface to *New Introductory Lectures on Psychoanalysis*, 1932. Reprinted in *A General Selection from the Works of Sigmund Freud*, edited by John Rickman (Garden City, N.Y.: Doubleday Anchor, 1957).

Other ideas found in Freud's "dream book" retain the vitality of having endured a century of research. Freud's thesis that dreams are meaningful clues to motives important in conscious, waking life is still treated with respect by many students of personality and biopsychology. With the discovery by twentieth century neuropsychologists—that dreaming episodes in sleep are accompanied by such distinctive neurophysiological signs as rapid eye movements—it became possible to study the nature of dreams with an objectivity greater than was possible for Freud. It appears that dreams are the result of random firing by neurons deep within the brain stem. Such dream episodes occur several times a night, and most are immediately forgotten. The few dreams that are remembered, however, may be precisely those that have personal significance.

IMPACT

Fundamentals of Freud's thought survive in psychoanalysis and in scientific psychology. Thousands of members of the International Psychoanalytic Association still practice their healing art. More important, basic Freudian ideas have become a vital, often unrecognized, part of mainstream psychology. Relationships between the quality of childhood-caretaker attachments and adult styles of relating to others form a popular focus for research in developmental psychology. The importance of implicit ("unconscious") adaptive styles, to cite another example, has become a key concern of cognitive psychology.

Post-Freudian art, literature, films, and television, no less than psychology, treat human emotions as subtle, complex, and often paradoxical, a view more consistent with Freud's portrayal of human nature than of prior nineteenth century conceptions of human rationality. Most of all, the study of the mind—which until 1900 was the domain of magic, religion, and speculative philosophy—has forever become the province of science. Without the stimulus of Freud's ideas, human understanding of life itself would not be at all the same.

See also Manic Depression; Pavlovian Reinforcement; REM Sleep; Split-Brain Experiments.

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—*Paul T. Mason and Thomas E. DeWolfe*

PULMONARY CIRCULATION

THE SCIENCE: Michael Servetus was the first person to publish his findings on how blood circulates from the heart, through the lungs, and then back to the heart, and how breathing has a function other than the cooling of the blood.

THE SCIENTISTS:
Michael Servetus (1511-1553), Spanish physician and church reformer
John Calvin (1509-1564), French Protestant theologian of the Reformation
William Harvey (1578-1657), English physician, first to establish firmly the function of the heart and describe the circulation of blood
Symphorien Champier (c. 1472-1539), French physician and founder of the medical faculty at Lyon, France
Johann Guenther von Andernach (c. 1505-1574), translator of Galen and a professor of medicine

THE RIGHT DIRECTION

During the Renaissance, the study of medicine relied primarily on the interpretation of the Greek and Latin texts of such figures as the Greek physician Hippocrates (c. 460-c. 377 B.C.E.) and the Roman physician Galen (129-c. 199). Although Servetus supported the medical views of his mentor Symphorien Champier, founder of the medical faculty at Lyon and a well-known Galenist, and while he expressed an acceptance of Galenism, his scholarly reflection allowed him to question strict Galenic ideas regarding the functions of the arterial and venous systems. In particular, he questioned the accepted notion that blood moved from the left to the right side of the heart through pores in the septum.

SERVETUS AND CALVIN: SCIENTIFIC PERSECUTION

Michael Servetus believed that the Church's teachings should be understandable to all the faithful, and his resultant theology was denied by Protestants and Catholics alike. In the period of the Reformation, such theological deviance could be life-threatening. Repudiated, Servetus fled to France.

He was welcomed to his new country by an arrest order from the Inquisition. Warned of the danger, he flirted with the idea of emigrating to the New World but instead enrolled at the University of Paris as Michel de Villeneuve. Later he moved to Vienne, just outside Lyons, where he was employed as editor and corrector for the firm of Trechsel. He quickly developed a friendship with Symphorien Champier, a local Humanist and doctor. In 1537, presumably on Champier's advice, Servetus returned to the University of Paris to study medicine. It was probably in Paris that Servetus made the medical discovery that is most commonly associated with his name: the concept of the pulmonary circulation of the blood. He supported himself by publishing medical pamphlets and lecturing on geography, but when he added astrology, he was soon in trouble again: He was brought before the Parlement of Paris to answer charges that included heresy. Fortunately he received a light sentence, but Servetus soon left Paris.

After two or three years at Charlieu, Servetus returned to Vienne, where spent the next twelve years (c. 1541-1553) working as physician and editor. There he initiated a correspondence with the Protestant reformer John Calvin—a former critic who did not welcome the communication. In 1546 Servetus sent a draft of what would become *Christianismi restitutio* (1553). In it, Servetus sought to restore the Church to its original nature and expanded on his idea that God is manifest in all things—skirting but not quite embracing pantheism. Calvin became increasingly exasperated and eventually stopped replying. Despite Servetus's requests, Calvin did not return his books and manuscripts, although he did send a copy of his own book, *Christianae religionis institutio* (1536; *Institutes of the Christian Religion*, 1561), which Servetus inscribed with sarcastic and critical annotations and returned.

Soon after the anonymous publication of *Christianismi restitutio* in January, 1553, Servetus was betrayed to the Inquisition. Calvin—who argued that Protestants should be no less ruthless than Catholics in the fight against heresy—had supplied evidence against him. Servetus escaped arrest but was found in August. Calvin worked to have Servetus prosecuted, and Servetus was condemned for heresy and sentenced to the stake. He was burned, dying in agony, on October 27, 1553. Calvin was never again challenged for control of Geneva.

Michael Servetus. (National Library of Medicine)

Servetus formulated his concept of pulmonary circulation for the first time in 1546, contradicting Galen's misconceptions involving the functions of the lungs, and he accepted theories declaring the existence of pores in the septum separating right and left ventricles. Servetus stated that blood could pass from the right ventricle to the left only by means of the pulmonary artery and the lungs. This significant discovery in human physiology was incorporated into a manuscript of Servetus's, one on theological ideas called *Christianismi restitutio* (1553; partial translation, 1953), which was his final work. In the hope that his treatise would bring about a return to Christianity in its original form, Servetus sought but failed to find a willing publisher, primarily because his work incorporated heretical religious views involving the Trinity and opposition to the sacrament of infant baptism. Servetus, however, secretly agreed to print the manuscript in 1553 at his expense. A draft of the work was sent in 1546 to the Reformer of Geneva, John Calvin, who became Servetus's main enemy. The book was criticized vehemently from the moment of its release and its theories and claims led to Servetus's execution.

Undeniably, the small section of Servetus's ill-fated treatise that contained a detailed description of the pulmonary circulatory system constituted a significant anatomical breakthrough. Not only did Servetus describe the circulation of blood in the heart and the lungs accurately; his work heralded the declaration of the existence of general blood circulation, which was to be fully described seventy-five years later by the English physician William Harvey.

Triple Spirit

Servetus's description of pulmonary circulation, however, was not an exercise in human anatomy alone. In addition, the work was theological. Servetus discussed the Holy Spirit, but he also argued, controversially, that there was a physiological basis to the principle of life. The principle of life was traditionally believed to be manifested in the form of a soul or vital spirit. Aristotle and Galen believed the heart to be the source of what was called animal heat, that blood circulated to warm the body, and that respiration's function was to cool the blood. Galenic thought, however, acknowledged that the vital spirit circulated in blood and originated in the liver. Servetus calculated that the soul of a human being was instilled during the first respiration at birth; the infant's first breath started the circulation of blood.

Servetus argued also for the existence of a "triple spirit" in humans: natural (specifically located in the liver and in the veins), vital (situated in the heart and arteries), and animal (seated in the brain and in the nerves). To explain how these parts of the spirit were joined together, Servetus reasoned that the vivifying factor resided in blood, which, because it constituted a moving component, connected all parts of the body. His idea was similar to the Hebrew conception that the soul resides in blood and originates from the "breath of lives." This conformed in large measure with Galen's teaching regarding the pneuma, that is, the soul or spirit.

Because Servetus had extensive knowledge of anatomical dissection, he could observe firsthand and thus describe the course of blood in the heart and the lungs precisely. Although he maintained the Galenic stance that the blood originated in the liver, Servetus amended Galen's claims that blood passes through orifices in the middle partition of the heart; Servetus had observed that in the heart, the primary movement of blood from right to left did not occur by way of the heart partition because it lacked orifices. This septum was not, according to Servetus, permeable to blood. Instead, he postulated that blood passed from the right ventricle to the left by means of a complex device, or communication joining the pulmonary artery with the pulmonary vein through a system of vessels by way of the lungs. Consequently, he figured that blood passed through the lungs to aerate, that is, to supply blood with oxygen through respiration; it was obvious to him that respiration was a physiological phenomenon. Yet he considered it also to be an aspect of divine process.

Impact

He showed that there were capillaries in the lungs and in the brain that join the veins with the arteries and perform special functions. This discovery of the pulmonary circulation of blood was a critical one whose effects are wide-ranging, and few figures in medicine can compare in stature and significance. In his final work, *Christianismi restitutio*, Servetus's description of the pulmonary circulation system linked oxygen, the air humans breathe, with life.

See also Blood Circulation; Human Anatomy.

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—*Karen R. Sorsby*

PULSARS

The Science: In 1968, Antony Hewish and Jocelyn Bell announced the discovery of pulsars, a new class of star that provides the key to understanding supernovae and neutron stars.

The Scientists:

Jocelyn Bell (b. 1943), graduate student in astronomy
Antony Hewish (b. 1924), radio astronomer and cowinner of the 1974 Nobel Prize in Physics

Identifying "Scruff"

The history of science is full of "accidental" discoveries that eclipse the original intention of the researcher and experiment. Jocelyn Bell's discovery of pulsars illustrates this phenomenon. (The word "pulsar" comes from "pulsating star.")

In 1965, astronomer Antony Hewish was constructing a new kind of radio telescope at the Mullard Radio Astronomy Observatory of the University of Cambridge. Although the telescope was designed to detect quasars (short for "quasi-stellar object"), quasars became the least significant part of the research. Bell, Hewish's graduate student, used the telescope to become the first person to identify a pulsar.

Radio astronomers locate objects in space by using radio telescopes to pick up the signals that these objects emit. While using these telescopes, astronomers may accidentally pick up something referred to as "noise." "Noise" generally means any unwanted radio signal or disturbance that interferes with the listener's ability to understand or use a desired incoming signal or to operate radio equipment. While learning how to use the new telescope, Bell discovered noise—something she called "scruff." The source of this unwanted signal noise was annoying, elusive, and invisible. Hewish's first thoughts were that the pulses were electrical noise within the instrument or perhaps some type of local noise such as ham-operated radios, automobile ignitions, or other electrical interference. Whatever the source, Bell was determined to find it.

Bell was able to distinguish whether the source was terrestrial or extraterrestrial using a simple but unique phenomenon: the difference between Earth time and star time. As the Earth makes its daily rotation about its axis, it also moves a little more than one degree around the Sun. Because of this, the Earth takes an extra four minutes to rotate in relation to the Sun, thus completing the twenty-four-hour day. In relation to the stars, however, a complete rotation of the Earth takes only twenty-three hours and fifty-six minutes. This is known as sidereal, or star, time. Bell observed the pulsating scruff over time and realized that it was synchronized not with Earth time but with sidereal time. This suggested an extraterrestrial origin for the scruff.

Jocelyn Bell. (The Open University)

Little Green Men or White Dwarfs?

Because the pulses occurred with incredible precision (each pulse arrived at intervals of 1.3373011 seconds), Hewish and Bell had to consider the possibility that these regular pulses could be tangible evidence of alien intelligence. In good humor, they identified the source as LGM 1 (Little Green Men 1). The two astronomers were presented with a fascinating dilemma: If they announced the discovery without all the evidence and were proved wrong later, their research would become a textbook example of an improperly conducted scientific investigation. Yet, if these pulses were evidence of alien intelligence, the discovery was monumental. Hewish and Bell decided to attack the problem in the spirit and method of good science.

The LGM hypothesis faded; they renamed the source “CP 1919" (for Cambridge pulsar and its sky position) and turned their attention to describing the phenomenon. Hewish continued the survey over the Christmas vacation in 1967 and placed the raw data on Bell’s desk. Upon her return, Bell began to analyze the chart and found a second source of pulses. Then, sources number three and four appeared. In the next two weeks, Bell was able to confirm that these were, indeed, independent sources. The nature of the source was still eluding Hewish, Bell, and other astronomers who had joined the search at Mullard Observatory. Nevertheless, Hewish and Bell announced their discovery in the journal *Nature* on February 24, 1968. They included a statement suggesting that these unusual sources might be traceable to white dwarf or neutron stars.

In publications later that year, Hewish seemed to favor the white-dwarf hypothesis. The editors of *Nature* seem to have favored the other option because on the cover of that issue were the words, “Possible Neutron Star.” At this point, the problem of identifying the nature of the pulsating sources passed to the world community of scientists. The final linking of the pulsar with a rapidly rotating neutron star came with the combined work of astronomers Franco Pacini and Thomas Gold in 1968.

Impact

The announcement by Hewish and Bell triggered a flood of observational and theoretical papers on pulsars. In the following year, the list of pulsar locations grew to more than twenty-four; the current list includes more than four hundred. Pulsars were not discovered sooner because radio astronomers were using centimeter wavelengths to look at the sky, as opposed to Hewish’s meter wavelengths. This was why the Hewish telescope was successful and Bell was able to resolve the pulses. For this and other outstanding work, Hewish shared the 1974 Nobel Prize in Physics with the British astronomer Sir Martin Ryle. It was the first awarded to astronomers. Hewish's award was based on his role in the detection of pulsars. Interestingly, Bell—the acknowledged discoverer—was not included in the Nobel recognition.

Bell, meanwhile, did not expect the instant celebrity status brought by the news of the discovery of pulsars, especially in the popular press. Bell quietly ended her observations, wrote her dissertation, and accepted a job in another field of research in another part of the country. The story of the pulsars became an appendix in her dissertation.

The history of pulsars appears to follow this sequence: First, a massive star explodes, causing a supernova; then, the core collapses, forming a neutron star. This star is rotating extremely rapidly, sending out beams of radio waves from two directions, or poles. These beams sweep through the universe much like the lights on top of a police cruiser. This becomes the scruff Bell identified on the radio telescope.

Pulsars stimulated further research on stellar evolution and its products such as white dwarfs, neutron stars, collapsars, frozen stars, and black holes. Observing binary neutron stars helps confirm Albert Einstein's general theory of relativity, the distortion of space-time near massive objects, and the existence of gravity waves. The way astronomers view the nature of the universe has changed because Jocelyn Bell persisted in understanding the nature of the scruff on her recording chart.

See also Big Bang; Black Holes; Brahe's Supernova; Cassini-Huygens Mission; Cepheid Variables; Chandrasekhar Limit; Copernican Revolution; Extrasolar Planets; Galactic Superclusters; Galaxies; Hubble Space Telescope; Neutron Stars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; X-Ray Astronomy.

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—*Richard C. Jones*

Qafzeh Hominids

The Science: A team of scientists dated a modern-looking *Homo sapiens* fossil at ninety-two thousand years, more than doubling the length of time that modern humans had been known to exist.

The Scientists:

Helène Valladas, French scientist at the Centre des Fables Radioactivités in France

Bernard Vandermeersch, French physical anthropologist and archaeologist

Dorothy Annie Elizabeth Garrod (1892-1968), English archaeologist and physical anthropologist

Sir Arthur Keith (1866-1955), eminent Scottish anthropologist

Theodore Doney McCown (1908-1969), American archaeologist and physical anthropologist

René Victor Neuville (1899-1952), French archaeologist

Out of Africa?

The origin of modern human beings has been a persistent and vexing problem for prehistorians. Part of the difficulty is that there is widespread disagreement over the relationship between modern humans and their closest extinct relative, Neanderthal man. Neanderthals differ from modern and some Archaic humans by the extreme robustness of their skeletons and by their heavy brow ridges, extremely large faces, and long and low skull caps. Neanderthals were once believed to have lived from approximately 100,000 to 50,000 years ago, while modern humans had been thought to have existed for 40,000 to 50,000 years. Although Neanderthals were originally assumed to have been the ancestors of modern humans, prehistorians now agree that they were too localized, too extreme, and too recent to have been forerunners of modern people.

Archaic fossil humans are less robust and make better candidates as ancestors of modern humans. These have been found in sub-Saharan Africa and also in the Middle East, where they overlap in both location and time with Neanderthals. No specimens of this type have been found in Europe.

Arguments regarding the origin of modern humans center on the issue of one ancestral group as opposed to many ancestral groups. One view assumes that modern humans evolved from many local Archaic types, including Neanderthal. A variation of this perspective holds that, while the ancestors of modern humans may have originated in one locality, they interbred with local peoples they met as they spread throughout the world. Both these views hold that this intermixture of genes explains the physical differences between modern populations.

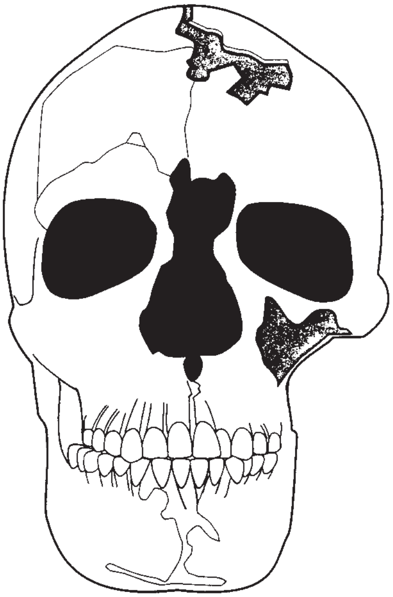
Opposed to this view is the single-origin perspective, which maintains that earlier humans were replaced completely by physically and technologically more advanced members of a new group. The most favored homeland for this new and improved type is sub-Saharan Africa, where there are early examples of possible forerunners of modern humans, but where there is no known example of Neanderthals.

Neanderthals in the Levant?

The region called Levant, which includes Israel, has been of considerable interest to holders of both of the theories just described because it forms a land bridge between Africa and the rest of the world. Any population moving from one region to the other had to pass through the Levant. This fact became particularly important when the first Neanderthal found outside Europe was discovered in Galilee in 1925.

Pursuing this lead, the English archaeologist Dorothy Annie Elizabeth Garrod excavated a series of caves on Mount Carmel, now in Israel, between 1929 and 1934. She was assisted by a young American, Theodore Doney McCown. In two of these caves, Tabun and Skhul, McCown discovered human remains with stone tools that had characteristics associated with Neanderthal remains.

Qafzeh 9 Skull



Back in England, McCown worked with the eminent Scottish anthropologist Sir Arthur Keith to analyze the bones. The fossils at Skhul, although Archaic, resembled modern humans in most characteristics; those at Tabun resembled Neanderthals, although these skulls' features were less exaggerated than those of classic Neanderthals.

Overlapping with Garrod's excavations at Mount Carmel were those by René Victor Neuville from the French consulate at Jerusalem. Neuville excavated the Qafzeh cave between 1933 and 1935, finding the remains of five individuals. Unfortunately, World War II (1939-1945) intervened, followed by the Israeli-Arab conflict of 1947. Neuville died without analyzing his material. From 1965 to 1975, the French archaeologist and physical anthropologist Bernard Vandermeersch continued Neuville's excavations, finding the remains of eight individuals who resembled the non-Neanderthals from Skhul.

The meaning of these remains was interpreted variously. McCown believed that the Mount Carmel population was in the process of diverging into two groups from a more generalized ancestor and that neither were modern humans. Others thought that the fossils represented a cross between Neanderthals and modern humans. A few others thought that Neanderthalls had been caught in the act of evolving into modern humans.

A major problem in making sense of the Levant fields lies in the inaccuracy of dates. Radiocarbon dating methods do not help because they are inaccurate for sites as old as Qafzeh, Tabun, or Skhul. Until recently, all that could be known was that humans of some sort had been in the Levant more than sixty thousand years ago and had lived there for an undetermined time.

Another method of dating, thermoluminescence, helped to clarify the dates. Thermoluminescent dating is used on objects such as pottery that were "fired," or heated during the time that they were used. When such objects are heated again in the laboratory, photons are released, producing thermoluminescence, or glow. The longer ago the object was fired, the more glow results. The greater the glow, the older the object. Thermoluminescence can be used to date much older material than can radiocarbon methods; unfortunately, it is not as accurate as radiocarbon.

The first objects to be dated by thermoluminescence in the Levant were burnt flints from the Neanderthal sites at Kebara. The dating was done by a French-Israeli team headed by Helène Valladas, with results being published in 1987. The Neanderthal site was dated at sixty thousand years, meaning that if the date is correct, Neanderthals were in the Middle East much later than had been thought.

In 1988, a team led by Valladas published a thermoluminescence date of ninety-two thousand years from Qafzeh. If this date is correct, then there were forerunners of modern humans living in the Levant twice as long ago as had been suspected. Furthermore, these individuals were there either before or at the same time as the Neanderthals.

IMPACT

Since thermoluminescence gives only a rough estimate, confirmation by another form of dating is desirable. In the meantime, there have been two dominant reactions by scientists. Those subscribing to the single-origin, out-of-Africa model see the Qafzeh date as confirmation of this hypothesis.

Others, such as the American Milford Wolpoff, dispute this assessment. Wolpoff believes that Neanderthals contributed to the genetic makeup of modern Europeans. He points out that the late Neanderthals in Europe are more like modern Europeans in some respects than are the more modern-looking fossils from Skhul or Qafzeh.

The dates from Qafzeh have been adjusted and continue to raises many questions—particularly between those paleoanthropologists who believe that Neantherthals were basically replaced by modern humans and those who think the relationship between the species is more complex and may involve genetic exchange. Paleoanthropologists such as Richard Klein argue against genetic exchange; Wolpoff and his colleagues cite evidence for a more nuanced interpretation of the evidence that allows for an intermingling of gene pools.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; *Zinjanthropus*.

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—*Lucy Jayne Botscharow*

QUANTIZED HALL EFFECT

THE SCIENCE: The discovery of the quantized Hall effect—that an electric current traveling along a conductor will be bent toward one side when a magnetic force is imposed on the current—led to accurate measurements of certain fundamental constants of nature.

THE SCIENTISTS:

Edwin Herbert Hall (1855-1938), American physicist who discovered the Hall effect in 1879

Klaus von Klitzing (b. 1943), German physicist and winner of the 1985 Nobel Prize in Physics

Robert Betts Laughlin (b. 1950), American physicist who, among other scientists, provided explanations for the integral and fractional quantized Hall effect

SEMICONDUCTORS

With the explosive growth in microelectronics technology, semiconductors became some of the most studied of materials. The understanding of the basic microscopic phenomena in these crystals has advanced to the point where semiconductors are manufactured and manipulated on a molecular level. The properties of silicon, for example, are perhaps the best understood among solids. The measurement of these properties often reflects the complicated nature of the microscopic structure of these materials as well as the specifications of the particular sample. Given such detailed knowledge, the discovery of a novel fundamental phenomenon in semiconductors was startling.

The measurement of the quantized Hall effect depends only upon fundamental constants of nature and not on sample irregularities or impurities. The properties of a solid are especially dependent on a host of internal and environmental parameters, such as the geometry, temperature, purity of the sample, and the history of its preparation. It was surprising to find a manifestation of quantum mechanical behavior in macroscopic samples that is so distinct and precise.

THE CLASSIC HALL EFFECT

The Hall effect is a class of phenomena that occur when a material carrying current is subject to a magnetic field perpendicular to the direction of the current. As first observed in 1879 by the American physicist Edwin Herbert Hall, an electric voltage results in a direction perpendicular to both the current and the magnetic field. The ratio of this voltage to the current is the Hall resistance. In comparison, the normal electrical resistance is the ratio of the voltage in the direction of the current to the current. In the "classic" Hall effect, which occurs for a wide range of temperatures, the Hall resistance increases linearly with the strength of the magnetic field. The constant of proportionality depends on the individual characteristics of the sample and is a measure of the density of electrons that carry current.

The classic Hall effect is well described by what is called an "electron gas," where the motion of the conducting electrons of the solid is considered to be independent from each other and can freely wander within the crystal matrix. The case of the quantized Hall effect, however, requires a two-dimensional electron gas, where the electrons are confined to a plane of conduction. This is realized at the interface between a semiconductor and an insulator, where an electric field draws the semiconductor's electrons toward the two-dimensional interface. Temperatures of a few Kelvins are needed to keep the electrons stuck to the surface.

QUANTUM MECHANICS MEETS THE HALL EFFECT

It was demonstrated in 1966 that electrons confined to motion in such a plane, typically 10 nanometers thick, result in new quantum mechanical effects. The motion of the electrons is quantized, that is, their energies assume one of several evenly spaced discrete values. The number of electrons that can assume a particular energy, called a "Landau level," is proportional to the strength of the magnetic field. Increasing the field strength also increases the spacing between the Landau levels. At low temperatures, the electrons try to minimize their energy, and therefore, the Landau levels are filled sequentially by energy. The highest filled energy is called the "Fermi level." Raising the magnetic field effectively lowers the Fermi level, since more electrons can then be accommodated per Landau level. Alternatively, the Fermi level can be altered simply by changing the number of electrons.

Certain general aspects of the quantized Hall effect were, in fact, predicted in 1975 (five years prior to Klaus von Klitzing's experiments) by the Japanese theorists Tsuneya Ando, Yukio Matsumoto, and Yasutada Uemura of the University of Tokyo. They recognized that when every Landau level is either completely filled or completely empty, the electrical resistance should vanish. Under these conditions of "integral filling," the Hall resistance would be a certain ratio of fundamental constants divided by the number of filled levels and would be independent of the geometry. Unfortunately, the theory was only approximate and would not have been considered reliable for the actual experimental situation. The crucially important aspects of the extreme precision and the robustness of the effect under varying conditions were unforeseen. Also, in experiments as early as 1977 performed by von Klitzing's coworker Thomas Englert, slight plateaus in the Hall resistance were visible in some samples. These anomalous plateaus were considered unexplained by any published theories.

Von Klitzing's Research

Von Klitzing's research through the 1970's included studies of silicon devices in high magnetic fields and under conditions of mechanical stress. In 1980, von Klitzing decided to investigate the anomalies in the Hall resistance. The high-quality samples he used were "metal oxide semiconductor field-effect transistors," or MOSFETs, constructed by his collaborators Gerhardt Dorda of the Siemens Research Laboratory in Munich and Michael Pepper of the University of Cambridge. A layer of insulating oxide is sandwiched between a metal strip, which provides a voltage potential, and the silicon, which supports the two-dimensional electron gas at its surface. The samples were typically about 0.4 millimeter long and .05 millimeter wide. By increasing the voltage on the metal electrode, more electrons could be drawn to the surface of the semiconductor, thereby raising the Fermi level.

Von Klitzing took his experiment to the High Field Magnetic Laboratory of the Max Planck Institute in Grenoble, France, to make measurements using their 20-tesla magnet, the magnetic field strength of which is roughly one million times stronger than the Earth's at ground level. Von Klitzing found for practically every sample that the Hall resistances were equal to the same fundamental ratio divided by integers to within a few percent, extending over well-developed plateaus in the variation of the

Fermi level. The subsequent high-precision results published were measured using the more stable 15-tesla magnet at the University of Würzburg. The accuracy improved to five parts per million, with the primary source of inaccuracy being the instability of the resistance standard. The ratio of the resistance at different plateaus, for example, was the ratio of integers to one part in thirty million. During the plateau regions, the electrical resistance fell very nearly to zero, ten times lower than any nonsuperconducting metal. Moreover, the resistivity continues to decrease as the temperature approaches absolute zero.

Lack of Resistance

The surprising features of the quantized Hall effect sent theoreticians into a flurry of activity. Impurities had been conventionally thought of as either trapping or deflecting electrons off their paths, giving rise to electrical resistance and causing variation in measurements from sample to sample. The seeming lack of involvement of impurities or defects was particularly enigmatic. In 1981, preliminary calculations by University of Maryland theorist Richard E. Prange suggested that although an electron can be trapped in a "localized state" around a defect in the crystal, under the condition that the Landau levels are integrally filled, the current lost to the trapped electron is exactly compensated by an increase in the velocity of electrons near the defect. The electrons move like a fluid, where flow speeds up around a barrier so that the total transported volume remains the same.

Theoreticians came to realize more generally that not only do impurities not cause resistance, but ironically they also are responsible for the plateaus in the Hall resistance as the magnetic field or the Fermi level is varied. The localized states act as a reservoir between Landau levels. As the Fermi level rises past complete filling of the conducting states of a given Landau level, only localized states are left to be filled up. The conducting electrons are effectively unaffected, giving rise to the constancy of the current as the Fermi level is varied.

Impact

The measurement accuracy of the fundamental ratio found in the quantized Hall resistance subsequently improved to one part in 108, and resulted in several immediate benefits. After a series of tests in independent laboratories was completed by the end of 1986, the quantized Hall effect was adopted as the international standard for resistance. The fine-structure constant, which is related to the fundamental Hall ratio by the speed of light, is a measure of the coupling of elementary particles to the electromagnetic field. Complementing high-energy accelerator experiments, the improved determination of the fine-structure constant provides a stringent test for theories of the fundamental electromagnetic interactions.

Soon after the integral quantized Hall effect was explained, a new "fractional" quantized Hall effect was discovered in 1982 by Dan C. Tsui, Horst L. Störmer, and Arthur Charles Gossard of Bell Laboratories. The type of sample they used for creating the two-dimensional electron gas, called a heterojunction, was made by a process called molecular beam epitaxy, where a layer of gallium arsenide positively doped with aluminum is grown onto a substrate layer of pure gallium arsenide. The gallium arsenide electrons are attracted toward the positively doped semiconductor and thus build up into a layer at the interface. The new device was a more perfect crystal and had better conduction properties, which were crucial for a successful observation of the fractional quantized Hall effect. In the fall of 1981, they brought their sample to the Francis Bitter Magnet Laboratory at MIT, where they used the 28-tesla magnet. They were searching at high fields and temperatures less than 1 Kelvin for an "electron crystal," where the electronic orbitals become arranged into a lattice. Instead, they found the same kind of plateaus and drops in the resistance observed in the integral quantized Hall effect, but occurring when only one-third or two-thirds of a Landau level is filled. Since then, many other fractions have appeared.

Theoretical investigations indicated that the observations could not be explained by an electron solid and demanded a radical description of the electronic behavior. In 1983, Robert Betts Laughlin gave a remarkable explanation in terms of a "quantum electronic liquid," in which the motions of the electrons are strongly affected by each other. The electronic liquid is incompressible: Rather than causing the density to increase, squeezing on the liquid causes a condensation of exotic fractional charges. These fractional charges play the role that electrons do in the integral Hall effect and so cause the plateaus at fractional values.

The impact on the field of physics reaches far beyond the accuracy of the measurement of the Hall resistance. Although the effect itself was not expected to be commercially significant, the MOSFET is essentially identical to components that may be important in the following generation of computers. Additionally, similarities emerged between the physical mechanisms of the fractional quantized Hall effect and those of high-temperature superconductors. Common features include a two-dimensional structure, low resistivity, and the collective motion of a macroscopic number of particles. The primary significance of the quantized Hall effects lies in revolutionizing and deepening an understanding of electronic properties of solids in high magnetic fields. For his work in this area, von Klitzing won the 1985 Nobel Prize in Physics.

See also Electron Tunneling; Quantum Mechanics.

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—*David Wu*

QUANTUM CHROMODYNAMICS

THE SCIENCE: Murray Gell-Mann developed the theory of quantum chromodynamics to describe the characteristics of elementary particles called quarks.

THE SCIENTISTS:
Murray Gell-Mann (b. 1929), American physicist
Harald Fritzsch (b. 1943), German physicist
William Bardeen (b. 1941), American physicist

THE ATOM DIVIDED

It was not until the beginning of the twentieth century that it was discovered that atoms were not, in fact, indivisible; instead, they were actually made up of even smaller parts. In 1904, the first suggestion was made that the atom incorporated tiny subparticles called "electrons," which orbited a central core. In 1910, Ernest Rutherford, the English physicist, discovered the atom's core, which was called the "nucleus." Three years later, one of Rutherford's students, Niels Bohr, a Danish physicist, qualified the nature of the electron's orbit around the nucleus. By 1927, the problem of determining the atom's structure had been largely solved. A new science called "quantum mechanics" defined the atom's internal structure as consisting of tiny electrons orbiting a nucleus that contained an assortment of relatively heavy protons and neutrons. By 1930, a concentrated effort had been launched by a newly emerging branch of physics—particle physics—to probe the atom's secrets. Much evidence existed that there were smaller particles yet to be discovered within the atom's core.

Smashing Atoms

The first particle accelerator (atom smasher) was put into experimental use in 1932. The purpose of the accelerator is to cause atoms to collide with one another at extremely high speeds and break up into their elementary parts. Physicists then record the particles as they fly off in the collision. It was during a series of these particle accelerator experiments in the early 1960's that a physicist at the California Institute of Technology, Murray Gell-Mann, developed a series of brilliant postulations regarding the results of these particle accelerator experiments.

By late 1963, Gell-Mann had enough evidence to publish his theory that the nucleus of protons and neutrons was made up of even smaller particles. In reference to a passage in James Joyce's book *Finnegans Wake* (1939), Gell-Mann called these small pieces of protons and neutrons "quarks." He said he chose this name as "a gag . . . a reaction against pretentious scientific language." He published the first discussion of quarks in February, 1964. In 1969, he was awarded the Nobel Prize for his subatomic classification schemes.

Quarks of a Different Color

Gell-Mann postulated six different kinds, or "flavors," of quarks (up, down, bottom, top, strange, and charm), each of which comes in three "colors" (red, green, or blue). The assignment of "colors" to quarks gave rise to a whole new branch of quantum physics—quantum chromodynamics (QCD).

There are no actual flavors in quantum mechanics (much less flavors defined as up, down, and so on), and likewise, at the subatomic level, there are no actual colors. These terms—"flavors" and "colors"—define the specific quantum characteristic of the elementary particle. Through classification and subclassification in the quantum chromodynamic nomenclature, the particles can be classed according to their characteristics and behavior.

Gell-Mann and his colleagues Harald Fritzsch and William Bardeen united the color concepts with the other quark ideas into a single formulation that united all the aspects of nuclear particles. Gell-Mann called presented this QCD theory in September, 1972. In the theory of QCD, the multicolored quarks are held together by a binding force called a gluon. This binding force is not only critical to any discussion of QCD but also fundamental to all of nature; it still drives the community of particle physics. Gluons make up what is called the "strong force," one of the four forces of nature.

IMPACT

QCD clarified a mixture of perplexing observations that had been compiled from numerous accelerator experiments. It enabled a clear understanding of some previously undefined observations. Furthermore, it so completely described the workings within the atomic nucleus that physicists were able to predict certain events before experiments were conducted—the ultimate validation of any theory.

QCD involves exceptionally difficult mathematics that strings together probabilistic mathematical events in a bewildering fashion. Because of this degree of difficulty, it becomes an intricate and enigmatic task to relate the data streaming in from particle accelerators to the field theory itself. Supercomputers have been employed to handle such processing, and all the final possible results from QCD have yet to be compiled.

Quantum chromodynamics is a scientific achievement that stands as a benchmark hypothesis on the landscape of physical theory. It fulfills the long-term dream of physicists of formulating a complete theory of the strong nuclear force (one of the four fundamental forces of nature) and the way in which it interacts with elementary particles at the atomic core. The final goal is to unify all four field theories of the forces of nature into a single grand unified theory of nature.

See also Quantum Mechanics; Quarks.

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—*Dennis Chamberland*

QUANTUM MECHANICS

THE SCIENCE: In attempting to resolve anomalies in the traditional explanation of radiation emitted from certain heated objects, Max Planck restricted the object's "resonators" to discrete (or quantized) energies, an ad hoc solution that proved to have revolutionary implications.

THE SCIENTISTS:

Max Planck (1858-1947), German physicist, director of the Institute for Theoretical Physics of the University of Berlin, and winner of 1918 Nobel Prize in Physics

Albert Einstein (1879-1955), German-born American physicist and winner of the 1921 Nobel Prize in Physics

Rudolf Clausius (1822-1888), German physicist whose studies of the second law of thermodynamics deeply influenced the development of quantum theory

Ludwig Boltzmann (1844-1906), Austrian physicist whose statistical interpretation of the second law of thermodynamics influenced the development of quantum theory

Wilhelm Wien (1864-1928), German physicist whose studies of heat radiation influenced the development of quantum theory

Niels Bohr (1885-1962), Danish physicist who was director of the Institute of Theoretical Physics of the University of Copenhagen and winner of the 1922 Nobel Prize in Physics

THE PROBLEM OF BLACKBODY RADIATION

Toward the end of the nineteenth century, many physicists believed that all the principles of physics had been discovered and little remained to be done, except to improve experimental methods to determine known values to a greater degree of accuracy. This attitude was somewhat justified by the great advances in physics that had been made up to that time. Advances in theory and practice had been made in electricity, hydrodynamics, thermodynamics, statistical mechanics, optics, and electromagnetic radiation.

These classical theories were thought to be complete, self-contained, and sufficient to explain the physical world. Yet, several experimental oddities remained to be explained. One of these was called "blackbody radiation," the radiation given off by material bodies when they are heated.

It is well known that when a piece of metal is heated, it turns a dull red and gets progressively redder as its temperature increases. As that body is heated even further, the color becomes white and eventually becomes blue as the temperature becomes higher and higher. There is a continual shift of the color of a heated object from the red through the white into the blue as it is heated to higher and higher temperatures. In terms of the frequency (the number of waves that pass a point per unit time), the radiation emitted goes from lower to a higher frequency as the temperature increases, because red is in a lower frequency region range of the spectrum than is blue. These observed colors are the frequencies that are being emitted in the greatest proportion. Any heated body will exhibit a frequency spectrum (a range of different intensities for each frequency). An ideal body, which emits and absorbs all frequencies, is called a blackbody; its radiation when heated is called blackbody radiation.

Image Not Available

The experimental blackbody radiation spectrum is bell-shaped, where the highest intensity—the top of the bell—occurs at a characteristic frequency for the material. The frequency at which this maximum occurs is dependent upon the temperature and increases as the temperature increases, as is the case for any heated object. Many theoretical physicists had attempted to derive expressions consistent with these experimental observations, but all failed. The expression that most closely resembles the experimental curve was that derived by John William Strutt, third Baron of Rayleigh, and Sir James Hopwood Jeans. Like the experimental curve, it predicts low intensities for small frequencies; however, it never resumes the bell shape at high frequencies. Instead, it diverges as the frequency increases. Because the values of the theoretical expression diverge in the ultraviolet (high-frequency) region, it was termed the ultraviolet catastrophe. In other words, the Rayleigh-Jeans expression held that a body at any temperature would have its maximum frequency in the ultraviolet region. This was a clear contradiction to the experimental evidence.

Planck's Solution

On December 14, 1900, a soft-spoken, articulate professor presented a solution to the problem of blackbody radiation: Max Planck offered a mathematical exercise that averted the ultraviolet catastrophe. He explained why the heat energy added was not all converted to (invisible) ultraviolet light. This explanation was, to Planck, merely an experiment, a sanding down of a rough theoretical edge. It was that theoretical edge, however, that brought Planck before the august body of the German Physics Society. Six weeks earlier, he had done what he described as a "lucky guess." His discovery did not take place in a laboratory; it took place in his mind. Planck had introduced a mathematical construct into the Rayleigh-Jeans formula. Upon its use in the formula, however, Planck realized the significance of his mathematics. As Planck described, "After a few weeks of the most strenuous work of my life, the darkness lifted and an unexpected vista appeared."

Planck had discovered that matter absorbed heat energy and emitted light energy discontinuously. (Discontinuously means in discrete amounts of quantities, called quanta.) Planck had determined from his observations that the energy of all electromagnetic radiation was determined by the frequency of that radiation. This was a direct contradiction to the accepted physical laws of the time; in fact, Planck also had difficulty believing it.

Quantum Theory

The work of Planck gave rise to quantum theory—a fundamental departure from the theory of light of his day. That theory stated that light waves behaved as mechanical waves. Mechanical waves, much like waves in a pond, are a collection of all possible waves at all frequencies, with a preponderance for higher frequency. In the mechanical wave theory, all waves appear when energy is introduced, and high-frequency waves

WHO REALLY DEVELOPED QUANTUM THEORY?

Until 1978, when historian of science Thomas Kuhn argued that Planck did not discover the quantization of radiant energy, a common interpretation was that Planck had understood these oscillators as actually emitting radiation in multiples of a definite energy that was proportional to its frequency. The proportionality constant, h, which came to be called Planck's constant, is an extremely small number that has the units of mechanical action. Planck saw this constant as a "mysterious messenger" from the microworld. He insisted that the "introduction of the quantum of action h" into physicists' theories about the atom "should be done as conservatively as possible." He knew that the classical wave theory of light had been shown to be true with many experimental observations, and he therefore wanted to preserve the continuous nature of radiation.

Nevertheless, Planck realized that he had accomplished something very important, because on December 14, 1900, when he first made his ideas on quantum theory public, he told his son Erwin that he had just made a discovery "as important as Newton's." On the other hand, he saw his greatest claim to fame in his radiation-law formula, since it agreed perfectly with energy distributions of radiations determined in laboratories for all wavelengths and temperatures.

The person who most profoundly understood the significance of Planck's work on quantum theory was Albert Einstein. He wholeheartedly embraced the idea of quantized energy and used it extensively in his work. For example, he used light quanta to explain the previously inexplicable photoelectric effect, an achievement for which he received the 1921 Nobel Prize in physics. Planck had won the 1918 Nobel Prize for "his discovery of energy quanta." By extending the discontinuity of energy to light as well as to the entire electromagnetic spectrum, and by his quantum studies of the interactions between light and matter, Einstein revealed the great power of the quantum idea.

In 1913, Niels Bohr developed his quantum theory of the hydrogen atom, using quantized electron energy states to account for the hydrogen spectrum. The full-fledged importance of the quantum idea became clear in quantum mechanics, developed in the 1920's by such eminent physicists as Louis de Broglie, Werner Heisenberg, and Erwin Schrödinger. So momentous was this new quantum theory that it has been the dominant theoretical tool for nearly a century, helping physicists and chemists to understand the microrealm of atoms and molecules.

fit more easily and therefore should be present in greater amounts. After empirical observation of blackbody radiation, Planck showed this to be incorrect.

He stated that light waves did not behave like mechanical waves. He postulated that the reason for the discrepancy lay in a new understanding of the relationship between energy and wave frequency. The energy either absorbed or emitted as light depended in some fashion on the frequency of light emitted. Somehow, the heat energy supplied to the glowing material failed to excite higher-frequency light waves unless the temperature of that body was very high. The high-frequency waves simply cost too much energy to be produced. Therefore, Planck created a formula that reflected this dependence of the energy upon the frequency of the waves. His formula said that the energy and frequency were directly proportional, related by a proportionality constant, now called Planck's constant. Higher frequency meant higher energy. Consequently, unless the energy of the heated body was high enough, the higher-frequency light was not seen. In other words, the available energy was a fixed amount at a given temperature. The release of that energy could be made only in exact amounts (later called quanta, or photons), by dividing up the energy exactly. Small divisions of the energy, resulting in large numbers of units, were favored over large divisions of small numbers of units. Lower frequencies (small units of energy) were favored over higher frequencies, and the blackbody radiation was explained.

Planck was quite reluctant to accept fully the discontinuous behavior of matter when it was involved with the emission of light or the absorption of heat energy. He was convinced that his guess would eventually be changed to a statement of real physical significance, for there was no way to see it, visualize it, or even connect it with any other formula. Yet, Planck's new mathematical idea had forced the appearance of a new and somewhat paradoxical physical picture.

IMPACT

Planck's simple formula started a furor in the world of physics, although he did not accept fully its conclusions. In fact, it was not accepted by most physicists at the time and was considered to be an ad hoc derivation. It was felt that in time a satisfactory classical derivation would be found. A few years later, however, the very same idea would be used in three different applications that would establish the quantum theory.

Albert Einstein—who understood the implications of Planck's work better than Planck himself—would use Planck's quantum theory to explain several other experimental oddities of the late nineteenth century. In 1905, Einstein explained the photoelectric effect using Planck's ideas. The phenomenon of the photoelectric effect is that light striking the surface of metals causes electrons to be ejected from that surface. Yet, it was also found that the phenomenon was frequency-dependent (not intensity-dependent). For example, a threshold frequency was needed to allow an electron to be ejected, not a threshold amount of energy caused by a high-intensity light source. Einstein showed that it was the frequency of the incident light that determined whether electrons would be ejected. He had used Planck's theory to explain that the threshold energy required to eject electrons was frequency-dependent. His correct theoretical explanation of the photoelectric effect won for him the 1921 Nobel Prize.

Two years later, in 1907, Einstein again utilized the quantum theory to explain one more "oddity." This explanation dealt with the capacity of objects to accept heat, their heat capacity. At the time, it was accepted that the heat capacity for any object at room-temperature conditions was constant. As the temperature of the object was decreased, however, the heat capacity was no longer at the classical value. In fact, these low-temperature heat capacities are quite contrary to classical theory. The classical result was for atoms vibrating about their equilibrium lattice positions. Einstein assumed that the oscillation of the atoms about their equilibrium lattice positions were quantized. In this instance, the mechanical vibrations of the atoms are subject to quantization. Therefore, in addition to electron oscillations and radiation itself, the motion of particles was found to be quantized.

In 1913, Niels Bohr used the ideas of the quantum theory to explain atomic structure. Bohr reasoned that the emission of radiation from excited atoms could only come about from a change in the energy of the electrons of those atoms. Yet, that radiation was found to be of discrete frequencies. Bohr determined that this implied that only certain quantized energy states were available to atoms and that the only means for change from one state to another was to have an exact (quantized) energy be emitted or absorbed. His theoretical explanation of the atom won for him the 1922 Nobel Prize.

Since these early successes of the quantum theory, the explanation of the microscopic has continued in quantum mechanics. The Planck quantum theory has become the basis for understanding of the fundamental theories of physics. In fact, all the "known" physics of the late nineteenth century has been shown to have a theoretical background based on the ideas of quantized light that converge to the classical theories at high temperatures and large numbers. Yet, the most basic understanding of matter and radiation physics has derived from the quantum theory.

See also Alpha Decay; Atomic Structure; Compton Effect; Electrons; Exclusion Principle; Grand Unified Theory; Heisenberg's Uncertainty Principle; Photoelectric Effect; Quantized Hall Effect; Quantum Chromodynamics; Schrödinger's Wave Equation; Superconductivity; Wave-Particle Duality of Light; X-Ray Fluorescence.

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—*Scott A. Davis*

QUARKS

The Science: Physicists Murray Gell-Mann and George Zweig independently discovered that the disturbingly large number of so-called elementary particles could be effectively organized by assuming that they are composed of quarks.

The Scientists:

- *Murray Gell-Mann* (b. 1929), American particle physicist who won the 1969 Nobel Prize in Physics
- *George Zweig* (b. 1937), particle physicist at the Swiss research institute CERN
- *Yuval Ne'eman* (b. 1925), particle physicist at the Imperial College of London

The Tiniest Units of Matter

At the end of the nineteenth century, the most elementary particles were thought to be atoms, the building blocks of molecules. During the early decades of the twentieth century, however, physicists discovered that the atom was composed of even smaller particles: protons, electrons, and neutrons. These "subatomic" particles were believed to be truly elementary.

Further developments in physics, however, began to reveal many more supposedly elementary particles. The number of such particles climbed from the familiar three in 1930 to more than one hundred by the 1980's. This large number was disconcerting to the physics community and became known as the "particle zoo." Physicists believed that all these particles could not be elementary.

The Eightfold Way

In 1964, in an attempt to simplify the field of elementary particle physics by identifying the smallest building blocks of matter, the existence of subatomic particles known as "quarks" was first postulated. It was suggested that many of the supposedly elementary particles were not elementary at all but were, instead, made up of these even smaller units.

As is often the case in science, this breakthrough was accomplished simultaneously by two scientists working independently: Murray Gell-Mann of the California Institute of Technology and George Zweig of Centre Européen de Recherche Nucléaire (CERN), a famous center for nuclear physics research in Zurich, Switzerland. Gell-Mann was led to the idea of quarks (he took the name from James Joyce's 1939 novel *Finnegans Wake*) by his analysis of mathematical and symmetrical relationships among some of the apparent groupings of the members of the particle zoo.

Together with Yuval Ne'eman, a particle physicist working in England, Gell-Mann had previously developed a way of organizing many of these particles into groups using a scheme called the "eightfold way." This scheme suggested that particles that appeared to be totally different were actually merely different versions of the same basic particle; the differences in appearance, Gell-Mann and Ne'eman theorized, were caused by different quantum numbers belonging to the various particles. (Quantum numbers specify certain physical properties of a particle, such as its charge and magnetic character.)

Aces, Quarks, and Triplets

While Gell-Mann was developing the quark theory by analyzing the deep mathematical symmetries among the elementary particles, Zweig was led to the same ideas while trying to explain an experimental result.

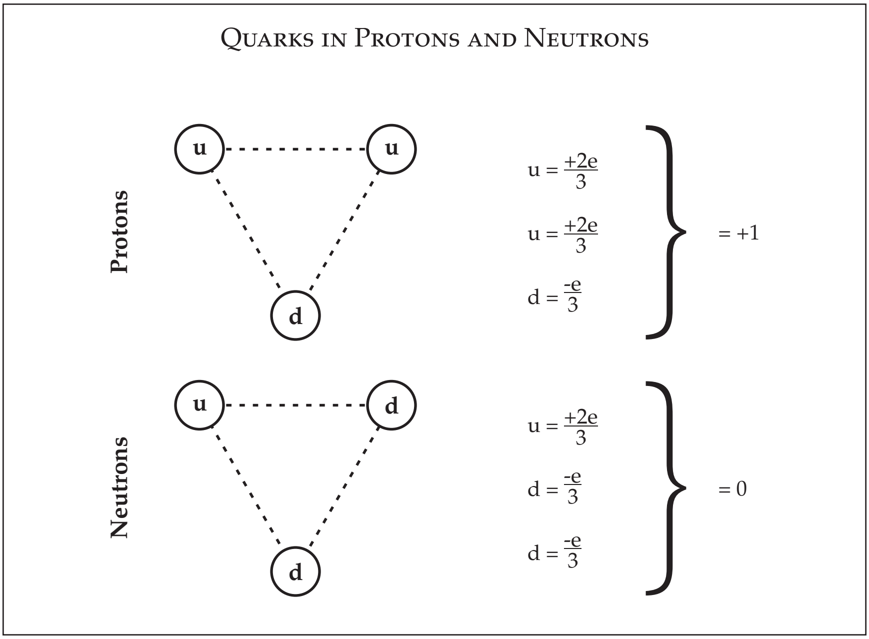
THE COMPLEXITY OF MURRAY GELL-MANN

Murray Gell-Mann was considered a child prodigy and entered Yale University early in his teens, graduating in 1948 at the age of nineteen. Before the age of thirty, he had earned his doctorate in physics from the Massachusetts Institute of Technology, spent a year at the Institute for Advanced Study in Princeton, taught at the University of Chicago, and advanced to full professor at the California Institute of Technology, which he would make his academic home. In addition to winning the Nobel Prize in 1969, he received the Ernest O. Lawrence Memorial Award of the Atomic Energy Commission, the Franklin Medal of the Franklin Institute, the Research Corporation Award, and the John J. Carty medal of the National Academy of Sciences, the 1989 Science for Peace prize, and a host of other awards. He also served on the President's Committee of Advisors on Science and Technology (1994-2001).

This litany of honors and accomplishments—far from complete—belies the scope of Gell-Mann's brilliance, for he is far more than a theoretical physicist. If one were simply to list his contributions to that field—strangeness, the renormalization group, the V-A interaction, the conserved vector current, the partially conserved axial current, the eightfold way, current algebra, the quark model, quantum chromodynamics—they would rival those of giants like Isaac Newton and Albert Einstein. However, his passions extend far beyond physics, embracing linguistics, archaeology, history, psychology, and all matters of biological, cultural, and epistemological evolution. These interests are not restricted to theory; he is deeply concerned with environmental policy as well as world politics. His concept of the "effective complexity" of adaptive systems (which he defines as "the algorithmic information content—a kind of minimum description length—of the regularities of the entity in question") touches on nearly all areas of human thinking.

At the Santa Fe Institute, Gell-Mann has also drawn on the talents of linguists, archaeologists, anthropologists, and geneticists to explore the human language families and their relationships, in the hope of tracing language to its beginnings. For example, the project employs powerful computer programs to analyze different root words for the same meaning, taking into account their changes over time.

As physicist and fellow Nobel laureate Sheldon Glashow told biographer George Johnson: "Not only did Gell-Mann devise the lion's share of today's particle lore, but on first acquaintance you would soon learn . . . that he knew far more than you about almost everything, from archaeology, birds and cacti to Yoruban myth and zymology."



Quarks do not exist as free particles. Rather, they combine to form subatomic particles with integer charges, such as the proton (with a charge of +1) and the neutron (with a charge of 0).

Zweig noticed that when a certain supposedly elementary particle, the pi-meson, disintegrated into other particles, it did so in an unusual way. To explain this unexpected finding, Zweig suggested that the pi-meson was composed of two parts, with individual properties (known as "strangeness") that were transmitted separately to the decay components. To make this scheme work theoretically, Zweig found it necessary to postulate that many of the particles were constructed from an underlying triplet of particles that he called "aces." It was soon determined that Zweig's "aces" were the same as Gell-Mann's "quarks," and "quarks" became the accepted term for the new fundamental triplet.

The nature of the individual quarks, however, was controversial. Gell-Mann believed that they might be purely mathematical entities that would never be detected in the way that other particles are—by the trail of bubbles that they leave in specially designed chambers used to chart their paths. Zweig, however, believed that quarks should be physically observable.

To resolve this dilemma, researchers began experiments to search for individual quarks. They searched in accelerators, in cosmic rays, in chunks of normal matter, even in oysters, but to no avail. Quarks were nowhere to be found, suggesting that Gell-Mann had been correct.

In 1968, however, experiments at the new Stanford Linear Accelerator Center (SLAC) showed that electrons bouncing off protons were recoiling in a way that suggested they were hitting something hard and small inside the proton. Nevertheless, no quarks were observed directly and individually, despite much effort to find them.

Physicists came to believe that quarks are bound together very tightly by particles called "gluons." The strength of the binding is so great that quarks can never be separated from one another. Thus, quarks are fundamental building blocks of larger particles, but they exist only in combination with other quarks and can never be observed independently.

IMPACT

The significance of the idea of quarks lies in the central role that it plays in the theories developed by the physics community to explain the interactions among the various kinds of natural forces. One of the deepest mysteries in twentieth century physics, for example, was the nature of the nuclear force that holds protons tightly packed together in the nucleus of an atom. Since protons are all positively charged, they experience a powerful electrical repulsive force that should push them apart. Yet there is a force—the "strong force"—that holds them together. The source of the strong force was a mystery until the development of the quark theory.

Perhaps the most significant accomplishment of the quark theory will be its role in the development of a "unified field" theory, the hunt for a grand unified theory. Scientists hope that such a theory will one day unify the explanations of all the various natural forces under a single theoretical umbrella. Some unity has been achieved via the creation of various grand unified theories. These theories show that the electromagnetic, weak, and strong forces are similar in that each has a "force carrier" called, respectively, the "photon," the "intermediate bosons," and the "gluon." Physicists are searching for the "graviton," the postulated carrier of the gravitational (and fourth) force. It has been suggested that all of these forces may have emerged from a single force during the first few moments of the "big bang" that created the universe. If an understanding of gravity can be incorporated into one of the grand unified theories, then scientists will have shown how all the forces are merely different manifestations of a single original force. The quark theory is an indispensable part of this grand search.

See also Quantum Chromodynamics.

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—*Karl W. Giberson*

QUASARS

THE SCIENCE: Maarten Schmidt recognized that previously mysterious "quasi-stellar objects," or "quasars," must be very luminous, very distant objects in space.

THE SCIENTISTS:

Maarten Schmidt (b. 1929), astronomer who discovered the nature of quasars

Allan Rex Sandage (b. 1926), astronomer at the Mount Wilson and Mount Palomar Observatories

Thomas A. Matthews (b. 1924), astronomer who specialized in identification of strong radio sources

Cyril Hazard (b. 1925), radio astronomer at Jodrell Bank Radio Observatory

GOD'S FINGER

Between 1960 and 1963, radio astronomy (which tries to detect objects in space by intercepting the radio signals that these objects emit) was faced with a major puzzle: Several sources of radio waves had been identified in the sky that seemed to have no visible counterpart. Whereas most previously studied radio sources were either peculiar galaxies or nearby gas clouds, this new type of source seemed to have no such identity. Known by their numbers in the massive Third Cambridge Catalog of Radio Sources (the 3C catalog), the best studied of these sources were labeled "3C 48," "3C 286," and "3C 196," referring to their positions in space. These sources would later be called "quasars." Diameters were measured for these objects in 1960 at the giant Jodrell Bank radio telescope in England by Cyril Hazard and his colleagues, who found them to be surprisingly small.

Intrigued by the peculiarities of these objects, Allan Rex Sandage took photographs of these radio sources in September, 1960, using the Palomar Observatory's 508-centimeter telescope, then the largest in the world. Sandage and Thomas A. Matthews, an expert at identifying radio sources, studied the photographs but found nothing that resembled a normal radio galaxy or gas cloud. They noticed, however, that the photograph of the area at the position of 3C 48 included a star with a peculiar feature: A faint wisp of light seemed to be pointing at it, "as if," as Sandage excitedly exclaimed, "God's finger were pointing to the true radio source." At the next opportunity, in October of that year, Sandage obtained a spectrum of this star and measured its colors. (A spectrum is a picture of the light of a star that has been spread out into all of its different colors, like a rainbow. This picture is marked by vertical black lines. Astronomers can use the black lines in a star's spectrum to discover the composition and velocity of the star.)

Sandage's spectrum of 3C 48 was extremely puzzling. As he explained to the members of the American Astronomical Society at their December, 1960, meeting, the spectrum resembled nothing that had been seen before. Instead of a bright continuum of light of different colors with various dark lines, the spectrum of 3C 48 had a weak continuum with broad, fuzzy lines. The most puzzling feature, however, was that none of these lines corresponded with any elements that were known to be contained in stars; the lines were completely unidentifiable. The only thing that the colors definitely showed was that it was a very hot object, with a temperature on the order of 100,000°.

The Moon as Yardstick

A major breakthrough occurred in 1962, when Hazard and his collaborators used the Parkes Radio Telescope in Australia to make a high-precision measurement of the position of 3C 273. As seen from Parkes, the

Moon happened to pass directly over the position of this object, and therefore a careful measurement of the time of its disappearance and later reappearance gave a very accurate measurement of its location, as the position of the moving Moon was known very accurately. When they compared the radio position with optical photographs of that part of the sky, the astronomers found that the position corresponded exactly with that of a fairly bright star. (The apparent brightness of this "star," which is the brightest quasar in the sky, is approximately six hundred times fainter than the faintest star visible without a telescope. Other quasars have since been found that are ten thousand times fainter.)

When this quite positive identification was announced, Maarten Schmidt of the California Institute of Technology decided to use the Palomar telescope to obtain a photograph and a spectrum of the "star." The photograph showed a bright stellar object with a faint wispy structure to one side, "pointing" toward the other object, much like what was found by Sandage next to 3C 48. The spectrum looked much like that of 3C 48, but with the broad emission lines in entirely different places. This remarkable fact threatened to confound the situation even more, until Schmidt had a brilliant insight as he examined the spectrum. He realized that the object's spectral lines would make sense if they were, in fact, normal lines of common elements but redshifted greatly to longer than usual wavelengths. (A source of light that is moving rapidly away from an observer will have all of its light shifted in wavelength to redder, longer wavelengths, by an amount that depends upon its velocity.) If he identified four of the lines as being caused by hydrogen gas—the most common element in the universe—then he found that the object must be moving away from Earth at about 48,000 kilometers per second. Comparing this information with the rate of speed at which the universe is believed to be expanding, it was possible to measure reliably the distance to 3C 273: about two billion light-years.

Maarten Schmidt. (California Institute of Technology)

Impact

It took nearly two decades of study for astronomers to accept that quasars are the extremely bright centers of normal galaxies. The mechanism that explains their nearly incredible amounts of energy must be gravitational collapse, since astronomers know of no other way to explain them. These galaxies probably draw material (mostly hydrogen gas) from neighboring galaxies. This material has fallen into the center of the object, where it has collapsed to form a very massive black hole (so called because the gravity of a black hole prevents light or any signals from escaping). The black hole is not seen; however, the newly captured gas that is falling toward it heats up to extreme temperatures (hundreds of thousands of degrees) and emits huge amounts of light (brighter than one trillion suns) as it is pulled toward oblivion.

Schmidt's discovery of the nature of the quasars in 1963 led to new and surprising insight into Earth's cosmic environment. Quasars represent the oldest and most distant objects that can be viewed, because they are seen as they appeared billions of years ago, when the universe was young. Thus, their properties can tell astronomers something about the properties of the universe long ago; for example, galaxy collisions and interactions were far more common then (billions of years ago), even more common than simple models would predict. The quasars also tell what happens when massive objects collapse, forming black holes at the centers of galaxies.

See also Big Bang; Black Holes; Brahe's Supernova; Cassini-Huygens Mission; Cepheid Variables; Chandrasekhar Limit; Copernican Revolution; Extrasolar Planets; Galactic Superclusters; Galaxies; Hubble Space Telescope; Neutron Stars; Pulsars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Stellar Evolution; X-Ray Astronomy.

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—*Ronald B. Guenther*

RADIO ASTRONOMY

THE SCIENCE: An antenna set up to detect the causes of interference with radio transmission detected the first radio signals from outside the solar system.

THE SCIENTISTS:

Karl Jansky (1905-1950), American radio engineer
Albert Melvin Skellett (b. 1901), American radio technician and astronomer
Grote Reber (1911-2002), American radio engineer who became the first radio astronomer

A STRANGE HISS

In 1928, Karl Jansky was hired by Bell Telephone Laboratories as a radio engineer. His first assignment was to investigate the causes of interference with transatlantic radio-telephone transmissions. This investigation required a sensitive antenna whose frequency response and sensitivity were very stable—ideal characteristics of any radio telescope. The device Jansky built, which was called a "Bruce array," consisted of two parallel frameworks of brass tubing; one frame was connected to a receiver, and the other acted as a signal reflector. The antenna was mounted on four Model-T Ford wheels and rotated every twenty minutes on a circular track. The antenna, which was about 20 meters long and 4 meters in width and height, was nicknamed the "merry-go-round."

Jansky discovered that there were three kinds of signals that his instrument could detect. Nearby thunderstorms created infrequent but powerful radio bursts. Distant thunderstorms created a weak but steady signal as their radio signals were reflected off the ionosphere, an electrically conducting layer in the upper atmosphere. The third signal, which created a steady hiss in receivers, was at first a mystery. Even though this signal was not a serious problem for radio reception, Jansky continued his efforts to identify the source. The signal varied in intensity in a daily cycle, and Jansky initially suspected that it might originate with the Sun. The problem with this theory was that the signals reached their highest point a few minutes earlier each day.

Jansky, who was unfamiliar with astronomy, did not appreciate the significance of this observation, but a friend of his, Albert Melvin Skellett, did. The Earth takes 23 hours and 56 minutes to rotate with respect to the stars. Because the Earth moves in its orbit by about one degree per day, it takes an extra four minutes to complete a rotation with respect to the Sun. The signals were following sidereal (star) time; that is, they came from a source that was fixed with respect to the stars. In 1933, after a full year of observations, Jansky published his estimate of the source's location: in the southern part of the Milky Way galaxy in the direction of Sagittarius. In 1935, after additional analysis, Jansky reported that signals originated from all along the Milky Way.

Cosmic Signals

Once Jansky understood the nature of the cosmic signals, he found that he was completely unable to detect the Sun, which he found quite puzzling. Jansky happened to be observing at a time of minimal sunspot activity. If he had observed at a time of great sunspot activity (at "sunspot maximum"), his equipment should have detected solar radio emissions. Had he observed at sunspot maximum, however, the upper atmosphere would have been nearly opaque at the wavelengths he studied, and he probably would not have detected radio waves from the Milky Way. Jansky realized that if he could not detect the Sun, the signals from the Milky Way were not likely to originate in the stars. He suggested that the radio signals originated from interstellar dust and gas instead, a suspicion that has proved to be correct.

Jansky's observations were described in a front-page article in *The New York Times* on May 5, 1933, and a national radio program broadcast a few seconds of cosmic radio noise. Nevertheless, the discovery had little significance for practical communications. Jansky proposed the construction of a 30-meter dish antenna to study the cosmic signals in greater detail, but his employers, believing that such investigations were more appropriate for academic researchers, turned down the proposal. Jansky went on to other areas of communications research and received a commendation for his work on radio direction finders during World War II. He had always been in poor health, and he died in 1950 at the age of forty-four, as radio astronomy was beginning to flourish.

One of the few people who had sufficient knowledge of both astronomy and radio to take advantage of Jansky's work was Grote Reber, who realized that investigating celestial radio sources would require completely different equipment from that Jansky had used. In 1937, Reber built a parabolic reflecting antenna with a diameter of 10 meters, which was used to make maps of the sky by aiming the parabolic dish at different elevations and letting the Earth's rotation sweep the antenna across the field of view.

IMPACT

The discovery of cosmic radio signals led to the field of radio astronomy—the first time astronomers used any part of the electromagnetic spectrum other than the range of frequencies containing visible and infrared light. This new tool allowed astronomers for the first time to investigate the universe without having to depend on optical telescopes: Because radio waves penetrate cosmic dust and gas clouds, which block visible light, these radio waves could be used to map the structure of the Milky Way galaxy. In the years since Jansky and Reber's work, radio astronomy has discovered great explosive bursts in other galaxies, some of which emit so much energy that their cause is became a focus of scientific investigation. Radio astronomy also discovered pulsars, as well as the faint background radiation that most astronomers consider to be the echo of the big bang. Astronomers were unprepared for the discovery that the universe could look so different at radio wavelengths.

Perhaps the most important effect of radio astronomy was to teach astronomers that every part of the electromagnetic spectrum reveals new phenomena and new types of celestial objects. The result has been new areas of investigation, including X-ray and ultraviolet astronomy.

See also Cosmic Microwave Background Radiation; Ionosphere; Isotopes; Pulsars; Quasars; Radio Galaxies; Radio Maps of the Universe; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe.

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—*Steven I. Dutch*

RADIO GALAXIES

THE SCIENCE: Martin Ryle's interferometric radio telescope detected and provided details on the structure of the first identifiable radio galaxy.

THE SCIENTISTS:

Karl Jansky (1905-1950), American radio engineer who detected the first cosmic radio waves
Grote Reber (1911-2002), American radio engineer who became the first radio astronomer
Sir Martin Ryle (1918-1984), English radio physicist and astronomer
Francis Graham Smith (b. 1923), English radio physicist and astronomer
Walter Baade (1893-1960), German American astronomer
Rudolf Minkowski (1895-1976), German American physicist

TUNING IN TO EXTRATERRESTRIAL RADIO

The initial measurements of cosmic radio emission by the American radio engineers Karl Jansky and Grote Reber between 1932 and 1940 showed reasonable similarity between the universe as it was revealed by radio waves and as it was seen by optical telescopes. This led many astronomers to conclude that most, if not all, celestial radio emissions came from interstellar gas, which was evenly distributed throughout the universe. Until the post-World War II period, the greatest drawback of the new discipline of radio astronomy was its limited accuracy in determining the celestial position and structural detail of an object detected from radio signals. A higher degree of accuracy was necessary in order to give optical astronomers a small enough "window" in which to look for an object discovered by radio telescopes.

Immediately following World War II, J. S. Hey used receivers from the Army Operational Radar Unit to study some of the extraterrestrial radio emissions reported earlier by Jansky and Reber. In 1946, Hey and his colleagues reported an observational discovery of particular import: that a radio source in the constellation Cygnus varied significantly in strength over very short time periods. In contrast to Reber, who had concluded that interstellar hydrogen between the stars was the source of all celestial radio signals, Hey argued that the fluctuations were too localized for interstellar gas and suggested instead the existence of a localized, starlike object.

In Australia, a similar group was formed under the direction of J. L. Pawsey. In 1946, the Australian group verified Hey's observations of a localized radio source in Cygnus, using one of the earliest radio interferometers. An interferometer is a series of radio telescopes connected over a wide area. The resolution, or receiving power, of this array is equal to that of a single radio telescope with a diameter equal to the distance between the farthest single radio telescopes. More "radio stars" were discovered by Pawsey's group in June, 1947, using an improved Lloyd's interferometer developed by L. McCready, Pawsey, and R. Payne-Scott. Incorporating an antenna mounted on top of a high cliff, this interferometer was able to use the ocean to reflect radio waves.

Ryle's Pyrometer

Almost simultaneously, using a different type of interferometer, Sir Martin Ryle at Cambridge found another intense localized radio source in the constellation Cassiopeia. Ryle and others had extensive wartime experience in developing airborne radar detectors, radar countermeasures, underwater sonar arrays, and signal detection and localization equipment. Ryle was joined in 1946 by Francis Graham Smith, who helped him rearrange his interferometer to cover a wider receiving area. Ryle's cosmic radio "pyrometer" was used successfully in June, 1946, to measure a large sunspot.

Hey and his colleagues remained unable to determine the accurate position of their radio source to better than 2°. The successful resolution of solar sunspots of small diameter, however, suggested to Ryle that improvements to the radio telescope were possible. In 1948, Ryle, Smith, and others made the first detailed radio observations of Cygnus A using an improved version of their pyrometric radio telescope. Ryle and Smith subsequently published an improved position for Cygnus A. Ryle and Smith's measurements included the discovery of short-period radio bursts, which they (incorrectly) used to argue that the ultimate radio source must be a radiating star of some unrecognized type.

Extragalactic Radio Sources

In 1949, astronomers decided to establish the locations of Cygnus A and Cassiopeia by constructing a very large interferometric radio telescope, with a maximum separation of 160 kilometers. In 1951, Ryle developed a new "phase-switching" receiver based on 1944 sonar detection efforts. Phase switching permits the radio receiver to reject sources with large size and thus improves the receiver's ability to emphasize and locate weaker sources. After completing the prototypes, in 1951 researchers again made measurements of Cygnus A and Cassiopeia. They discovered that the radio sources were clearly not stars and that the Cygnus A source was actually two distinct sources. Ryle's phase-switched records were such improvements that his colleagues compiled the first radio object catalog, which listed more than fifty cosmic radio sources.

By late 1951, Smith had further localized the coordinates of Ryle's two radio stars, reducing the original error windows of Hey and others by a

Ryle's Radio Telescopes

In 1964, Sir Martin Ryle implemented his first history-making radio telescope, the "one-mile telescope," using the principle of aperture synthesis. Aperture synthesis uses small telescope dishes to produce the angular resolution of a much larger telescope dish. A telescope's angular resolution is its ability to distinguish between two relatively close point sources of radiation. The method of aperture synthesis keeps one or more small dishes fixed and moves one or more other dishes over Earth's surface, comparing the phases of the radiation collected by the fixed and movable dishes. Ryle's instrument was unique because he accounted for the effects of Earth's rotation in moving the array of dishes and provided a baseline for the angular resolution which was a large fraction of Earth's diameter.

The telescope had a resolution superior to that of existing instruments, and it could detect much fainter sources, including quasars. Quasars are among the most distant, and therefore youngest and most powerful, objects in the universe. They may represent the stage galaxies go through before their radio radiations subside and they become visible at optical wavelengths. With Allan Sandage, Ryle developed a technique for identifying quasars at optical wavelengths, based on the fact that they emit much more ultraviolet energy than single, normal stars.

Ryle's survey of radio sources showed, as suspected, that the number of faint sources per unit volume of space increased with distance—but far more rapidly than anticipated. This finding supported the big bang theory of the universe, which then was in conflict with the prevailing "steady state" theory. Over time, Ryle's evidence was bolstered by other research, and today the big bang theory is dominant.

In 1974, Ryle won the Nobel Prize in Physics for construction and use of the five-kilometer telescope. Like the one-mile telescope, it consisted of a linear, east-west array of dishes, some fixed and some movable, all carried by Earth's rotation. The resolution of this instrument was, remarkably, one second of arc. The new telescope detected fainter and more distant galaxies with greater precision, allowing many more objects to be used for statistical studies and the radio and optical components of the most distant objects to be matched. The five-kilometer telescope was also used to study individual stars in the Milky Way that were just being born. Ryle's telescopes thus opened a new window on the universe, revealing previously undetectable objects and insights.

factor of sixty. Smith then approached the director of the Cambridge Observatory to seek visual identification of the two radio sources. While part of the Cassiopeia source, a supernova remnant, was found in 1951, the poor atmospheric observing conditions in England prevented the Cambridge observers from making a complete identification. Shortly thereafter, Smith sent his data to Walter Baade and Rudolf Minkowski of the Palomar Observatory in Southern California.

The objects of Baade and Minkowski's visual search were discovered only after many difficulties; they were hidden among many other stars and faint galaxies. In 1952, Baade wrote to Smith that the result of his visual search was puzzling. He had found a cluster of galaxies, and the position of the radio source coincided closely with the position of one of the brightest members of the cluster. Moreover, the source seemed to be receding at a high velocity. These findings suggested that the source of the radio transmissions was outside the galaxy.

At first, there was notable skepticism over the notion of extragalactic radio sources. Because of this climate of disbelief, Baade and Minkowski did not publish their results until 1954. Subsequent research, however, confirmed the extragalactic location of these objects, forcing cosmologists to find a place for these sources in their theories of the universe.

Impact

Perhaps the most decisive radio data came from Ryle and Scheuer in 1955. They found that the most "normal" galaxies emit radio signals comparable in intensity to those emitted by the Milky Way galaxy. Nevertheless, there were many other galaxies—many not different in their optical appearances from normal galaxies—which are much more powerful sources; these became known as "radio galaxies." By the time of the 1958 Solvay Conference on the Structure and Evolution of the Universe, the existence of at least eighteen extragalactic radio objects had been confirmed, opening a new era in cosmology.

See also Cosmic Microwave Background Radiation; Ionosphere; Isotopes; Pulsars; Quasars; Radio Astronomy; Radio Maps of the Universe; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe.

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—*Gerardo G. Tango*

RADIO MAPS OF THE UNIVERSE

THE SCIENCE: Grote Reber built the first radio telescope and used it to record the first radio contour maps of the Milky Way, establishing the foundations of a new type of astronomy.

THE SCIENTISTS:

Grote Reber (1911-2002), American radio engineer and amateur astronomer

Karl Jansky (1905-1950), American radio engineer

Sir William Herschel (1738-1822), German English musician and astronomer

Harlow Shapley (1885-1972), American astronomer

OPENING AN INVISIBLE WINDOW

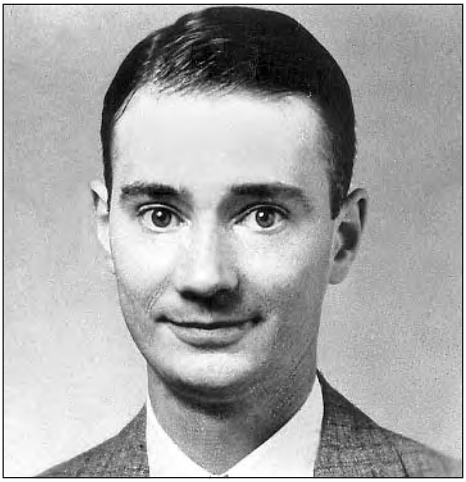
Grote Reber's recording of the first radio contour maps of the universe was a new and unexpected application of radio technology. Reber's work opened the invisible window of radio frequencies, allowing astronomers to see new features of the universe.

Sir William Herschel was one of the first astronomers to recognize the true nature of the dense band of stars across the sky called the Milky Way. From counting stars in various directions in the Milky Way, he concluded in 1785 that the vast majority of stars are contained within a flattened disk shape, forming an island universe or galaxy in space, with the solar system reduced to a tiny speck in the vast universe of stars. Early in the twentieth century, Harlow Shapley was able to use the 254-centimeter Mount Wilson telescope to show that the Milky Way galaxy is far larger than any previous estimate, and that the Sun is far from the galactic center, which he located in the direction of the constellation Sagittarius.

In 1932, Karl Jansky reported his accidental discovery of radio waves from space. Using a rotating array of antennas sensitive to 15-meter radio waves, he detected a steady hiss whose emission corresponded to the daily motion of the stars. He concluded that he was receiving cosmic radio waves from beyond the solar system. He was able to identify the source of the most intense radiation in the direction of Sagittarius, suggesting that it came from the center of the Milky Way galaxy. He also showed that weaker radio waves came from all directions in the Milky Way and suggested that their source was in the stars or in the interstellar matter between the stars.

The Lone Radio Astronomer

Jansky's work was so unrelated to traditional astronomy that no professional astronomer followed it up. As a young radio engineer at the Stewart-Warner Company in Chicago, Reber read Jansky's papers and began to plan how he could measure the detailed distribution of the radiation intensity throughout the sky at different wavelengths. In 1937, he built a 9.4-meter parabolic reflecting dish in his yard, mounted so that it could be pointed in a north-south direction; scanning west to east would result from the Earth's rotation. For ten years, he operated this radio telescope in Wheaton, Illinois, as the only radio astronomer in the world.


Grote Reber. (National Radio Astronomy Observatory, operated by Associated Universities, under contract with the National Science Foundation)

As the Milky Way crossed the meridian late at night, Reber measured the increasing intensity of the cosmic radio waves. He published his initial results in the February, 1940, *Proceedings of the Institute of Radio Engineers*, where he noted that the intensity of the radiation was too low to come from stars, as Jansky had proposed, but suggested the possibility of radiation from interstellar gases.

In 1941, Reber began a complete sky survey with an automatic chart recorder and more sensitive receiving equipment. The recording pen would slowly rise and fall as the reflecting dish rotated with the Earth. After collecting approximately two hundred chart recordings, he plotted the resulting radio contours on the two hemispheres of the sky. The resulting radio maps, published in the *Astrophysical Journal* in November, 1944, revealed interesting details: The greatest radio intensity was coming from the center of the galaxy, in Sagittarius; less intense radio waves were coming from the constellations Cygnus and Cassiopeia. More important was his recognition that radio waves could penetrate the interstellar dust that obscures much visible light in the Milky Way.

Reber's last observations in Wheaton were made from 1945 to 1947. The resulting radio maps, published in the *Proceedings of the Institute of Radio Engineers* in October, 1948, now revealed two noise peaks in the Cygnus region, later identified as a radio galaxy (Cygnus A) and a source associated with a spiral arm of the Milky Way (Cygnus X). An intensity peak in Taurus was later identified with the eleventh century supernova remnant in the Crab nebula, and another in Cassiopeia matches the position of a seventeenth century supernova explosion. These results were the beginning of many important discoveries in the field of radio astronomy.

Impact

Reber's pioneering work and resulting radio maps led to a growing interest in radio astronomy and many unexpected discoveries with radio telescopes of increasing sophistication and size. In 1945, a graduate student at the University of Leiden, in the Netherlands, Hendrik Christoffel van de Hulst, predicted that neutral hydrogen should emit 21-centimeter radio waves. By 1949, the Harvard physicist Edward Mills Purcell had begun to search for these radio waves with Harold Irving Ewen, a graduate student who was sent to confer with Reber on techniques in radio astronomy. Ewen and Purcell developed special equipment and by 1951 had succeeded in detecting the predicted 21-centimeter radio waves. A group headed by Dutch astronomer Jan Hendrik Oort then began a seven-year collaboration with Australian radio astronomers to map the spiral arms of the Milky Way galaxy.

In 1960, two radio sources were identified with what appeared to be stars, but each emitted much more radio energy than Earth's sun or any other known star. Four of these "quasars" (quasi-stellar radio sources) had been discovered by 1963. At distances of billions of light-years, these objects would have to be more than one hundred times brighter than entire galaxies and would appear to be some kind of highly energetic stage in the early formation of a galaxy.

Another dramatic event in radio astronomy occurred in 1967, when Jocelyn Bell, a graduate student in radio astronomy at Cambridge, discovered pulsars. These are believed to be fast-spinning "neutron stars" with high magnetic fields that produce a rotating beam of radio emission. A pulsar in the Crab nebula was later identified with the collapsed core of the supernova remnant that had appeared on Reber's radio maps.

Perhaps the most important discovery in radio astronomy was the 1965 detection of cosmic microwave background radiation by radio astronomers Arno Penzias and Robert Woodrow Wilson. Using a 6-meter horn antenna at the Bell Telephone Laboratories in Holmdel, New Jersey, they found an unexpected excess of steady radiation with no directional variation. This matched current predictions of cosmic radiation from a primeval fireball in the "big bang" theory. Thus, radio astronomy provided confirmation of the creation and expansion of the universe.

See also Cosmic Microwave Background Radiation; Ionosphere; Isotopes; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe.

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—*Joseph L. Spradley*

RADIOACTIVE ELEMENTS

THE SCIENCE: Frédéric Joliot and Irène Joliot-Curie used alpha particles from polonium to bombard aluminum and create phosphorus 30, an artificial nucleus that is radioactive.

THE SCIENTISTS:

Irène Joliot-Curie (1897-1956), French physicist who shared the 1935 Nobel Prize in Chemistry with her husband, Frédéric Joliot

Frédéric Joliot (1900-1958), French physicist who shared the 1935 Nobel Prize in Chemistry with his wife, Irène Joliot-Curie

NEUTRONS AND POSITRONS

In 1930, a German team of scientists reported that beryllium bombarded by alpha particles emitted a new sort of penetrating radiation. In France, the husband-wife team of Irène Joliot-Curie and Frédéric Joliot confirmed the German results and in the process came close to proving the existence of the neutron, of which the new radiation was composed. This particle, which has no charge but has the same mass as the proton, joins the proton to form the nucleus of the atom. British physicist James Chadwick won a Nobel Prize in Physics for making the actual discovery of the neutron.

In 1932, the Joliot-Curies, studying cosmic radiation in the high Alps, observed the positron, a particle with the same mass as the electron but with a positive rather than a negative charge. They failed to follow up their observation, and that same year, an American physicist, Carl David Anderson, identified the positron, using equipment similar to that used by the Joliot-Curies.

ALPHA BOMBARDMENT

By early 1933, the Joliot-Curies were using alpha particles produced from polonium to bombard boron, beryllium, fluorine, aluminum, and sodium. After the bombardment, these elements emitted neutrons and both positrons and electrons. The accuracy of the results of their experiments was questioned at the Seventh Solvay Conference, which was attended by most of the major physicists in Europe. They returned to Paris with damaged pride and a new determination to prove conclusively that neutrons and positrons were emitted at the same time from their irradiated targets.

To conduct the necessary experiments, they were forced to modify their experimental apparatus. Until now, the Geiger counter, which detected radioactivity, had been automatically turned off when the radioactive source (the source of the alpha particles) was removed. In the new arrangement, it would be left on after the source was removed. With this arrangement, they noticed that aluminum continued to emit positrons for some time after the removal of the radioactive source. This meant that the aluminum target had been made artificially radioactive by bombardment with alpha particles.

Irène Joliot-Curie. (Library of Congress)

The Joliot-Curies were certain that they had produced artificial radioactivity. In order to place their discovery beyond doubt, they needed to separate chemically the source of the new radioactivity and to demonstrate that it had nothing to do with the original aluminum target. On January 15, 1934, friends, including Irène's famous mother, Marie Curie, received frantic telephone calls from the young researchers and rushed to the laboratory. From makeshift apparatus scattered in apparent disarray over several tables, the Joliot-Curies bombarded aluminum with alpha particles and separated from the irradiated samples an isotope of phosphorus with a half-life of only three minutes and fifteen seconds. Marie Curie, who was dying of the leukemia produced by her lifetime work with radioactivity, was handed a tiny tube containing the first sample of artificially produced radioactivity. Her face expressed joy and excitement. Other colleagues filled the room with lively discussions.

The Joliot-Curies soon repeated their experiments with boron and magnesium, producing still other sources of artificial radioactivity. They promptly sent off a report of their discovery to the scientific press. Its publication opened a floodgate of new experiments on the transmutation of nuclei, which led directly to the discovery of "nuclear fission" five years later.

IMPACT

The report of the discovery of artificial radioactivity was published early in 1934 and in 1935 earned for the husband and wife a shared Nobel Prize in Chemistry. The scientific community almost immediately recognized the discovery as equal to that of the neutron or the positron. Physicist Enrico Fermi and his group in Rome quickly noted that neutrons were more effective in producing artificial radioactivity than the alpha particles used in the original experiments. The entire community, including the Joliot-Curies, began to study artificial radioactivity produced by bombarding different elements with neutrons. Studies on uranium in Rome, Berlin, and Paris led to confusing results, which were finally interpreted as nuclear fission in 1939. (Nuclear fission is the splitting of an atomic nucleus into two parts, especially when bombarded by a neutron. When the nuclei of uranium atoms are split, great amounts of energy are released.)

Science and Romance

Irène Joliot-Curie was the daughter of the legendary Marie Curie, the physical chemist who twice won the Nobel Prize, and a member of the French scientific elite by birth as well as a brilliant physicist in her own right. As a teenager, she had worked alongside her mother, using X-ray equipment to treat soldiers wounded during World War I. She published her first paper in physics in 1921, and in 1932 she succeeded her mother as director of the Radium Institute.

Frédéric Joliot grew up in a middle-class family and attended the École de Physique et de Chimie Industrielle de la Ville de Paris rather than one of the prestigious French universities. Because of his unquestionable ability as an experimenter, he was recommended to Marie Curie as an assistant by a close friend, French physicist Paul Langevin. He joined the laboratory at the end of 1924 and gradually acquired the necessary degrees. Because of his background, he found it difficult to break into the inner circle of French science, despite his personal charm and ability.

The outgoing, charming, handsome Frédéric fell in love with the quiet, capable, socially awkward Irène. In 1926, they were wed, beginning a very happy marriage and an extremely successful scientific collaboration. During the first four years of the 1930's, they embarked upon a remarkable series of experiments in nuclear physics that led to the creation of radioactive elements in the laboratory. Their achievement led directly to nuclear fission, achieved in 1939.

The Joliot-Curies continued to lead a rich family life hampered only by poor health caused, in Irène's case, by her early work with large amounts of radioactive materials. Frédéric Joliot was now accepted as a member of the French scientific elite and not as an upstart who had married Madame Curie's daughter. As World War II loomed on the horizon, Frédéric Joliot was drafted into the military. Recognizing the possibility of a nuclear fission bomb, he took steps to secure uranium for France and began negotiations for a large supply of "heavy water" located in Norway. With the Nazis closing in, he and his colleagues smuggled the heavy water to Britain and hid the uranium in Morocco just ahead of Adolf Hitler's advancing troops. During the war, Joliot used the prestige of his Nobel Prize to conceal his activities in support of the French Resistance. Thus, in addition to being a major scientific contributor in his own right, Joliot helped tilt the war in the direction of the Allies.

See also Amino Acids; Atomic Nucleus; Atomic Structure; Atomic Theory of Matter; Boyle's Law; Buckminsterfullerene; Carbon Dioxide; Chlorofluorocarbons; Citric Acid Cycle; Definite Proportions Law; Isotopes; Liquid Helium; Neutrons; Osmosis; Oxygen; Periodic Table of Elements; Photosynthesis; Plutonium; Spectroscopy; Vitamin C; Vitamin D; Water; X-Ray Crystallography; X-Ray Fluorescence.

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—*Ruth H. Howes*

RADIOMETRIC DATING

THE SCIENCE: Bertram Borden Boltwood pioneered the radiometric dating of rocks, leading to the use of nuclear methods in geology and establishing a new chronology of Earth.

THE SCIENTISTS:

Bertram Borden Boltwood (1870-1927), the first American scientist to study radioactive transformations
Ernest Rutherford (1871-1937), English physicist who won the 1908 Nobel Prize in Chemistry
William Thomson, Lord Kelvin (1824-1907), English physicist

NOT ENOUGH TIME

Radioactivity is the property exhibited by certain chemical elements that, during spontaneous nuclear decay, emit radiation in the form of alpha particles, beta particles, or gamma rays. Related to this property is the process of nuclear disintegration. In this process, an atomic nucleus, through its emission of particles or rays, undergoes a change in structure. To take an example, the presence of helium in rocks is the result of radioactive elements in the rocks emitting alpha particles during disintegration.

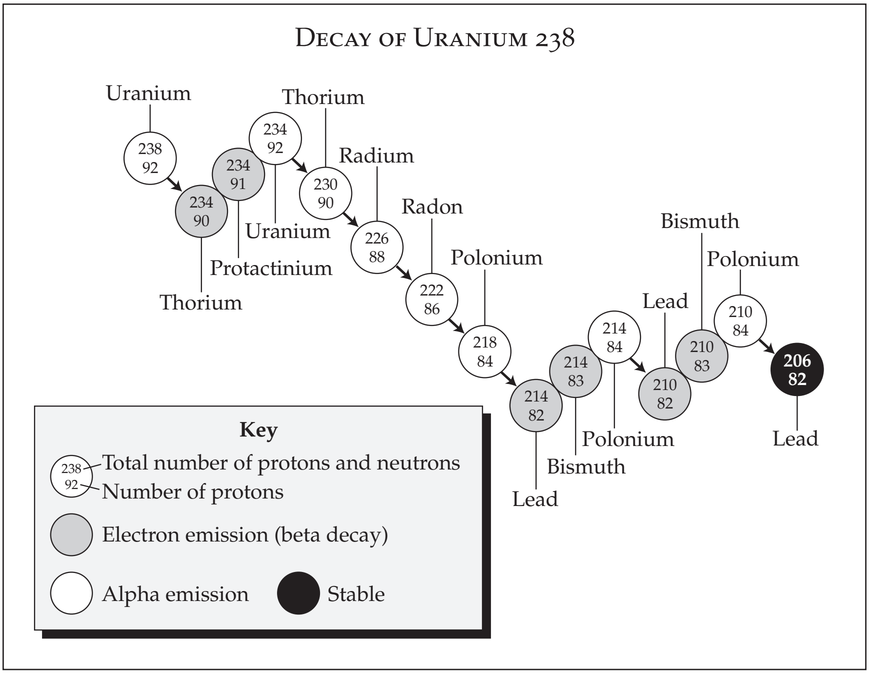
Bertram Borden Boltwood was fascinated by the theory of radioactive disintegrations proposed in 1903 by McGill University scientists Ernest Rutherford and Frederick Soddy. According to that theory, radioactivity is always accompanied by the production of new chemical elements on an atom-by-atom basis. In 1904, Boltwood impressed Rutherford by demonstrating that all uranium minerals contain the same number of radium atoms per gram of uranium. This confirmation of the theory of radioactivity marked the beginning of a close collaboration between the two scientists.

The significance of Boltwood's work can be seen in the light of a chronological controversy raging at that time between geologists and physicists. It had been accepted generally that the Earth, at some time in its history, was a liquid ball and that its solid crust was formed when the temperature was reduced by cooling. The geological age of Earth was, thus, defined as the period of time necessary to cool it down from the melting point to its present temperature. Using these guidelines, several estimates of that time were made by the famous physicist Sir William Thomson, Lord Kelvin, who in 1877 claimed that the age of the Earth was probably close to 20 million years and certainly not as large as 40 million. His calculations were mathematically correct but did not take into account radioactivity, which had been discovered the year before.

Geologists believed that 40 million years simply was not enough time to create continents, to erode mountains, or to supply oceans with minerals and salts. Studies of sequences of layers (stratigraphy) and of fossils (paleontology) led them to believe that the Earth was older than 100 million years, but they were not able to prove it.

Earth Clocks

Boltwood and Rutherford proved that geologists were right. This came as a by-product of their research on the nature of radioactivity. Rutherford knew that helium was always present in natural deposits of uranium, and this led him to believe that in radioactive minerals, alpha particles somehow were turned into ordinary atoms of helium. Accordingly, each rock of a radioactive mineral is a generator of helium. The accumulation of the gas proceeds more or less uniformly so that the age of the rock can be determined from the amount of trapped helium. In that sense, radioactive rocks are natural clocks.



Uranium 238 decays naturally, over a predictable period of time, to form lead. Boltwood realized that the accumulation of lead in rocks could be used to determine their age.

Knowing how much helium is produced from each gram of uranium per billion years, Rutherford and his collaborators were able to see that naturally radioactive rocks are often older than 100 million years. The ages of some samples exceeded 500 million years. Moreover, Rutherford was aware that in assigning ages he would have to account for helium that was escaping from the rocks.

Impressed by these results, and trying to eliminate the uncertainties associated with the leakage of helium, Boltwood decided to work on another method of dating. This decision stemmed from his earlier attempts to demonstrate that, as in the case of radium, all uranium minerals contain the same number of atoms of lead per gram of uranium. Chemical data, however, did not confirm this expectation—the measured lead-to-uranium ratios were found to be different in minerals from different locations.

According to Rutherford and Soddy's theory, a spontaneous transformation of uranium into a final product proceeds through a set of steps, in which alpha particles and electrons are emitted, one after another. Boltwood realized that lead must be the final product and that its accumulation could be used to date minerals. By focusing on lead rather than helium, he hoped to reduce the uncertainties associated with the leakage.

Lead, he argued, is less likely to escape from rocks than helium because, once trapped, lead becomes part of a solid structure.

Motivated by these ideas, Boltwood proceeded with the development of the uranium-lead method of dating. To accomplish this, he had to determine the rate at which lead is produced from uranium. Having achieved this, Boltwood started his investigations in 1905, and before the end of the year, he had analyzed twenty-six samples. One of them was identified as 570 million years old. In a formal publication, which appeared in 1907, he described forty-six minerals collected in different locations; their reported ages were between 410 and 2,200 million years old.

Similar results had been reported earlier by Rutherford from his laboratory in Montreal and by the English physicist Robert John Strutt, Lord Rayleigh, from the Imperial College in London, both of whom had used helium methods. Although there was a wide variation in dates, it became clear that many rocks were at least ten times older than what had been calculated by Lord Kelvin.

Impact

The main results of the pioneering work of Boltwood and his successors was the realization that geological times must be expressed in hundreds and thousands of millions of years, rather than in tens of millions of years, as advocated by Lord Kelvin. This was particularly significant for the acceptance of the theory of evolution by biologists and, in general, for a better understanding of many long-term processes on Earth.

Geochronology, for example, has been used in investigations of reversals of the terrestrial magnetic field. Such reversals occurred many times during the geological history of Earth. They were discovered and studied by dating pieces of lava, naturally magnetized during solidification. The most recent reversal took place approximately 700,000 years ago.

It is clear, in retrospect, that the discovery of radioactivity affected geochronology in two ways: by providing tools for radiometric dating and by invalidating the thermodynamic calculations of Lord Kelvin. These calculations were based on the assumption that the geothermal energy lost by Earth is not replenished. The existence of radioactive heating, discovered in 1903 in France, contradicted that assumption and prepared scientists for the acceptance of Boltwood's findings. Lord Kelvin died in the same year in which these findings were published, but he knew about Rutherford's findings as early as spring, 1904. He was very interested in radioactive heating but never came forth with a public retraction of his earlier pronouncements.

See also Fossils; Geologic Change; Geomagnetic Reversals; Mass Extinctions; Microfossils; Radioactivity.

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—*Ludwik Kowalski*

RECOMBINANT DNA TECHNOLOGY

THE SCIENCE: Molecular geneticists pioneered techniques that allow scientists to insert DNA from any source into bacteria and detect the expression of the foreign genes in these simple cells.

THE SCIENTISTS:

Stanley Norman Cohen (b. 1935), American molecular geneticist
Herbert Wayne Boyer (b. 1936), American biochemist
Paul Berg (b. 1926), American biochemist
Hugh Oliver Smith (b. 1929), American molecular geneticist

Bacterial Hosts

Recombinant DNA (deoxyribonucleic acid) technology—known also in various guises as "genetic engineering," "genetic modification," and "gene cloning"—is an area of scientific investigation and applied biology that has, since its inception in 1973, revolutionized molecular biology, allowing scientists to address questions in cell biology that could not be addressed by earlier methods. Recombinant DNA methods allow molecular biologists to add one or a small number of genes from essentially any organism to simple bacterial cells. These foreign genes can be made to become an integral part of the bacterium, replicating along with the bacterial genetic material and thus stably transmitted from one bacterial generation to the next. The foreign genes can also be made to be functional in their bacterial host—that is, they can be induced to make their normal gene products.

Bacteria are very simple single-celled organisms that are ubiquitous in nature. Although some are capable of causing disease, most bacteria are harmless to humans. Some, like the common intestinal bacterium *Escherichia coli* (*E. coli*), are normal inhabitants of the human body that are essential to human life. Each *E. coli* cell has a single circular DNA molecule, or chromosome, containing between two thousand and three thousand genes. In addition, some cells have one or more additional small circular DNA molecules called plasmids. A typical plasmid contains on the order of five to ten genes and is therefore much smaller than the *E. coli* chromosome. These plasmids are semiautonomous, meaning that while they are incapable of leading a cell-free existence, they generally remain separate from the larger chromosome and control and direct their own replication and transmission to each daughter cell at cell division. Plasmids that contain genes for resistance to certain antibiotics, viruses, and so forth can provide the host cell with useful properties.

THE PROCESS

The "basic experiment" of recombinant DNA technology involves four essential elements: a method of generating pieces of DNA from different sources and splicing them back together; a "vector" molecule (often a plasmid) that can replicate both itself and any foreign DNA linked to it; a way to get this composite, or recombinant, DNA molecule back into a suitable bacterial host; and a means to separate those bacterial cells that have picked up the desired recombinant plasmid from those cells that have not.

As part of the process, the recombinant plasmids are then reintroduced back into *E. coli* host cells in a process called "transformation." An essential feature of transformation is treatment of the host cells with calcium chloride, which weakens the cell walls and membranes, allowing the reconstituted plasmid DNA to be taken up inside the cells. If all has gone well,

STANLEY COHEN AND EGF

Stanley Cohen was born November 17, 1922, in Brooklyn, New York, to Jewish emigrants from Russia. He majored in biology and chemistry at tuition-free Brooklyn College, the only college at which he could afford to enroll. Cohen went on to earn his master's degree with a concentration in zoology from Oberlin College in 1945. At the University of Michigan, he earned his Ph.D. in biochemistry in 1948. Then he moved to the University of Colorado, where he studied the metabolism of premature infants.

In 1952, Cohen moved to Washington University in St. Louis and learned the isotope methodology for studying metabolism as a postdoctoral fellow of the American Cancer Society, later working on nerve growth factor with Rita Levi-Montalcini. In 1959, he moved to Vanderbilt University, where he studied epidermal growth factor (EGF), a protein, which he identified in the early 1960's. Because of the difficulty of amino acid sequencing at that time and the unusual structure of the protein, Cohen and his colleagues were unable to determine EGF's amino acid sequence until the early 1970's. EGF has been found in many different species, including humans (as urogastrone), and is recognized as significant in embryonic and fetal development. The potential of EGF for accelerating wound growth, healing, and growth of skin cells in culture for burn victims prompted the interest of pharmaceutical companies.

(The Nobel Foundation)

Cohen's persistent work on growth factors, at a time when growth factors were not popular in scientific circles and in many cases were held to be suspect, laid the groundwork for another extremely important field that was to develop only in the 1980's with the development of recombinant DNA technology. The ability to clone selected genes from the genetic material (DNA) of the cell and to read the DNA base sequence to determine what protein the gene would make led to the identification of oncogenes, which are viral genes that cause normal cells to develop as tumors. Many oncogenes are now recognized for producing growth factors or proteins that mimic the receptor protein; this protein, however, is always turned "on" to cause cell division. Cohen's work was therefore instrumental in the understanding of mechanisms of cancer induction by viruses.

these genetically engineered clones of bacterial cells will then stably replicate the foreign DNA, along with the rest of the chromosomal and plasmid DNA of each cell generation; the products of the foreign genes—ribonucleic acid (RNA) or protein—will be made as well.

The First Recombination

By the early 1970's, the stage was set for the advent of recombinant DNA technology. DNA "ligases" (enzymes that play a significant role in the process) had been discovered and purified independently in five separate laboratories in 1967. Hugh Oliver Smith described the first restriction endonuclease enzyme in 1970, and shortly thereafter Herbert Wayne Boyer described the isolation of EcoRI, a restriction endonuclease that became extremely important in the development of cloning methods. Paul Berg and his group described the construction of the first recombinant DNA molecules in a test tube, and at about the same time researchers in Stanley Norman Cohen's laboratory reported on the first successful transformation experiments in *E. coli*.

In the fall of 1973, Cohen and Boyer were the first researchers to describe successfully a complete recombinant DNA experiment. Their report detailed the mixing and subsequent reconstitution of DNAs from two separate plasmids in *E. coli*. Shortly thereafter, they described experiments in which DNA from a plasmid found in an unrelated bacterium was successfully cloned in *E. coli*, and one year later they reported on the first successful cloning of animal genes in *E. coli*.

Impact

Recombinant DNA technology is widely considered to be the most significant advance in molecular biology since the elucidation of the molecular structure of DNA in 1953 by biophysicists James Watson and Francis Crick. It soon became apparent, however, that the technology had opened a Pandora's box of social, ethical, and political issues unprecedented in scientific history. The research held the potential of addressing biological problems of fundamental theoretical and practical importance, yet it generated real concerns also, because some experiments might present new and unacceptable dangers. Even in the course of scholarly research with the best intentions, there was concern that a laboratory accident or an unanticipated experimental result might introduce dangerous genes into the environment, with *E. coli* carrying them.

Soon after the scientific concerns were first voiced, a conference was planned to allow many of the leading researchers in molecular biology to try to assess the potential dangers of recombinant DNA technology. The conference was held at the Asilomar Conference Center in February of 1975. Six months earlier, however, eleven respected authorities in molecular biology, including Cohen, Boyer, Berg, and others who helped develop recombinant DNA techniques, signed a letter that was simultaneously published in three English and American scientific journals. This letter called for a voluntary moratorium on recombinant DNA experiments until questions about potential hazards could be resolved. The development of a set of guidelines for recombinant DNA research, a modification of which was later adopted by the National Institutes of Health, was discussed at the Asilomar Conference. Levels of both biological and physical "containment" were defined, and each type of recombinant DNA experiment was assigned to an appropriate level. Some types of experiments were banned. In the years that followed the initial furor, guidelines have been modified accordingly, as many of the initial fears about possible dangers have proved to be groundless.

As predicted, recombinant DNA technology has proved to have extensive practical applications, particularly in the fields of medicine and agriculture. Virtually all insulin-dependent diabetics now take human insulin made by genetically engineered bacteria. Human growth hormone, prolactin, interferon, and other human gene products with specific therapeutic uses in medicine are available only because they can be made in quantity by using cloning. In agriculture, improved species of genetically modified crop plants have been designed to help address problems in global food supplies. Of particular note is the effort to clone the bacterial genes for nitrogen fixation into crop plants, thus obviating the need for most fertilizers.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Ribozymes; Stem Cells; Viruses.

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—*Jeffrey A. Knight*

RELATIVITY

THE SCIENCE: Albert Einstein's articulation of special and general relativity not only explained gravitation and motion between contained systems but also created a new view of space and time that laid the foundation for models that have been proposed to explain the creation and evolution of the universe.

THE SCIENTISTS:

Albert Einstein (1879-1955), German-Swiss American physicist
David Hilbert (1862-1943), German mathematician
Sir Arthur Stanley Eddington (1882-1944), English astronomer, philosopher, and physicist

A MATTER OF SOME GRAVITY

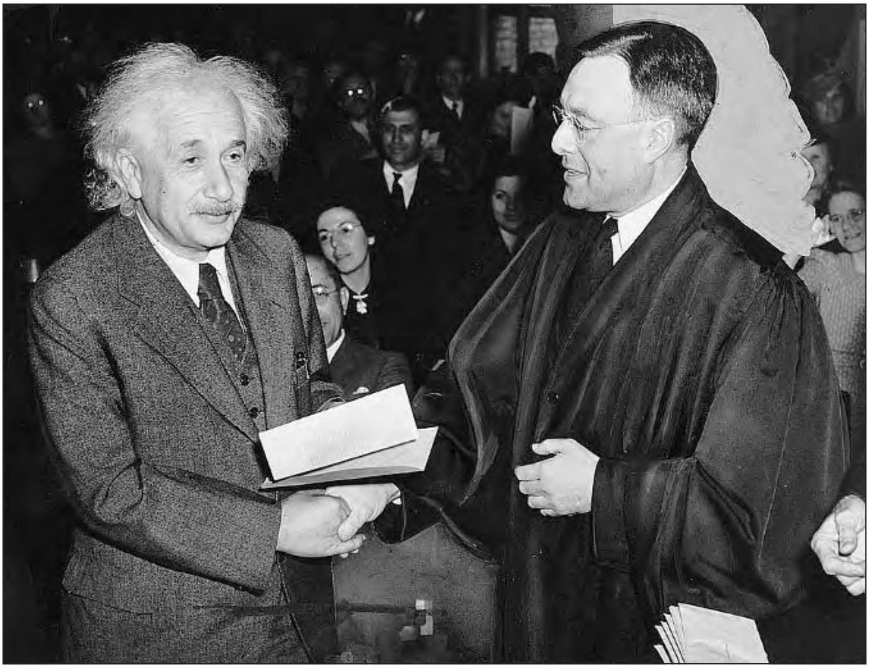
Although Sir Isaac Newton's law of gravity was very successful at making predictions, it did not explain how gravity worked. In fact, Newton stated that explaining gravity was not his goal: "Gravity must be caused by an agent acting constantly according to certain laws; but whether this agent should be material or immaterial, I have left to the consideration of my readers." For almost two hundred years, however, Newton's readers cared little about this question. Newton's law can be described as an "as if" law. Two bodies act as if there is a force between them that acts like the force of gravity that Newton proposed. Newton did not address the question of how or why this force operated.

Furthermore, Newton's physics could not explain why, in calculating gravitational attraction between objects, gravitational mass turns out to be exactly equal to inertial mass. (Gravitational mass determines the strength of the gravity acting on an object, and inertial mass determines that object's resistance to any force.) It is because of this equality that all bodies that fall under the influence of gravity alone have the same acceleration, their different masses notwithstanding. It was this strange equality that directed Einstein's thoughts toward a theory of gravity when almost no one else considered it to be an important question.

It's All Relative

When Einstein developed his special theory of relativity in 1905, he did it in an environment in which many other scientists were working on the same problem. The questions involved were the burning issues of the time, and other scientists were also coming close to the answers. The situation in which the general theory of relativity was developed was much different. Einstein did receive some help from his friend Marcel Grossman, a mathematician, and there was a later parallel effort to develop the same theory by the famous mathematician David Hilbert, who was inspired to do so by Einstein. Aside from these minor exceptions, however, Einstein's work on general relativity was entirely his own, and it was performed in an atmosphere in which there was little independent interest in the problem.

Einstein began to work on general relativity after he examined the defi-



Albert Einstein receiving his certificate of U.S. citizenship in 1940. (Library of Congress)

EINSTEIN ON THE SCIENTIFIC IMPULSE

In 1950—more than three decades after he first presented his general theory of relativity—Albert Einstein philosophized on the human impulse toward theoretical science:

> What, then, impels us to devise theory after theory? Why do we devise theories at all? The answer to the latter question is simply: Because we enjoy "comprehending," *i.e.*, reducing phenomena by the process of logic to something already known or (apparently) evident. New theories are first of all necessary when we encounter new facts which cannot be "explained" by existing theories. But this motivation for setting up new theories is, so to speak, trivial, imposed from without. There is another, more subtle motive of no less importance. This is the striving toward unification and simplification of the premises of the theory as a whole. . . .
>
> There exists a passion for comprehension, just as there exists a passion for music. That passion is rather common in children, but gets lost in most people later on. Without this passion, there would be neither mathematics nor natural science. Time and again the passion for understanding has led to the illusion that man is able to comprehend the objective world rationally, by pure thought, without any empirical foundations—in short, by metaphysics. I believe that every true theorist is a kind of tamed metaphysicist, no matter how pure a "positivist" he may fancy himself. The metaphysicist believes that the logically simple is also the real. The tamed metaphysicist believes that not all that is logically simple is embodied in experienced reality, but that the totality of all sensory experience can be "comprehended" on the basis of a conceptual system built on premises of great simplicity. The skeptic will say that this is a "miracle creed." Admittedly so, but it is a miracle creed which has been borne out to an amazing extent by the development of science.

Source: Albert Einstein, "On the Generalized Theory of Gravitation: An Account of the Newly Published Extension of the General Theory of Relativity Against Its Historical and Philosophical Background." *Scientific American* 182, no. 4 (April, 1950).

ciencies of the special theory of relativity. Gravity and relativity were incompatible. In particular, in order to incorporate an understanding of gravity into the special theory of relativity, it was necessary to deny the equality of gravitational mass and inertial mass. Because that equality could be established experimentally to a high degree of accuracy, however, it was impossible to ignore. Furthermore, the triumph of special relativity was that it established that all motion was relative. There was no longer any concept of absolute velocity; only the idea of relative velocity remained. Acceleration, however, was left as an absolute. Einstein thought that acceleration should be relative if velocity was relative. The apparent discrepancy, along with the problem of gravity, disturbed Einstein and led him to develop his theory of gravity, which is known as the general theory of relativity.

The crucial step in the development of the general theory of relativity was the publication of the "Principle of Equivalence" in 1907. In this paper, it was proposed that, in any small region of space, one could not distinguish between gravity and acceleration. This meant that a person in a closed room who saw objects fall when they were dropped had no way of knowing whether those objects fell because the room was at rest on the surface of a planet or because the room was in a rocket ship that was accelerating in the direction opposite to the direction of the falling objects. Because gravity and acceleration were equivalent, the equivalence of gravitational mass and inertial mass was thus explained.

In 1911, Einstein used the principle of equivalence to establish that, because light seen by an accelerated observer is bent, gravity must also bend light. Between 1911 and 1916, Einstein worked on developing the complicated mathematics of his complete theory. In doing so, he discovered the correct value for the bending of light. Light follows the shortest distance between two points. When the shortest distance between two points appears to be curved, it means that the area of space that is involved is curved. For example, a straight line drawn on the two-dimensional surface of a globe will, if it is projected onto a flat map, appear to be curved. By using this line of reasoning, Einstein concluded that the curved path of light near a mass means that the four-dimensional space-time around that mass is curved. Furthermore, in 1917, Einstein used general relativity to show that the total mass of the universe affects the structure or shape of the universe as a whole.

IMPACT

Newton's theory of gravity was almost—but not quite—perfect, but Einstein's theory, as Einstein himself found in 1915, corrected those imperfections. More important to the acceptance of this theory, however, was the verification of its predictions for the bending of light. The experiment that was needed required, among other things, a total eclipse of the Sun so that light from the stars could be checked to see whether it was bent as it passed the Sun. This experiment was carried out in Africa in 1919 by the British astronomer Sir Arthur Eddington, and its results verified Einstein's theory.

Since that time, the "geometrification" of space has led to the idea of microscopic "wormholes" connecting one point in space to another. On a larger scale, this geometrification is manifested in searches for "black holes" from which not even light can escape. Such black holes are caused by the extreme warping of space that results when stars collapse. On the largest scale, this new view of space and time provides the basis for the various models that have been proposed to explain the creation and evolution of the universe.

See also Black Holes; Compton Effect; Electron Tunneling; Gravitation: Einstein; Mössbauer Effect; Speed of Light.

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—*Carl G. Adler*

REM SLEEP

THE SCIENCE: Eugene Aserinsky's discovery of rapid eye movements (REMs) in normal human sleep provided the first objective method of studying neural function and behavioral patterns associated with dreaming.

THE SCIENTISTS:

Eugene Aserinsky (1921-1998), graduate student of physiology at the University of Chicago

Nathaniel Kleitman (1895-1999), professor of physiology at the University of Chicago

William Dement (b. 1928), American physiologist

Laboratory Dreaming

As early as 1867, German psychiatrist Wilhelm Griesinger speculated on the occurrence of eye movements during dreams. These eye movements, he believed, occurred both during the transition from wakefulness to sleep and during dreaming. From these observations, he concluded that sleep was not a passive but rather an active state. It was another eighty-five years before Eugene Aserinsky discovered that sleep is not a homogeneous process but is organized in rhythmic cycles of different stages.

In 1952, Aserinsky, a graduate student working on his dissertation in the physiology laboratory of Nathaniel Kleitman at the University of Chicago, achieved a breakthrough in modern sleep research. Aserinsky turned his focus to the study of attention in children, using his young son, Armond, as one of his subjects. While making clinical observations of his young subject's efforts to pay attention, he noticed that eye closure was associated with attention lapse, and thus decided to record these eyelid movements using the electrooculogram (EOG).

Aserinsky and Kleitman observed that a series of bursts of rapid eye movements (REMs) occurred about four to six times during the night. The first such REM period took place about an hour after the onset of sleep and lasted from five to ten minutes. Succeeding REM periods occurred at intervals of about ninety minutes each and lasted progressively longer; the final period occupied approximately thirty minutes.

Suspecting a correlation of eye movements with dreaming, Aserinsky and Kleitman awakened subjects during REM periods and asked them whether they had been dreaming. In a large majority of such awakenings, the subjects acknowledged that they had been dreaming and proceeded to relate their dreams. When subjects were awakened while their eyes were motionless, they could rarely remember a dream. Therefore, Aserinsky and Kleitman concluded that rapid eye movements were an objective signal of dreaming. Although investigators still had to rely upon the dreamer's verbal report to ascertain the content of the dream, the process of dreaming was now opened up to objective study under laboratory conditions.

The Sleep of Cats and Children

In order to obtain a more complete picture of the mental state of his subjects, Aserinsky also recorded brain-wave activity with an electroencephalograph (EEG). Using both the EEG and the EOG enabled Aserinsky to register brain-wave activity during sleep from the moment it began, regardless of the time of day. This combination proved fortuitous because, unlike adults, children often enter the REM phase immediately at sleep onset, and such sleep-onset REM periods are especially likely to occur during daytime naps.

When Aserinsky's subjects lost attentional focus and fell asleep, their EEGs showed an activation pattern, and their EOGs showed rapid eye movements. Kleitman quickly deduced that this brain-activated sleep state, with its rapid eye movements, might be associated with dreaming. The two investigators immediately applied the combined EEG and EOG measures to the sleep of adult humans and were able to observe the periodic alternations of REM and non-REM sleep throughout the night. In addition, when the investigators awakened their subjects during REM sleep, these subjects related accounts of dreams.

In 1953, Aserinsky and Kleitman reported their findings in the journal *Science* in an article titled "Regularly Occurring Periods of Eye Motility and Concomitant Phenomena During Sleep." As is the case with many breakthrough articles, this one was relatively brief (barely two pages). Yet it included the observation that during REM sleep, other physiological functions vary according to the state of the brain: Respiratory frequency and heart rate fluctuate, and their rhythm becomes irregular.

Physiologist William Dement later confirmed Aserinsky and Kleitman's hypothesis. Following Aserinsky and Kleitman's groundbreaking 1953 article and their recognition of REM as the physiological basis of dreaming, Dement established that an identical phase of sleep occurs in cats; he published his results in the 1958 *EEG Journal*.

Impact

Studies that have attempted to show a relationship between the subject matter of dreams and the physiological changes that occur during REM periods have not established any close correlation between the two phenomena. Although early investigations indicated that the pattern of eye movements is correlated with the directions in which the dreamer is looking in the dream, subsequent evidence raised doubts concerning this hypothesis.

More conclusive evidence exists to support the theory that dreaming can sometimes occur during non-REM periods. This possibility suggests that dreaming may be more or less continuous during sleep but that conditions for the recall of dreams are most favorable following REM awakenings. In any case, the prevailing view is that REMs are not an objective sign of all dreaming but that they do indicate when a dream is most likely to be recalled.

Aserinsky's discovery of a stage of sleep during which most dreaming seems to occur led to experiments to investigate what would happen if a sleeping person were deprived of REM sleep. These studies concluded that there is an overwhelming demand for REM sleep. Because REM sleep usually accompanies dreaming, it was also concluded from these studies that there is a strong need to dream. Later studies with prolonged deprivation of REM sleep, however, did not confirm the degree of behavioral changes noted earlier. Thus, it can be concluded that there is definitely a need for REM sleep, but the question of whether there is also a need to dream is still open to debate.

By using an EEG to monitor sleep during the night and by awakening subjects during REM periods, it has been conclusively established that everyone normally dreams every night. Even a person who has never remembered a dream in his or her life will typically do so if awakened during a REM period.

See also Manic Depression; Pavlovian Reinforcement; Psychoanalysis; Split-Brain Experiments.

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—*Genevieve Slomski*

RIBOZYMES

THE SCIENCE: The demonstration the RNA can act as an enzyme to catalyze biochemical reactions provided evidence of the process of chemical evolution.

THE SCIENTISTS:
Thomas R. Cech (b. 1947), biologist who discovered catalytic RNA
Arthur J. Zaug, colleague of Cech
Sidney Altman (b. 1939), molecular biologist who also discovered the catalytic properties of RNA

Tan Inoue, collaborator with Thomas Cech who later showed the ability of RNA to catalyze biochemical reactions

Primordial Soup

In the 1920's, Aleksandr Ivanovich Oparin and John Burdon Sanderson Haldane independently proposed that the early Earth atmosphere lacked oxygen but contained an abundant amount of hydrogen-containing compounds, such as ammonia, methane, water vapor, hydrogen gas, hydrogen cyanide, carbon monoxide, carbon dioxide, and nitrogen. They both proposed that these gases spontaneously combined in the presence of energy. There was no lack of energy on the surface of the early Earth because of volcanic eruptions, lightning, and ultraviolet radiation. Oparin and Haldane hypothesized that it was in this type of environment—a reducing atmosphere without oxygen present—that life on Earth began.

Their model was tested in 1953 by Stanley Miller, a graduate student at the University of Chicago. He built a system of interconnecting tubes and flasks designed to simulate the primitive Earth atmosphere and primordial ocean. After a week, he analyzed the results and found simple organic acids and amino acids, the building blocks of proteins. Miller's experiment paved the way for others. Utilizing different mixtures of gases, later researchers produced virtually all the organic building blocks necessary for life and found in cells, including nucleotides, sugars, and fatty acids.

Once all the building blocks were formed, the next important step was to link these simple molecules into long chains, or polymers. An example of polymerization would be the linking of amino acids to form a long chain called a protein. Another polymer would be the polynucleotide, a long chain of single nucleotides. There are two types of nucleotides, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), which are very similar in structure. They differ in that DNA contains the pentose sugar deoxyribose, while RNA contains the pentose sugar ribose. Ribose has a hydroxyl group, —OH, instead of a hydrogen atom, —H, at the number 2 carbon atom. DNA also contains the four nucleotide bases adenine (A), guanine (G), cytosine (C), and thymine (T), while RNA contains the same nucleotide bases as DNA except that uracil (U) replaces thymine.

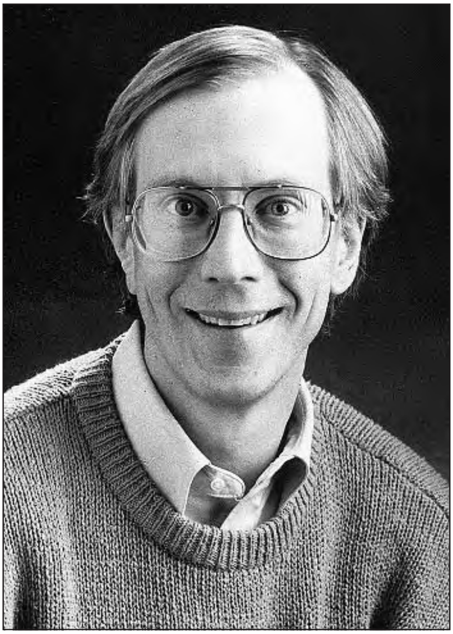
Many hypotheses suggest the early polymers may have been formed by different mechanisms. One means by which the organic molecules might have been concentrated is the process of evaporation. Another possibility is that clay particles in the soil, with their characteristic charges that attract and adsorb ions and organic molecules to their surfaces, might have brought early organic molecules close enough to one another that they could polymerize into long chains. The adsorbed metal ions also might have provided a site for the formation of polynucleotides. Once the polynucleotides formed, they then could have acted as a templates specifying "complementary sequences" for the formation of new polynucleotides. These complementary sequences would have resulted from the preferential bonding of certain nucleotides to one another (such as adenine with uracil or thymine, and guanine with cytosine). Geneticists have long known that this simple mechanism accounts for the transfer of genetic information from cell to cell and generation to generation.

The process of polymerization of nucleotides is slow and relatively ineffective; it would have been hindered by the conditions found on the primitive Earth. Even the clay and metal ions would have been slow. Presently, enzymes, which are proteins, function to catalyze (speed up the biochemical reactions involved in) the formation of polynucleotides. In the prebiotic solution or "primordial soup" of the early Earth, however, these enzymes would not yet have been present.

Ancient Enzymes

A discovery in 1981 by Thomas Cech and Arthur J. Zaug indicated how the early polynucleotides might have been replicated. RNA was thought to be a simple molecule, but now this appears not to be the case. Research with the ciliated protozoan *Tetrahymena thermophila* showed the existence of an RNA molecule with catalytic activity. Ribosomal RNA (rRNA) is synthesized as large molecules, which is then spliced to the correct size. In *Tetrahymena*, the surprise came when this reaction was found to occur without the presence of proteins to catalyze the reaction. The only requirement for the reaction to occur was magnesium ions and the nucleotide guanosine triphosphate (GTP). This was a surprising result because in 1981 the dogma in science stated that enzymes were proteins and catalyzed all the reactions of a cell.

Cech later showed that the RNA molecule contained the catalytic activity to splice itself. This self-splicing mechanism resembled the activity of an enzyme and Cech coined the term "ribozyme" to describe the RNA enzyme. A ribozyme is distinguished from an enzyme because it works on itself, unlike other enzymes, which work only on other molecules. Later, Cech studied the properties of the ribozyme and found it similar to enzymes in that it accelerated the reaction and was highly specific. In addition, the three-dimensional structure, as in enzymes, was found to be critical in the activity of the ribozyme. Cech's research showed that if the ribozyme was put in a solution that prevented folding, then the ribozyme



Thomas R. Cech. (The Nobel Foundation)

showed no catalytic activity, similar to any other enzyme.

The mechanism still needed refinement. Knowing that the folding was important in the catalytic activity aided in discovering the process. Cech and colleagues Brenda L. Bass, Francis X. Sullivan, Tan Inoue, and Michael D. Been discovered that the folding was essential in creating binding sites for GTP. This also activated the phosphate group and increased the likelihood for splitting the RNA molecules. The reaction catalyzed by the ribozyme was speeded up by a factor of 10 billion. Thus, the ribozyme was established as having many enzyme-like properties, such as accelerating the reaction and having a three-dimensional structure like an enzyme. It was observed that the ribozyme kept acting on itself. A true catalyst is not converted in the reaction, and the ribozyme was altered in the reaction. In 1983, this distinction also appeared. Zaug and Cech began working with *Tetrahymena* so that a shortened form of the RNA intron could work as a true enzyme.

RNA "GENES"

Another surprise came out of this research. As the ribozyme acted as an enzyme by splicing another RNA chain, it also was synthesizing a nucleotide polymer of cytosine. Not only was the ribozyme acting as a splicer—it was also behaving as a polymerase enzyme by synthesizing chains of RNA molecules that were up to thirty nucleotides long. Later, other researchers strung together strings of nucleotides up to forty-five nucleotides long. These results led to the implication that RNA can duplicate RNA genes.

In 1982, sequences of RNA molecules, introns (intervening sequences in genes), were found to be similar in different types of cells, such as fungi (yeast and *Neurospora crassa*) and protozoans. Remarkably, this discovery of a self-splicing RNA molecule was also found in a bacterial virus. This was a startling discovery, because fungi, protozoans, and viruses were thought to be only very distantly related. A conserved sequence implies an essential function even in the face of evolutionary divergence. This indicates the ribozyme may have evolved relatively early in the evolution of life.

Impact

Thomas Cech's work led to geneticists' current understanding of how RNA can duplicate RNA. These conclusions had a profound impact on the theory of the origin of life and chemical evolution. The fact that RNA can act as a catalyst supported the now widely accepted theory of an "RNA world" in which RNA was the primordial genetic material. These functions have now been taken over by DNA and proteins.

It is now known that RNA and DNA store genetic information, but only RNA, as shown by Cech, can act as a catalyst to speed up chemical reactions. Cech's discovery of splicing of RNA by RNA implies that proteins that may have been in existence might not have been needed for gene duplication. The self-splicing of RNA can be considered a primitive form of genetic recombination, since new combinations of RNA sequences are thereby created. Thus, the first genes are thought to be composed of RNA. RNA genes that were combined in a molecule that provided useful products could be at an advantage in the primordial mix.

Cech's discovery that RNA can replicate itself also led researchers to speculate that RNA might catalyze other reactions. Although RNA does not exhibit a high rate of catalytic activity, even a modest rate and some specificity would have been faster than what would have occurred with no enzyme at all.

It is therefore believed that RNA had a significant role to play in the the evolution of life beyond self-replication. If primitive cells, which were surrounded by a membrane, contained these ribozymes, they would have been at a selective advantage over other such cells. Thus, the primitive genetic material of these cells would have been duplicated and passed to other cells. In addition, ribozymes could also bind amino acids in close proximity to allow the amino acids to combine into short polypeptides. These polypeptides could then act as a primitive enzyme, and if they aided the cell in replication and survival of RNA, then the cell could split and pass the genes on to other cells.

Cech's work established a plausible scenario in which RNA might have been the primordial genetic material and enzyme. These functions have been taken over by DNA and proteins, but they are linked together by RNA. The specifics of how life started still remain a mystery, but the pieces

Sidney Altman and RNase P

In 1983, Canadian biologist Sidney Altman discovered the catalyst RNase P, which consists of both protein and RNA and demonstrated that the RNA is the catalytic part of the molecule. He and his colleagues performed the research that led to this discovery independently of Thomas R. Cech and his team, and virtually simultaneously. For this work Altman shared the 1989 Nobel Prize in Chemistry with Cech.


(The Nobel Foundation)

In his Nobel lecture, Altman gave his perspective on the flow of genetic information within cells, highlighting the role of transfer RNA (tRNA) in the translation of information from RNA into protein. In studying how tRNA is formed from its longer precursor RNA, Altman discovered the enzyme RNase P. This enzyme made a single cut within the longer precursor, cutting it at the site required to produce one particular end of the mature tRNA—an unusually precise reaction for an RNase. Early in his studies of this enzyme, its strong negative charge made Altman suspect that it might be associated with some type of nucleic acid.

Altman's graduate student Benjamin Stark succeeded in purifying and identifying a high-molecular-weight RNA called M1 RNA as a component of RNase P in 1978. He found that the M1 RNA was required for enzymatic activity. Altman described his own reaction: The involvement of an RNA subunit was enough heresy; neither he nor Stark even suspected that the RNA component of RNase P could in itself be a sufficient catalyst for the reaction. Another associate of Altman, Ryszard Kole, then found that the large M1 RNA and the small associated C5 protein of RNase P could be separated into inactive components and then recombined to recover their catalytic ability. By analogy with the ribosome (a very large RNA-protein complex), they began to consider seriously that M1 RNA was contributing to the active site of the enzyme.

At this point, recombinant DNA techniques enabled the Altman group to prepare large quantities of the M1 RNA and the C5 protein and to characterize their structures in detail. In an experiment designed to reconstitute RNase P from two different bacterial species, using *Escherichia coli* M1 RNA and *Baccilus subtilis* C5 protein, Cecilia Guerrier-Takada made the breakthrough discovery. When she tested the M1 RNA alone, under the conditions recommended for the *Baccilus subtilis* RNase P, the M1 RNA alone catalyzed the reaction. The discovery opened the door to speculation of a primordial "RNA world" before the dawn of life.

of the puzzle are coming together. Cech received the 1989 Nobel Prize in Chemistry for this work; he shared it with Sidney Altman, who independently and nearly simultaneously discovered the catalyst RNase P, which consists of both protein and RNA, and demonstrated that the RNA is the catalytic part of the molecule.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Stem Cells; Viruses.

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—*Lonnie J. Guralnick*

ROSETTA STONE

THE SCIENCE: The discovery of the Rosetta stone provided the key to decipher hieroglyphics, the ancient Egyptian system of writing, and so revealed the long lost, rich culture and history of the civilization.

THE SCIENTISTS:

Jean François Champollion (1790-1832), linguist and Egyptologist who deciphered hieroglyphics

Thomas Young (1773-1829), physician who worked on deciphering hieroglyphics and made invaluable contributions to the understanding of demotic script

NAPOLEON IN EGYPT

In 1798, Napoleon Bonaparte, general of the French military and a national hero, led a military expedition to Egypt. He had defeated most of the enemies of the French Republic except for Britain. He believed that a successful invasion of Britain could not be accomplished until its trade with India was disrupted. To that end, Napoleon planned to conquer Egypt and use it as a military base. Napoleon also had a personal interest in the country, wishing to secure its wealth, strategic value, and potential for development as a French colony. He decided to take 167 scholars with the troops when he left France in May.

Foreigners had ruled Egypt for centuries. The Persians conquered Egypt in 525 B.C.E., were driven out by 380 B.C.E., and returned by 343 B.C.E. The Greeks, led by Alexander the Great, conquered Egypt in 332 B.C.E. By the time of Julius Caesar (100-44 B.C.E.), Egypt no longer spoke its own language. Greek eventually gave way to Latin; the western influence gave way to Arab and then Islamic domination starting in 640 C.E.; and in Napoleon's time the Ottomans ruled the country. When Napoleon's expedition arrived, Egypt had been under the control of the Ottoman Turks for more than three hundred years.

The scholars whom Napoleon brought to Egypt consisted of specialists from all branches of astronomers, engineers, linguists, painters, draftsmen, poets, musicians, mathematicians, chemists, inventors, naturalists, mineralogists, and geographers. Over a three-year period, these "savants" recorded massive amounts of information and provided valuable drawings and sketches that helped spark a renewed interest in Egypt.

A CHANCE DISCOVERY

On August 22, 1798, Napoleon established the Institut d'Égypte (Egyptian Institute of Arts and Sciences) at Cairo, where the savants conducted research and studied the country's history, industry, and nature. On July 19, 1799, a soldier named d'Hautpoul was working to demolish a ruined wall at Fort Rashid (renamed Fort Julien) when he discovered a dark gray stone slab with inscriptions on one side. He reported the discovery to Lieutenant Pierre François Xavier Bouchard, who then informed his superior, Michel-Ange Lancret.

Lancret recognized one of the three scripts as Greek and another as hieroglyphics. The third script was unknown. Bouchard transported the stone to Cairo so that the savants at the institute could examine it. The savants copied the inscriptions using rubbings, drawings, and casts and sent them to scholars throughout Europe so that they could begin working on translating the hieroglyphics.

The Rosetta stone was a basalt slab weighing three-quarters of a ton and measuring 3 feet, 9 inches long, 2 feet, 4.5 inches wide, and 11 inches thick. The stone was damaged, especially the upper portion with the hieroglyphics. The middle section displayed the unknown language—later identified as demotic script—and the bottom portion was Greek.

Identifying the Code

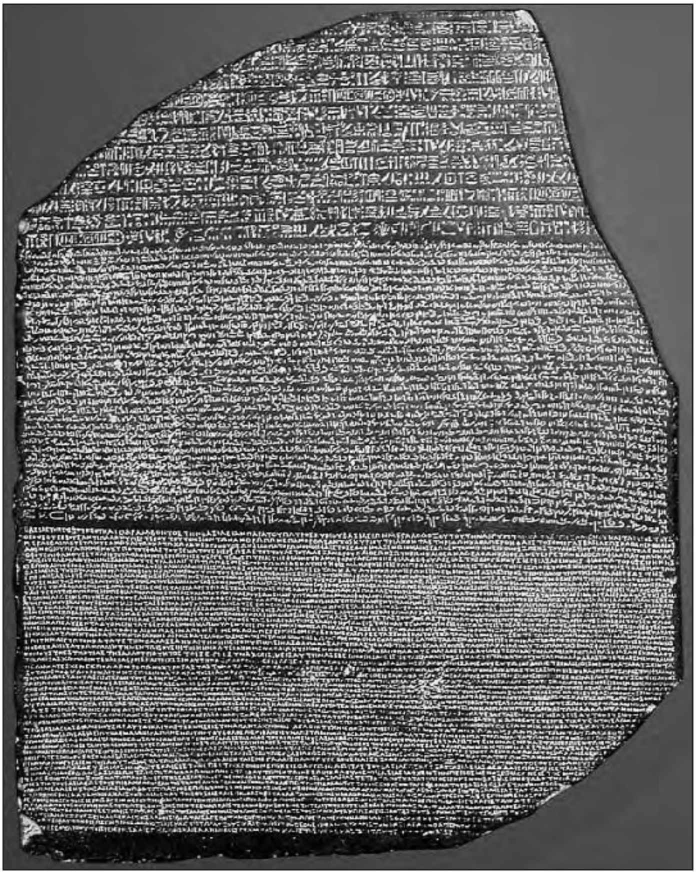
In ancient Egypt, there were two types of writing: hieroglyphics, used in formal writing, and hieratic script, a cursive form of hieroglyphics (simplified and faster), used for everyday writing. By 650 B.C.E., the hieratic script and language had changed so much that it was called demotic. The last known use of hieroglyphics dated from 394 C.E., at a temple in Upper Egypt. Although hieroglyphics had been used for more than three thousand years, no one had read or understood hieroglyphics for fifteen hundred years, so in Napoleon's time the ancient Egyptian civilization was essentially a mystery—lost even though the glyphs were visible on papyrus scrolls, temples, and monuments. By 250 C.E., Coptic—a mixture of demotic and the Greek used by Christian Egyptians—was common in Egypt and marked the first time that vowels had been introduced. Eventually, the Coptic language was replaced, but because it continued to live in the formal Christian liturgy, scholars still could understand the spoken and written forms.

The Greek text on the Rosetta stone was a decree by the priests of Memphis, dated 196 B.C.E., commemorating Ptolemy V Ephiphanes, who ruled Egypt from 204 to 180 B.C.E. According to the decree, Ptolemy V restored the economy and peace, reduced taxes, and was a just ruler, so statues were to be erected and festivals held in his honor. The most exciting part, however, was the conclusion of the text, which indicated that the decree would be inscribed in holy (hieroglyphic), native (demotic), and Greek languages. This directive made it clear that the other parts of the stone essentially were translations of the Greek portion. Reasonably certain that all three scripts recorded the same information, the savants believed that the secret of reading hieroglyphics would be quickly and easily solved.

The Fight over Rosetta

Napoleon left Egypt in August, 1799, to return to France. He took only a few soldiers and some of the savants back with him, as he needed to travel quickly and did not want to appear to give up the Egyptian military campaign. The campaign had failed once the British cut off the supply line, but Napoleon presented the expedition as a success. With severe economic problems fostering a climate for a governmental coup, Napoleon became part of a triumvirate of consuls governing France. In December, 1804, he declared himself Emperor of France.

The remaining troops and savants in Egypt negotiated with the British to leave in early 1800 but were delayed until late 1801. The British wanted to keep all of the records and collections gathered by the savants, but they eventually relented. The British did take back to Britain some major items, however—including the Rosetta stone. Several of the savants decided to go to Britain in order to retain control over their records and collections that the British claimed. Eventually, twenty volumes titled *Description de l'Égypte* (description of Egypt) were published between 1809 and 1828, based on the information collected by the savants. The work covered the



The Rosetta stone.

monuments, natural history, and the modern country as of 1800, and also included the first comprehensive map of Egypt.

In early 1802, the Rosetta stone arrived in Britain and was taken to the Society of Antiquaries in London, where plaster casts were made for universities and engravings were distributed to academic institutions throughout Europe. The stone itself was housed in the British Museum by the end of 1802.

"This decree shall be inscribed . . ."

The text of the Rosetta stone is dated March 27, 196 B.C.E. Below is an excerpt of the original, unattributed English translation prepared for the British Museum.

Decree. . . . Whereas King Ptolemy, the ever-living, the beloved of Ptah, the god Epiphanes Eucharistos, the son of King Ptolemy and Queen Arsinoe, the Gods Philopatores, has been a benefactor both to the temple and to those who dwell in them, as well as all those who are his subjects. . . .

With propitious fortune: It was resolved by the priests of all the temples in the land to increase greatly the existing honours of King Ptolemy, the ever-living, the beloved of Ptah, the god Epiphanes Eucharistos . . . to set up in the most prominent place of every temple an image of the ever-living King Ptolemy, the beloved of Ptah, the god Epiphanes Eucharistos, which shall be called that of "Ptolemy, the defender of Egypt," beside which shall stand the principal god of the temple, handing him the scimitar of victory, all of which shall be manufactured in the Egyptian fashion; and that the priests shall pay homage to the images three times a day, and put upon them the sacred garments, and perform the other usual honours such as are given to the other gods in the Egyptian festivals; and to establish . . . a statue and golden shrine in each of the temples, and to set it up in the inner chamber with the other shrines; and in the great festivals in which the shrines are carried in procession the shrine of the God Epiphanes Eucharistos shall be carried in procession with them. And in order that it may be easily distinguishable now and for all time, there shall be set upon the shrine ten gold crowns of the king, to which shall be added a cobra exactly as on all the crowns adorned with cobras. . . .

This decree shall be inscribed on a stela of hard stone in sacred and native and Greek characters and set up in each of the first, second and third rank temples beside the image of the ever-living king.

Source: Excerpted from (London, Trustees of the British Museum, 1981). Available at http://pw1.netcom.com/~qkstart/rosetta.html. Accessed September, 2005.

DECIPHERING HIEROGLYPHICS

Although scholars across Europe worked on translating hieroglyphics, the most important were Jean-François Champollion of France and Dr. Thomas Young of England. Champollion was in Paris by 1807 at age seventeen and working on a copy of the Rosetta stone inscriptions. He realized that hieroglyphics were not only a type of sign but also a hybrid of two classes of language: phonetic (representing sound) and pictorial or ideological (representing pictures or ideas). Eventually, he understood the relationship between hieroglyphics, hieratic, and demotic script, experiencing a breakthrough on September 14, 1822. He later established that hieroglyphics were based on pictograms, ideograms, and phonetic symbols, as well as signs used in special ways. Champollion became the first person able to read hieroglyphics in more than fifteen hundred years.

Young began his work on hieroglyphics in 1814. He realized that some of the hieroglyphics were pictorial, some indicated plurality, and some expressed numbers. He also determined that demotic script uses letters to spell out foreign sounds and was not entirely alphabetic, as some scholars had believed. Young's work on hieroglyphics was published anonymously as a supplement to *The Encyclopaedia Britannica* in 1819. Although Young's system of deciphering did not work, he was the first scholar to make a serious study of demotic script, and his work was invaluable in that regard.

IMPACT

The discovery of the Rosetta stone made it possible for the first time to unlock the mystery of Egyptian hieroglyphics. Although the stone was discovered in 1799, it would take twenty-three years before hieroglyphics were translated. Once translated, however, the Rosetta stone launched the modern subdiscipline of Egyptology, the study of Egypt and its past.

Both Champollion and Young came to their conclusions independently of one another, and both contributed greatly to understanding hieroglyphic, hieratic, and demotic scripts. By understanding the ancient writing, they helped reveal the history of Egypt and its people to the world. The tremendous amount of written material that had survived on papyri and monuments could now unlock insights into the ancient Egyptian culture that had not been available for any other ancient civilization. Travel to Egypt and the collection and preservation of the ancient monuments and artifacts became a focus of much archaeology over the next two centuries, yielding remarkable information about the complexity of the civilization.

See also Dead Sea Scrolls; Pompeii; Stonehenge; Troy.

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—*Virginia L. Salmon*

RUSSELL'S PARADOX

THE SCIENCE: The logical paradox discovered by Bertrand Russell challenged the long-accepted belief in the consistency of mathematics.

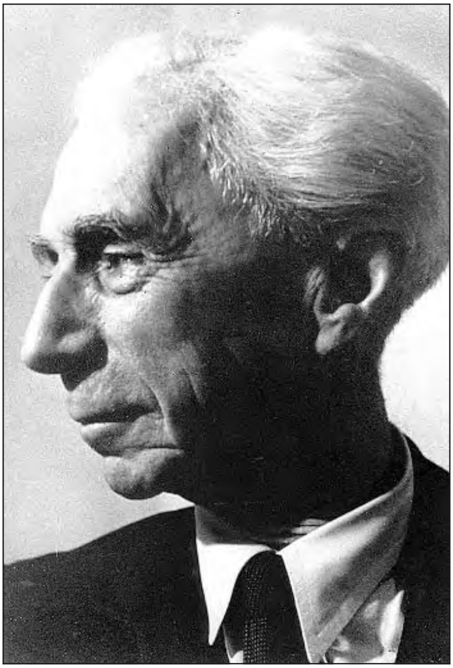
THE SCIENTISTS:

Bertrand Russell (1872-1970), English philosopher
Gottlob Frege (1848-1925), German logician
David Hilbert (1862-1943), German mathematician
Kurt Gödel (1906-1978), Austrian mathematician
Luitzen E. J. Brouwer (1881-1966), Dutch mathematician

MATHEMATICS LOOKS INWARD

The late nineteenth and the early twentieth centuries were characterized by self-reflection within various intellectual domains. For example, Impressionism and later schools of art investigated the very methods of creating art, focusing on "art for art's sake." Sigmund Freud and others founded the field of psychology, which consists of the human psyche looking at itself. Literature, music, architecture, and science (which paid particular attention to the "scientific method") also turned inward.

Mathematics was no exception to this trend; the methods of mathematics were themselves being scrutinized. For example, Gottlob Frege was intensely investigating mathematical logic, the method of mathematical thinking. Central to Frege's work was the mathematically pervasive concept of the "set"—a collection of objects, real or abstract, that could be



Bertrand Russell. (The Nobel Foundation)

defined by either listing its elements or providing a property that characterized only those elements. For example, one set might be defined as {2,4,6} or as those positive even numbers lower than 8. The property-based mode of definition must be used to define infinite sets (such as the set of integers), because infinite sets cannot be listed.

Frege's work was well advanced when Bertrand Russell encountered a peculiar problem in his definition of sets by properties. Unable to see the solution, he wrote to Frege in 1902 to inquire about the problem. The older logician replied with one of the most gracious responses to bad news ever written, stating that he had never noticed the problem and that he could not see a solution for it. Thus, it was discovered that the foundation of Frege's life work was seriously flawed.

The Paradox

This problem, now called Russell's paradox, is deceptively simple to delineate. Because sets are well defined, they may be collected into other sets. For example, the set A may be defined as consisting of all sets with more than two elements. Set A would therefore contain the set of planets, the set of negative numbers, the set of polygons, and so forth. Because these are three sets collected by A, then set A itself has more than two elements. Therefore, set A is a member of itself. This fact may seem strange, but the defining property is absolutely unambiguous: "sets with more than two members." Thus, sets may be elements of themselves.

Russell then considered the set D, which consists of those sets that do not contain themselves. Then he asked, "Does D contain itself?" If it does, it is one of those sets that it must not contain. Therefore, D must not contain itself, but D is also one of those sets that it must contain. D contains itself only if it does not contain itself!

Paradoxes of ordinary language are well known. Two examples are the Cretan Epimenides' remark that "all Cretans are liars" (the liar paradox) and the sentence "This sentence is false." Both statements are true only if they are false. Russell's observation, however, represented the first time that the specter of paradox had arisen within mathematical thought. The seriousness of Russell's paradox stems from the assumption that mathematics embodied a higher truth and was therefore free from error, consistent, and unambiguous. Russell demonstrated that this assumption was false.

Impact

Many mathematicians, philosophers, and computer scientists regarded Russell's paradox as an assault on the very foundations of mathematics. If inconsistency could arise in an area as rigorous as set theory, how could consistency be guaranteed in more common areas of mathematics?

Russell and the philosopher Alfred North Whitehead set out to improve upon Frege's work (the Logicist school of thought). If mathematics could be derived from basic, self-evident axioms, no inconsistency would be possible. Russell and Whitehead's *Principia Mathematica* (1910) led to new uses of logic, but its means of avoiding paradox was too arbitrary for all mathematics, since it states that sets cannot contain both objects and other sets.

The Formalist school of David Hilbert, however, sought to establish the foundations of mathematics in the realm of symbol manipulation. The rules that governed such manipulation would be very simple and precise. Such a "proof-theoretic" or "metamathematical" analysis of proof was expected to confirm the consistency of mathematical systems. Much that was useful in mathematics and computer science came out of this work, but in 1931, the young Kurt Gödel astounded the world of mathematics by proving that the Formalist ideal was unreachable—that most mathematical systems could not be proved, by noncontroversial means, to be fully adequate and consistent.

The Intuitionist school of Luitzen E. J. Brouwer grew out of the work of Leopold Kronecker and therefore was not a response to Russell's paradox, but the Intuitionists believed that their insistence on meaning in mathematics would avoid paradox. Intuitionists limit mathematics to what actually can be "constructed" by the human mind. Therefore, infinite sets are ruled out, as is automatic acceptance of the "law of the excluded middle" (which states, basically, that any statement must be either true or false). In this school, the truth or falsity of any statement must be demonstrated. Both of these objections apply to Russell's paradox: D is an infinite set, and the assumption that "D contains D or it does not" is an application of the law of the excluded middle.

The Intuitionist/Constructivist school has not found wide acceptance, because it is viewed as too restrictive by many mathematicians. It is very important, however, in the field of computer science, in which most results must be demonstrated constructively.

It is possible that, before the discovery of Russell's paradox, an easily understood problem had never caused such a major crisis in a scientific field. Russell's paradox had this effect because it forced mathematicians and philosophers to reexamine traditional assumptions about mathematical truth.

See also Abstract Algebra; Axiom of Choice; Bell Curve; Boolean Logic; Bourbaki Project; Calculus; Chaotic Systems; D'Alembert's Axioms of Motion; Decimals and Negative Numbers; Euclidean Geometry; Fermat's Last Theorem; Fractals; Game Theory; Hilbert's Twenty-Three Problems; Hydrostatics; Incompleteness of Formal Systems; Independence of Continuum Hypothesis; Integral Calculus; Integration Theory; Kepler's Laws of Planetary Motion; Linked Probabilities; Mathematical Logic; Pendulum; Polynomials; Probability Theory; Speed of Light.

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—*J. Paul Myers, Jr.*

SATURN'S RINGS

THE SCIENCE: After developing an improved technique to grind lenses to precise shapes, Huygens constructed an improved 50-power telescope that helped him identify the unusual elongation of Saturn as a ring or disk surrounding the planet. Huygens also discovered Titan, Saturn's largest moon.

THE SCIENTISTS:

Christiaan Huygens (1629-1695), Dutch astronomer who identified Saturn's rings

Galileo Galilei (1564-1642), Italian astronomer who first observed Saturn's rings but thought they were large moons on both sides of the planet

Gian Domenico Cassini (1625-1712), Italian astronomer who believed Saturn's rings were a multitude of small particles in orbit around the planet

Galileo

In 1610, Galileo the first to observe Saturn with a telescope. He recorded that Saturn had an odd appearance, with projections that appeared to be "handles" at both sides. Galileo, however, did not understand his observations. He thought the handles could be two large moons, one on each side of the planet, so he described Saturn as a group of three, nearly touching objects that do not move relative to one another. Two years later, in 1612, Galileo became even more puzzled when he observed that Saturn's "handles" had disappeared.

Although Saturn's ring system was first observed by Galileo, Dutch physicist and mathematician Christiaan Huygens is credited with their discovery because he was the first person to identify the observed elongation of Saturn as the presence of a disk or ring surrounding the planet.

Christiaan Huygens

Huygens had studied law and mathematics at the University of Leiden from 1645 until 1647, and he published a series of papers on mathematics, but actually he had trained to be a diplomat. In 1649, Huygens was a member of a diplomatic team that was sent to Denmark, but he was not offered a permanent position in diplomacy. In 1650, Huygens returned home and lived on an allowance from his father.

Both Huygens and his brother Constantine were interested in astronomy, but they found that the telescopes then available were too short to resolve features on the planets. The brothers gained an interest in lens grinding and telescope construction to improve the quality of their observations, and, around 1654, they developed a new and better way of grinding lenses for telescopes. Their techniques significantly reduced "chromatic aberration," an effect that causes simple lenses to focus different colors of light at different points of the telescope lens. They also introduced the use of "optical stops," masks along the tube of a telescope that intercept light reflected from the walls of the tube, keeping reflected light from reaching the lens and blurring the image.

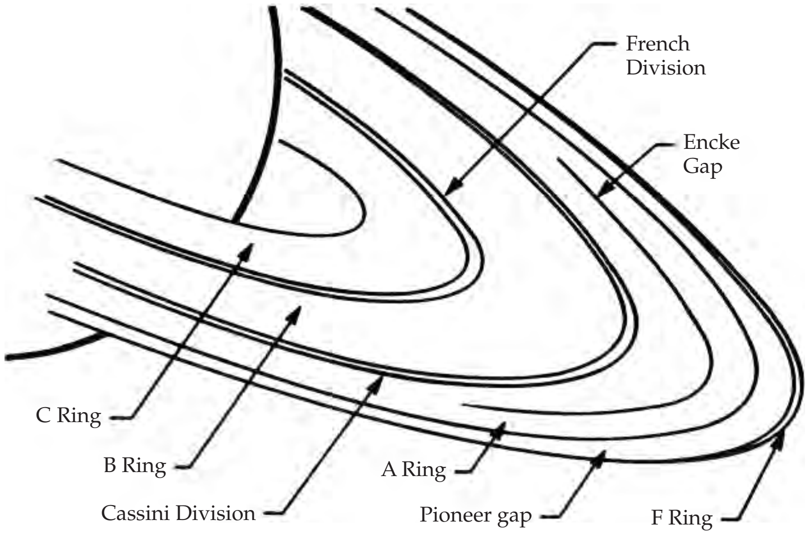
Titan Discovered

Using one of his own lenses, Christiaan Huygens built a self-designed 50-power refracting telescope. With this new telescope, in 1655, he discovered Titan, the first and largest moon of Saturn. Later that year, he visited Paris and informed the astronomers there, including Ismaël Boulliau (1605-1694), of his discovery. By this time, Boulliau was a well-recognized astronomer who had published his *Astronomia philolaica* (1645), in which he adopted Johannes Kepler's idea that planets moved in elliptical orbits around the Sun. Huygens's discovery of Titan was near the time of the "ring plane crossing" phenomenon, that is, when Saturn's rings are viewed edge-on from the Earth, making them difficult to see. Thus, Huygens was unable to see the rings when he discovered Titan.

The Ring Debate

In February of 1656, the true shape of the Saturn's rings was apparent to Huygens. He recognized that the bulge, which Galileo thought were two moons, actually was a thin, flat disk or ring, which did not touch the planet and was inclined to the ecliptic plane. Huygens reported his conclusions in

Rings of Saturn



Source: Morrison, David. *Voyages to Saturn*. NASA SP-451. Washington, D.C.: National Aeronautics and Space Administration, 1982, p. 25.

a message to Boulliau, in order to establish the priority of his discovery. However, Huygens did not make a public announcement of his results until 1658, in a letter to the scientific academy in Paris.

Huygens's description of Saturn's rings was not immediately accepted. At least three other astronomers offered different explanations for Saturn's bulge after Huygens's discovery. Gilles Personne de Roberval (1602-1675) proposed that Saturn emitted vapors, like a volcano, from its equatorial region. When the concentration of vapors was high enough, they would become visible as a belt around the planet. Johannes Hevelius, an astronomer from Gdansk, proposed that Saturn was not a sphere, but rather an ellipsoidal, and the bulge was simply part of the planet. Giovanni Battista Odierna (1597-1660) suggested that Saturn had two large dark areas at its equator, which appeared to observers as "handles."

Even with the excellent view of Saturn that Huygens had through his improved telescope, it was not until 1659 that he correctly inferred the geometry of Saturn's rings, because he had to wait until he had observed them over a significant part of their cycle. In his *Systema Saturnium, sive De causis mirandorum Saturni phænomenôn, et comite ejus planeta novo* (1659; the system of Saturn, or on the matter of Saturn's remarkable appearance, and its satellite, the new planet; better known as *Systema Saturnium*), Huygens

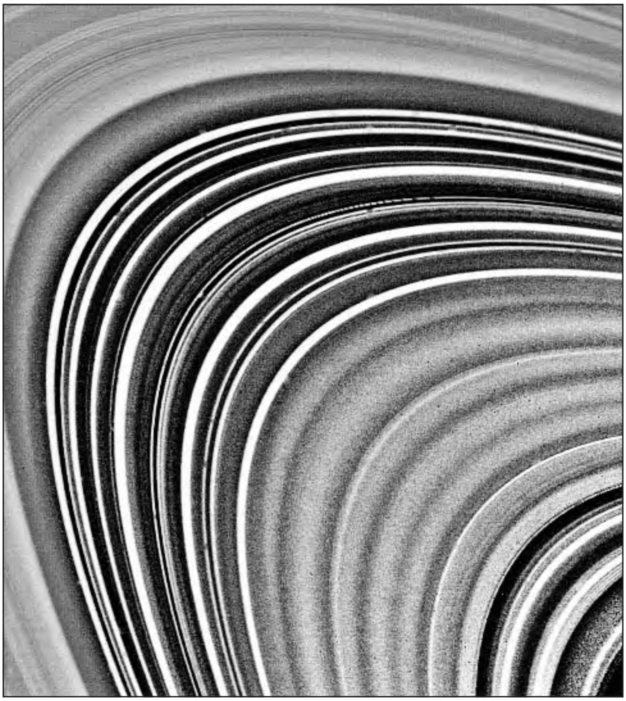


Image of Saturn's rings captured by Voyager 2 in 1981.
(NASA/JPL)

explained the phases and changes in the shape of the ring based on the expected view of a rigid disk surrounding the planet and inclined relative to the Earth's orbital path around the Sun. Huygens noted that all earlier observations of Saturn suffered from inadequate resolution. He argued against the models proposed by Roberval, Hevelius, and Hodierna, and offered his idea of a disk surrounding Saturn at its equator but tilted at an angle of about 20° to the plane of Saturn's orbit. He explained that this tilt is what causes the appearance of Saturn's ring to vary as Saturn moves around the Sun.

Although Boulliau generally accepted Huygens's idea of a ring, he believed the ring should still be seen from Earth even when edge-on. Many other astronomers were not convinced. In 1660, Eustachio Divini (1610-1685), an Italian instrument (and telescope) maker, published his "Brevis annotatio in *Systema Saturnium* Christiani Eugenii" (brief comment on Christian Huygens's *Systema Saturnium*), which attacked not only Huygens's ring theory but also the validity of his observations. This book suggested Saturn had four moons, two dark ones near the planet and two bright ones farther out. The handles appeared when the bright moons were in front of the dark ones, partially blocking them from Earth.

Huygens quickly replied with his "Brevis assertio *Systematis Saturnii* sui" (1660; brief defense of *Systema Saturnium*), pointing out that the work of other astronomers contained incorrect observations, which could be explained only by their use of inferior telescopes. Hevelius accepted the ring theory after reading "Brevis assertio *Systematis Saturnii* sui." By 1665, the matter was finally settled, when telescope quality had improved to the point that most astronomers were able to replicate Huygens's observations.

A Solid Ring?

The question that faced the astronomers next was how such a disk could be stable. Huygens thought the ring was a solid structure, but Gian Domenico Cassini proposed that the ring consisted of a large number of small particles, all orbiting around Saturn. Cassini, who conducted extensive observations of Saturn using telescopes at the new Paris Observatory, noted that there was a dark gap separating the ring into two separate rings. This showed that Saturn's rings could not be a single, rigid disk, as proposed by Huygens.

In was not until 1858 that James Clerk Maxwell (1831-1879), a Scottish physicist, was able to perform a detailed mathematical analysis that showed how a ring composed of many tiny particles could be stable. By the end of the nineteenth century, astronomers were able to measure the speed of the particles at the inner and outer edges of the ring. This measurement was inconsistent with a solid rotating disk, and it agreed with the orbital speeds calculated from Kepler's laws of motion.

IMPACT

The rings remained a planetary feature unique to Saturn until 1977, when fainter rings were discovered around Uranus and, shortly after, around the two other gas giant planets, Jupiter and Neptune.

Even more important than these observations, however, was Huygens's insight that the Saturnian system was a miniature solar system, with Titan orbiting Saturn the way Earth orbits the Sun, as Nicolaus Copernicus and Kepler had proposed. Thus, Huygens's observations supported the Copernican idea of a Sun-centered (heliocentric) rather than an Earth-centered (geocentric) solar system. His work was done at a time when a great debate on the issue of a heliocentric versus geocentric system was raging among the best minds in astronomy in Europe.

Because of his great contribution to the understanding of Saturn, the National Aeronautics and Space Administration (NASA) named its Titan space probe the Huygens probe. The probe, which reached Titan in January, 2005, during the Cassini-Huygens mission, fittingly transmitted some of the most important data on Titan to date.

See also Cassini-Huygens Mission; Extrasolar Planets; Galileo Mission; Herschel's Telescope; International Space Station; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mars Exploration Rovers; Moon Landing; Nebular Hypothesis; Space Shuttle; Voyager Missions.

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—*George J. Flynn*

SCHICK TEST

THE SCIENCE: Béla Schick developed the Schick test, which is performed on the skin to find out how susceptible a person is to diphtheria.

THE SCIENTISTS:

Béla Schick (1877-1967), Hungarian microbiologist and pediatrician

Edwin Klebs (1834-1913) and Friedrich Löffler (1852-1915), German microbiologists who identified the bacteria that cause diphtheria

Pierre-Paul-Émile Roux (1853-1933), French microbiologist

Alexandre Yersin (1863-1943), Swiss microbiologist

Emil von Behring (1854-1917), German microbiologist who discovered a diphtheria antitoxin

A KILLER DISEASE

Diphtheria is a serious disease of the upper respiratory tract—the mouth, nose, and pharynx. The person with this disease may have a fever, a sore throat, and pain all over the body. If the disease is not treated with antibiotics, the infection spreads and causes tissue damage in the heart or kidneys and the victim will eventually die.

Diphtheria is caused by *Corynebacterium diphtheriae*, a rod-shaped species of bacteria. The bacterium can be spread from one person to another by touching or by droplets (for example, from sneezes). Once it enters a person's body, the bacterium releases protein toxins that destroy the membranes and inner structures of cells.

In the 1800's, this disease was not yet understood, but the first steps toward that task were taken. Louis Pasteur, Robert Koch, and other microbiologists (scientists who study organisms too small to be seen by the naked eye) established the germ theory of disease, showing that infectious diseases are carried by microorganisms, usually bacteria or viruses. Diphtheria, typhoid fever, scarlet fever, tuberculosis, and several other diseases were major killers in the nineteenth century, especially among patients in hospitals. Microbiologists were determined to discover the microorganisms that caused these diseases.

In 1883, the German microbiologists Edwin Klebs and Friedrich Löffler raised guinea pigs infected with diphtheria. Under microscopes, they observed rod-shaped bacteria growing in blood samples from the infected animals. When this bacterium was injected into healthy guinea pigs, they became ill with diphtheria, too. In this way, the scientists proved that this rod-shaped bacterium was the cause of diphtheria.

Löffler believed that these bacteria hurt their victims by releasing a toxin (a chemical that damages cells). In 1888, microbiologists Pierre-Paul-Émile Roux and Alexandre Yersin, working together at the Pasteur Institute in Paris, separated the diphtheria bacteria from the serum in which they were being grown. Roux and Yersin then injected the bacteria-free serum into healthy animals. The animals soon came down with diphtheria, even though they had not been exposed to the bacteria. The scientists realized that a toxin was being released by the *Corynebacterium diphtheriae* into the growth serum, and that it was this toxin that made people and animals ill.

Fighting Diphtheria

Now microbiologists could go to work finding a vaccine and designing methods of diagnosing and treating diphtheria victims. In 1890, German microbiologist Emil von Behring discovered that the blood of animals infected with diphtheria produced an antitoxin, a chemical that binds to a toxin and makes it harmless. Behring realized that the antitoxin might be helpful in producing a vaccine to protect people against diphtheria. He injected animals with weakened diphtheria toxin—just enough so that their immune systems would create antitoxin but not enough to hurt the animals. Unfortunately, this diphtheria toxin was too dangerous to use on humans. Behring's work, however, led to the later use of diphtheria antitoxin produced in horses as a treatment for human victims of the disease. In 1923, a formalin-treated toxin was used to vaccinate people against diphtheria and was found to be safe.

Detecting Susceptibility

In 1908, Béla Schick, a pediatrician and microbiologist from Boglár, Hungary, became an assistant to Theodor Escherich at the University of Vienna, Austria. These two scientists began studying diseases caused by bacteria, including diphtheria and scarlet fever.

In 1913, Schick used Behring's work with antitoxins to develop a test that would show how susceptible a person was to catching diphtheria. The result was the Schick test, which proved to be simple and reliable. About 0.1 milliliter of a weakened toxin solution is injected just under the skin inside a patient's arm. The toxin is treated so that it will lead to a bit of swelling in susceptible persons without hurting them. If the patient is susceptible to diphtheria, a reddened, swollen rash (caused by damaged skin cells) will appear around the injection site within a few days. A person who is not susceptible will have no reaction, since the toxin is not causing damage.

Those who test positive with the Schick test should be immunized. People who are already suffering from diphtheria can be treated with a combination of antibiotics and horse serum antitoxin. Antibiotics destroy the *Corynebacterium diphtheriae* bacteria, while the horse serum antitoxin destroys the diphtheria toxin until the victim's body is strong enough to make enough of its own antitoxin.

Impact

Schick's test for diphtheria became a valuable tool for identifying the disease and which people most needed immunization. For his findings, Schick was named Extraordinary Professor of Children's Diseases at the University of Vienna in 1918. His test saved thousands of lives, especially among children, who tend to be susceptible to diphtheria. In the middle-to-late 1920's, when the first successful toxoid vaccine was available, the number of cases of diphtheria around the world dropped dramatically.

During the first two decades of the twentieth century, before the test and vaccine were available, there were between 150,000 and 200,000 diphtheria cases every year in the United States alone. By the 1970's, the number of diphtheria cases had dropped to ten per year.

The work of Schick and others also helped show how microorganisms are present everywhere in the environment and can cause disease once they are inside the human body. This led to a better understanding of the importance of antisepsis and sterilization. Before the 1900's, surgical instruments were kept clean, but they were never sterile (clear of all microorganisms); as a result, many patients died after surgery. Microbiological research in Schick's day led to the sterilization of surgical equipment, antiseptic treatment to keep all hospital rooms and equipment clean, and the sanitation of water.

See also Diphtheria Vaccine.

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—*David Wason Hollar, Jr.*

SCHRÖDINGER'S WAVE EQUATION

THE SCIENCE: Erwin Schrödinger proposed that electrons in an atom travel in waves like those of light.

THE SCIENTISTS:
Erwin Schrödinger (1887-1961), Austrian physicist
Louis de Broglie (1892-1987), French physicist
Niels Bohr (1885-1962), Danish physicist
Werner Heisenberg (1901-1976), German physicist

WAVES IN MATTER?

The first three decades of the twentieth century were a time of great change in the manner in which scientists viewed the world. In this short span of time, the early concept of the atom as an indivisible piece of matter was transformed into a picture of an atom made of different particles with different properties interacting with one another to form one unit. In 1922, Niels Bohr was awarded the Nobel Prize in Physics for his theory that the electrons in an atom orbit the nucleus only at certain distances, or energy levels. These levels are determined by a constant discovered by Max

Planck (1858-1947), which relates to units, or quanta, of light. Although Bohr's theory was widely acclaimed by such eminent scientists as Albert Einstein (1879-1955), there were still problems with it.

Louis de Broglie expanded on Bohr's and Planck's work in his hypothesis that, if light could have some of the properties of particles, perhaps matter could have some of the properties of waves. In thinking about the possibility of "matter waves," he was especially interested in finding exact positions of the electrons in an atom by treating them as if they moved in the same wavelike patterns as those of light. In 1923, de Broglie suggested that the energy levels Bohr had found were simply certain numbers multiplied by Planck's constant.

Standing Waves

One of de Broglie's biggest problems was that he could not find enough mathematical evidence to support his theory. Bohr had believed that electrons orbited the nucleus in the same way that planets orbit the Sun. De Broglie realized that atomic structure was more complicated than this, and experimental evidence was soon found that backed him up. No means had been found, however, to predict where an electron would go in any particular atom.

At this time, Erwin Schrödinger was teaching at the University of Zurich, Switzerland, in the same position that Einstein had occupied several years before. Schrödinger was fascinated by Bohr's and de Broglie's theories but found several flaws in them. Both of these earlier theories assumed that the light waves that could be associated with certain atoms (their "spectra") came from electromagnetic waves radiating from the atoms. Schrödinger studied these atoms from a slightly different point of view: He believed that the energy levels found by the earlier theories were the result of "standing waves"—that is, waves that overlapped each other so exactly that they did not allow any other radiation to escape—rather than of continuously radiating energy. Radiation could be detected only when electrons moved from one energy level to another, while the overlap of their paths did not form a standing wave.

Schrödinger developed a complicated equation, known as the Schrödinger wave equation, that could be used to predict where in an atom an electron would be at a certain time. He presented this equation, along with its development, support, and consequences, in a series of six papers published in the last half of 1926. It was quickly shown that the values found by calculating Schrödinger's wave equation for certain numbers corresponded exactly to Bohr's energy levels, as well as to other data, such as the spectral lines of the chemical elements (lines of certain colors of light that depend on the wavelength of the light; the chemical elements have their own, discrete spectral emissions).

Heisenberg's Matrix Mechanics

At almost the same time that Schrödinger was working on his wave-mechanical view of the atom, Werner Heisenberg was using much of the same data to develop a "matrix-mechanical" view of the atom. Heisenberg's model was based entirely on experimental evidence rather than on ideas of what the atom should look like. The two scientists published their discoveries within a year of each other, and Schrödinger soon showed that he could generate the same results with his wave equation that Heisenberg had with his matrices. The combination of these two theories gave a firm basis for the complete theory called "quantum mechanics."

Impact

Although Schrödinger received the Nobel Prize in Physics for his work in 1933, he was not completely satisfied with his conclusions. He had not eliminated from the earlier theories the concept of quantum jumps, or electrons "jumping" through space while going from one energy level to another. Although he had given a logical explanation of the reasons for this occurrence, the existence of quantum jumps was one of the original flaws he had found in Bohr's theory. Various aspects of this flaw continued to be bones of contention among Schrödinger, Heisenberg, and other physicists for years to come, although the more established names in theoretical physics, such as Einstein and Planck, accepted Schrödinger's theories enthusiastically.

Erwin Schrödinger. (The Nobel Foundation)

Schrödinger's wave equation gave rise to a whole new branch of physics, became the basis for virtually all subsequent developments in the field of chemistry, and had a great impact on many other areas of science, including astronomy and biology. In chemistry, Schrödinger's equation has been used to explain bond energies and bond lengths between the

SCHRÖDINGER'S CAT

In quantum mechanics, the laws of physics are governed by probability. Unlike the rest of science, quantum mechanics does not offer models of what will happen given a certain set of circumstances; quantum mechanics merely describes how probabilities change with time. Upset by the absurd implications of this position, Erwin Schrödinger in 1935 framed a famous thought experiment designed to expose it:

> One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The Psi function for the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.

The experiment is constructed such that the detector is switched on long enough so that there is a fifty-fifty chance that one of the atoms in the radioactive material will decay and that the detector will record the presence of a particle. If the detector does record such an event, the poison container is broken and the cat dies. If the detector does not record the presence of a particle, the cat lives. In the world of ordinary experience, there is a fifty-fifty chance that the cat will be killed. Without examining the contents of the box, it is safe to assert that the cat is *either* dead *or* alive.

However, if one accepts quantum mechanics, then the atomic decay has neither occurred nor not occurred—*until* one opens the box and observes the outcome—and since the fate of the feline is tied to the state of the radioactive material, one cannot assert the simple truth (on a macro level) that the cat must be either dead or alive. This implication, Schrödinger declared, revealed the absurdity of quantum mechanics.

Source: Quotation from Erwin Schrödinger, "Die gegenwartige Situation in der Quantenmechanik." *Naturwissenschaften* 23 (1935). Translated by John D. Trimmer in *Proceedings of the American Philosophical Society* 124 (1980).

atoms in a molecule, and it continues to suggest other properties of chemical bonds. The area of molecular biology developed from the introduction of the theories of quantum mechanics into chemistry. Quantum theory has also made great contributions to astronomy, affecting research in such subjects as the composition of the Sun and stars, the rate at which stars generate energy, and the structure of stars.

Other scientists skirted the edges of quantum theory, but no other provided such concrete evidence as Schrödinger had with his wave equation. Few other discoveries have had such far-reaching implications for the future of science. Scientists are still finding new applications and implications of Schrödinger's work, and they will continue to do so for a long time to come.

See also Exclusion Principle; Gravitation: Einstein; Heisenberg's Uncertainty Principle; Lasers; Photoelectric Effect; Quantum Mechanics; Spectroscopy; Speed of Light; Superconductivity; Superconductivity at High Temperatures; Thermodynamics: First and Second Laws; Thermodynamics: Third Law; Wave-Particle Duality of Light; X Radiation; X-Ray Crystallography; X-Ray Fluorescence.

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—*Margaret Hawthorne*

SCIENTIFIC METHOD: ARISTOTLE

THE SCIENCE: Aristotle was the first philosopher to approach the study of nature in a systematic way, establishing science as a discipline and providing a starting place for natural philosophers into the late Middle Ages.

THE SCIENTIST:

Aristotle (384-322 B.C.E.), founder and head of the Lyceum in Athens

ORGANIZING KNOWLEDGE

Born in Stagira in northern Greece and the son of the physician to Amyntas II of Macedonia (r. c. 393-370/369), Aristotle came to Athens when he was seventeen years old and studied at Plato's Academy for twenty years. When Plato died in 347 B.C.E., Aristotle left the academy and traveled for twelve years, visiting various centers of learning in Asia Minor and Macedonia. During this period of travel, he developed his interest in the natural sciences, to which he applied his method of inquiry. He returned to Athens in 335 B.C.E. after a brief period of tutoring Alexander the Great (356-323 B.C.E.), Amyntas's grandson, and established the Lyceum, a school that became a center of learning. He taught there until a year before his death.

The range of topics discussed and developed by Aristotle at the Lyceum is overwhelming: natural philosophy with its considerations of space, time, and motion; the heavenly bodies; life and psychic activities; ethical and political problems; animals and biological matters; and rhetoric and poetics. He is sometimes credited with creating new fields of research, such as terrestrial dynamics and optics. He also taxonomized plants and animals and organized earlier Greeks' ideas about planetary astronomy in *Peri ouranou* (c. 350 B.C.E.; *On the Heavens*, 1939).

Perhaps the most significant aspect of Aristotle's work is his development of a "scientific" approach to these studies. This approach recognizes the existence of independent disciplines, each employing its own principles and hypotheses. Such an approach also works out a methodology or procedure for each field of study, aiming at true and certain knowledge.

The Greek term that Aristotle uses for "scientific knowledge" is *episteme*, which can best be translated as "true knowledge" or the "most certain knowledge." This knowledge includes the awareness of an object, of its causes, and that it can be no other way. Medieval scholars translated the Greek episteme as the Latin scientia, which came into English as "science."

In recognizing independent fields of study, Aristotle showed a significant departure from Plato's philosophy. Plato had envisioned one single science. For him, true knowledge was the contemplation of the Forms: Virtue, Justice, Beauty, and Goodness. All other disciplines were subordinate to knowledge of the Forms. Aristotle, on the other hand, did not advocate a hierarchical structure of knowledge. Each study locates its own particular subject matter and defines its principles from which conclusions are to be

ARISTOTLE'S SCIENTIFIC METHOD

Students learn from a young age that the "scientific method" involves an empirical approach to reality:

(1) Make observations (empiricism).
(2) Develop a tentative explanation, or "hypothesis."
(3) Make predictions of fact based on the hypothesis.
(4) Develop experiments to test the predictions of the hypothesis.
(5) Note where the hypothesis fails and refine it.

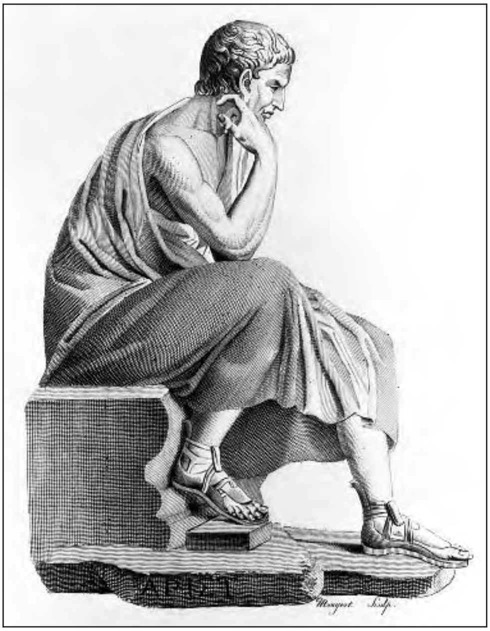
Aristotle, by contrast, counseled in his *Posterior Analytics* that science must proceed from "primary premises"—self-evident principles or propositions, based in fact and stating a logically indemonstrable truth:

> [I]t is clear that we must get to know the primary premises by induction; for the method by which even sense-perception implants the universal is inductive. Now of the thinking states by which we grasp truth, some are unfailingly true, others admit of error—opinion, for instance, and calculation, whereas scientific knowing and intuition are always true: further, no other kind of thought except intuition is more accurate than scientific knowledge, whereas primary premises are more knowable than demonstrations, and all scientific knowledge is discursive. From these considerations it follows that there will be no scientific knowledge of the primary premises, and since except intuition nothing can be truer than scientific knowledge, it will be intuition that apprehends the primary premises—a result which also follows from the fact that demonstration cannot be the originative source of demonstration, nor, consequently, scientific knowledge of scientific knowledge. If, therefore, it is the only other kind of true thinking except scientific knowing, intuition will be the originative source of scientific knowledge. And the originative source of science grasps the original basic premise, while science as a whole is similarly related as originative source to the whole body of fact.

What Aristotle called his scientific method was actually somewhat deductive, as Francis Bacon would later point out. Aristotle's "primary premises" arose from sense perceptions, gathered over time and formed intuitively into abstractions—hence, from the many (sense experiences) came the one (premise). To Aristotle, this was induction. However, when sense perceptions are faulty, incomplete, or inaccessible (not all facts can be detected by the human senses alone), the premise would be in error as well, no matter how logically consistent it might be. Still, Aristotle's belief in working from the particular to the general laid the foundation for scientific methodology for nearly two millennia, until Bacon made it truly inductive.

Source: Aristotle, *Posterior Analytics*, translated by G. R. G. Mure. Available at The Internet Classics Archive, http://classics.mit.edu. Accessed September, 2005.

drawn. Almost all his treatises begin with the same format: "Our task here concerns demonstrative science" (that is, logic) or "Human conduct belongs to political science."



Aristotle. (Library of Congress)

Aristotle's insistence on the division of sciences, each using special principles, is indicative of his rejection of any absolute master plan of knowledge. He does, however, recognize "common principles," or principles shared by more than one science. For example, the "equals from equals" principle of mathematics can be used in geometry to deduce a conclusion about a line. Aristotle warns the geometrician, however, that this can be done "if he assumes the truth not universally, but only of magnitudes." Aristotle never intends the same common principles to be universally applied in exactly the same way throughout all the sciences. If this were the case, there would not be "sciences," but rather "Science."

Aristotle's Methodology

One of the most important features of Aristotle's scientific approach concerns methodology. In the *Analytica posterioria* (335-323 B.C.E.; *Posterior Analytics*, 1812), he develops the general technique that the particular disciplines are to employ in order to achieve scientific knowledge. First, an investigation must always begin with what is "better known" to humans—with observable data and facts—and not construct wild hypotheses. Second, human beings must proceed to a knowledge of the cause of the facts; mere observation is not enough. Observing something only indicates that something is the case; it does not explain why it is the case. Learning the cause tells people why, and this involves a logical demonstration. Third, the cause or reason of the fact must be of "that fact and no other." This criterion is the basis for a scientific law because it demands a universal connection between the subject and its attributes.

Deduction and Induction

The second and third criteria require a deductive system of demonstration that is expressed in the universal positive form of the syllogism that Aristotle developed in the *Analytica priora* (335-323 B.C.E.; *Prior Analytics*, 1812). There is also what might be called an "inductive" approach to his method of science. Aristotle raises the question of how humans know the universal principles from which demonstration is to proceed. He answers that human knowledge of such principles begins with many sense perceptions of similar events. Human memory unifies these perceptions into a single experience. The human intellect or mind then understands the universal import of the experience. From many similar experiences, humans recognize a universal pattern.

Aristotle's method of science combines the theoretical and the practical. The theoretical aspect includes logical demonstrations and universal principles. The practical includes the necessary role of sense perception as it relates to particular objects. In the *Metaphysica* (335-323 B.C.E.; *Metaphysics*, 1801), he warns that physicians do not cure men-in-general in a universal sense; rather they cure Socrates or Callias, a particular man. He adds that one who knows medical theory dealing with universals without experience with particulars will fail to effect a cure. Instead, he advises the use of procedures grounded in common sense that have proven their validity in practice.

One application of this method is in Aristotle's writings on biology. He makes theoretical interpretations based on his dissection of marine animals and empirical observations, although he does also rely on other writers' descriptions of some animals. Based on these researches, he arranges a "ladder of nature." Because he can see changes in the realm of plants and animals, he affirms the reality of nature and the value of its study. He is optimistic that he could use natural history to find causal explanations of physiology.

Impact

For Aristotle, scientific knowledge included the observation of concrete data, the formulation of universal principles, and the construction of logical proofs. Greek "science" prior to Aristotle, largely a melange of philosophical and quasimythological assumptions, blossomed after his investigations into the specialized work of Theophrastus (c. 372-c. 287 B.C.E.) in botany, Herophilus (c. 335-c. 280 B.C.E.) in medicine, and Aristarchus of Samos (c. 310-c. 230 B.C.E.) in astronomy.

Aristotle also pioneered the notion that there are many, distinct disciplines of knowledge rather than a single, unified science; that there are multiple structuring principles for these disciplines rather than one, overarching set of concepts applicable to them all; that standards of scientific rigor vary among disciplines; and that there is no single, universal scientific method. At the same time, he believed in systematic, empirical investigation of natural phenomena, from which general theories might arise, as opposed to creating a theoretical structure and then fitting the data into it. Although the Aristotelianism that survived in the Middle Ages would be questioned and corrected by natural scientists and philosophers such as Francis Bacon, Aristotle's identification of many of the scientific disciplines and his methodology for studying them remain largely valid today.

See also Galen's Medicine; Greek Astronomy; Greek Medicine; Heliocentric Universe; Herschel's Telescope; Medieval Physics; Scientific Method: Bacon; Scientific Method: Early Empiricism.

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—*Joseph J. Romano and Amy Ackerberg-Hastings*

SCIENTIFIC METHOD: BACON

THE SCIENCE: Sir Francis Bacon's *Novum Organum* established an impressive agenda for modern science and inspired the work of later groups, such as the Royal Society of London.

THE SCIENTIST:
Sir Francis Bacon (1561-1626), lord chancellor of England, 1618-1621

SURVEYING THE STATE OF KNOWLEDGE

In the early seventeenth century, the Renaissance was at its height in England and a new age of exploration and scientific instruments had yielded discoveries that required a rethinking of how knowledge was organized, assimilated, and consumed. England was still full of "Renaissance men" with the financial means to avoid narrow specializations and, in Francis Bacon's famous phrase, to "take all knowledge for their province." A number of learned women thrived as well—including Bacon's mother, who translated a religious work from Latin—and the next generation saw the emergence of "female virtuosos" such as the poet and chemist Margaret Cavendish, duchess of Newcastle. Bacon, however, undertook to organize the new learning and to mobilize the students for the monumental task of perfecting God's creation.

The first part of Bacon's great plan was a survey of the arts and sciences. He made his preliminary survey in *The Twoo Bookes of Francis Bacon of the Proficience and Advancement of Learning, Divine and Humane* (1605; enlarged as *De Augmentis Scientiarum*, 1623; best known as *Advancement of Learning*), which he dedicated to the new king of England, James I. In the treatise, he judged certain sciences to have reached a degree of "proficiency," detailed the "deficiency" of others, and made recommendations for their improvement. It was like attempting to write an entire university catalog from scratch.

BACON'S *NOVUM ORGANUM*

In 1620, the second part of Bacon's plan was ready, a description of his method for the brave new world of learning. He called his method the *Novum Organum* (1620; English translation, 1802), or new system of rules, and in doing so, he announced that his method would replace the old rules. It was an outrageously ambitious book. Ever since the rise of the universities in the Middle Ages, the six books of Aristotle's logic had dominated the curriculum. Collectively known as the *Organum* or *Organon*, they were enshrined as the final authority in all debate under the Elizabethan Statutes at Cambridge University, where Bacon had studied. Aristotle's logic was based on syllogism and on deduction from universal precepts to specific conclusions. Bacon's method, by contrast, worked by induction from observations to axioms.

Bacon wrote in Latin so he could reach an international audience. He planned a Latin translation of the *Advancement of Learning* and presented the *Novum Organum* as the second part of a vast work that he called the *Instauratio Magna* (great restoration). He explained that he wanted to help restore human knowledge to the condition that Adam was said to have had in Paradise, before the Fall, and to restore human communication to the universal language that humankind was said to have had at Babel, before the confusion of tongues described in the Old Testament book of Genesis. The large folio volume, printed in London, had an engraved title page that showed a ship sailing beyond the Pillars of Hercules, as the Straits of Gibraltar were once called, and thus going beyond the lands known to the ancient world. The motto on the title page was taken from a prophecy in the Book of Daniel, translated in the King James Bible to read "Many shall run to and fro, and knowledge shall be increased." The implication was that the discoveries in the new age of science, along with the geographical discoveries in the age of exploration, would lead humankind into a golden age.

The *Novum Organum* began with a personal statement, "Francis of Verulam reasoned thus with himself and judged it to be for the interest of the present and future generations that they should be made acquainted with his thoughts." Bacon voiced his fear that the thoughts would die with him

Francis Bacon. (Library of Congress)

if they were not written down and made public. In the preface that followed, he explained that his great work would have six parts.

The first was his survey of learning to date, which had not yet been translated from English. The second part was "The New Organum: Or, Directions Concerning the Interpretation of Nature" and provided the method for what was to follow. The third part would record the "histories" of all the natural and experimental sciences. The fourth would be a set of "instances" discovered about the sciences and pointing to further experiments. The fifth would be a list of axioms that could be inferred provisionally from these instances. The sixth, which would have to be written by Bacon's heirs in a later age, would be the true science toward which he looked. This was a sign of modesty on Bacon's part. His fragmentary notes for part three included 130 subjects for "histories." Here were proposed histories of the elements he knew: fire, air, water, and earth. It would take a later age and the atomic theory to understand hydrogen, oxygen, carbon, and the many other elements.

The *Novum Organum* itself was divided into two books, each of which was written in a series of numbered paragraphs, called "aphorisms" in the translation. The first book discussed the nature of knowledge and the obstacles to knowledge, and among these obstacles included the "idols" that people fashion—distortions that can be tracked to human nature or to individual quirks, to the use of language or the abuse of a philosophical system. The second book was a demonstration of the inductive method he proposed. Here, Bacon set forth an example by investigating the property of heat and creating separate "tables" for studying the presence of heat, the absence of heat, and the increase or decrease of heat. He dedicated his work, once again, to King James. The king wrote a letter of thanks, promising to read the book, but probably never did.

The Restorer of Science

Two centuries later, Thomas Macauley remarked, famously, that Bacon wrote philosophy like a lord chancellor. Bacon was actually appointed lord chancellor of England in 1618, reaching the peak of the legal profession and marking the end of a long ascent that had taken him from solicitor general to attorney general and lord keeper of the seal. Bacon thought he was in a unique position to dispense justice. At times in his writings, he seems quite highhanded as he presides over the arts and sciences. At times, he is dead wrong. For example, he is sometimes said to underestimate the importance of mathematics.

Bacon was made Lord Verulam in 1618, when he became lord chancel-

BACON'S METHOD: INDUCTION VS. DEDUCTION

In Novum Organum, *Francis Bacon addressed the "Interpretation of Nature and the Kingdom of Man" in a series of aphorisms that expressed the importance of drawing inferences inductively from empirical evidence, rather than deductively, from logic, as Aristotle had advocated:*

> XII. The logic now in use serves rather to fix and give stability to the errors which have their foundation in commonly received notions than to help the search after truth. So it does more harm than good.
>
> XIII. The syllogism is not applied to the first principles of sciences, and is applied in vain to intermediate axioms; being no match for the subtlety of nature. It commands assent therefore to the proposition, but does not take hold of the thing.
>
> XIV. The syllogism consists of propositions, propositions consist of words, words are symbols of notions. Therefore if the notions themselves (which is the root of the matter) are confused and over-hastily abstracted from the facts, there can be no firmness in the superstructure. Our only hope therefore lies in a true induction. . . .
>
> XIX. There are and can be only two ways of searching into and discovering truth. The one flies from the senses and particulars to the most general axioms, and from these principles, the truth of which it takes for settled and immovable, proceeds to judgment and to the discovery of middle axioms. And this way is now in fashion. The other derives axioms from the senses and particulars, rising by a gradual and unbroken ascent, so that it arrives at the most general axioms last of all. This is the true way, but as yet untried.

lor, and he received the further title of Viscount Saint Albans in 1621. Later that year, he was accused of accepting bribes in court cases. He admitted his guilt and apologized profusely, but his public career was over. Banished from court by an act of Parliament, he was imprisoned briefly in the Tower of London. His family's house in London was given to his old ally, the marquis of Buckingham (who would become duke of Buckingham in 1623). Bacon retired to the country house his father had built and married an heiress. He spent his last years making experiments and notes for experiments. He is said to have died of a chill he caught while conducting an experiment with ice.

An expanded Latin version of *Advancement of Learning* appeared in 1623, and the projected volume on natural history appeared posthumously as *Sylva sylvarum* (1627). Bacon never wrote the rest of his masterwork except in fragments, but he left a science-fiction story that suggests what his dream looked like toward the end. In *The New Atlantis* (1627), he imagined a kingdom of science, presided over by a second Solomon. King James was no Solomon; his grandson, Charles II, dabbled in chemistry, however, and became the first patron of the Royal Society. When the society's official history was published in 1667, the frontispiece showed the lord chancellor seated in a room full of books and scientific instruments; at his feet was the motto *artium instaurator*, which may be translated "the restorer of science."

Impact

Bacon's *Novum Organum* reversed the accepted Aristotelian methodology of science. Aristotle advocated applying universal rules, known in advance, to specific instances in order to determine their scientific meaning. Bacon, on the other hand, advocated a new empiricism, observing nature in all its manifestations in order to deduce new hitherto unknown rules or principles. The *Novum Organum*, then, is an important part of the age of Scientific Revolution, in which Sir Isaac Newton would deduce the laws of gravitation and the heirs of Nicolaus Copernicus, Johannes Kepler, and Galileo, would establish empirically that the Earth was not the center of the universe. While Bacon's work was not a necessary precursor of any of these other thinkers' triumphs, it was nevertheless a singular and influential expression of a crucial seventeenth century cultural trend, one that informed both the history of science and the broader philosophical Enlightenment of the next century.

See also Heliocentric Universe; Magnetism; Medieval Physics; Scientific Method: Aristotle; Scientific Method: Early Empiricism.

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—*Thomas Willard*

SCIENTIFIC METHOD: EARLY EMPIRICISM

THE SCIENCE: Early Greek philosophers began to devise theories of the cosmos that abandoned previous mythopoeic explanations, instead depending on observations of nature, or empiricism. This new way of thinking launched a scientific revolution that set the stage for the modern scientific method.

THE SCIENTISTS:
Hesiod (fl. c. 700 B.C.E.), Greek epic poet
Thales of Miletus (c. 624-c. 548 B.C.E.), Greek philosopher and scientist
Anaximander (c. 610-c. 547 B.C.E.), Greek philosopher often called the founder of astronomy
Anaximenes of Miletus (early sixth century-latter sixth century B.C.E.), Greek philosopher and scientist
Xenophanes (c. 570-c. 478 B.C.E.), Greek philosopher and poet
Pythagoras (c. 580-c. 500 B.C.E.), Greek philosopher, astronomer, and mathematician
Heraclitus of Ephesus (c. 540-c. 480 B.C.E.), Greek philosopher known for his book *On Nature*
Parmenides (c. 515-after 436 B.C.E.), Greek philosopher of metaphysics
Democritus (c. 460-c. 370 B.C.E.), Greek philosopher associated with atomism

MYTH AND SCIENCE

Before the sixth century B.C.E., human beings everywhere explained the world in mythological terms. These myths depicted humankind dependent on the wills of inscrutable forces, envisioned as gods, that created the world and acted on whim. The prelogical mentality of early people understood the forces of nature to possess powerful consciousnesses similar to human will. No other explanation or scientific foundation on which to build a different understanding of the world and nature yet existed.

Similarly, most Greeks honored the epic poets Homer (early ninth century-late ninth century B.C.E.) and Hesiod as their teachers. Hesiod's *Theogony* (c. 700 B.C.E.; English translation, 1728) is the earliest Greek version of the origins of the cosmos. The Greek term *kosmos* (cosmos) refers to the organized world order. In Hesiod's account, the origin of all things was *chaos*, formless space or a yawning watery deep, the opposite of cosmos. In time there emerged, either independently or by sexual union, Gaia (Earth), Tartaros (Hades), Eros (Love), Night, Day, and Aither (upper air), Sea, and Ouranos (Sky), and boundless Okeanos (Ocean). A generation of powerful Titans was engendered, and finally the Olympian gods descended from Ouranos and Gaia.

A New Worldview

About 600 B.C.E., in Ionia (western Turkey), a new way of perceiving the world was beginning. Confronted by the confusing mythologies of ancient Near Eastern peoples, their own no better, a handful of Greeks over three generations attempted to explain the origins and components of the seen world without mythology. Their great discovery was that to one seeking knowledge—the philosopher—the world manifests internal order and discernible regularity. Nature can be understood. The world is a cosmos.

From allusions in Homer and Hesiod came hints. The sky was thought to be a metallic hemispheric bowl covering the disk of Earth. The lower space immediately above the disk was *aër*, breathable air; the upper part of the bowl-space was *ouranos* or *aither*. Below its surface, the Earth's deep roots reached down to Tartaros, the deepest part of Hades (the underworld realm of the dead), as far below Earth as sky is above it. *Okeanos* (ocean), infinitely wide, encircled the disk of Earth and was the source of all fresh and salt waters. Such a mixture of the empirical and the imaginative was common to most mythopoeic cosmologies.

Thales of Miletus

Thales of Miletus was the first to rationalize the myths. He conceived the Earth-disk as floating on the ocean and held the single substance of the world to be water. His reasoning, according to Aristotle, was that water can be gaseous, liquid, and solid; life requires water; Homer had surrounded the Earth by Okeanos. As a unified source of all things, Thales' choice of water was a good guess, but it begged for alternatives. More important, in reducing multiple things to water, Thales had taken a first step in establishing inductive reasoning (from particular examples to general principles) as a scientific methodology.

Anaximander

Anaximander, companion of Thales, was a polymath: astronomer, geographer, evolutionist, philosopher-cosmologist. It is nearly impossible to do justice to his intellectual achievement. He was the first Greek to write in prose. He said that animal life began in the sea and that humans evolved from other animals. He made the first world map, a circle showing Europe and Asia plus Africa equal in size, all surrounded by ocean. Anaximander's cosmos was a sphere with a drum-shaped earth floating in space at its center. The Sun, stars, and Moon revolved around the Earth, seen through openings in the metallic dome of the sky.

In place of Thales' water, Anaximander offered *apeiron*, an eternal, undefined, and inexhaustible basic stuff from which everything came to be and to which everything returns—a sophisticated chaos. Convinced by his own logic, Anaximander imputed an ethical necessity to this process. Things coming to be and claiming their share of *apeiron* thus deprive others of existence. In his words, "they must render atonement each to the other according to the ordinances of Time." This eternal process operates throughout the cosmos. Using terms such as *kosmos* (order), *diké* (justice), and *tisis* (retribution), Anaximander enunciated the exalted idea that nature itself is subject to universal moral laws.

Anaximenes of Miletus

The contributions of Anaximenes of Miletus pale before those of Anaximander. What best defines Anaximenes is his empirical approach. He posited air as the primal stuff that gives rise to all things. Observing air condensing into water, he conceived a maximum condensation of air into stone. Similarly, by rarefaction, air becomes fire or soul. The Earth and other heavenly bodies, being flat, ride on air in its constant motion.

Xenophanes

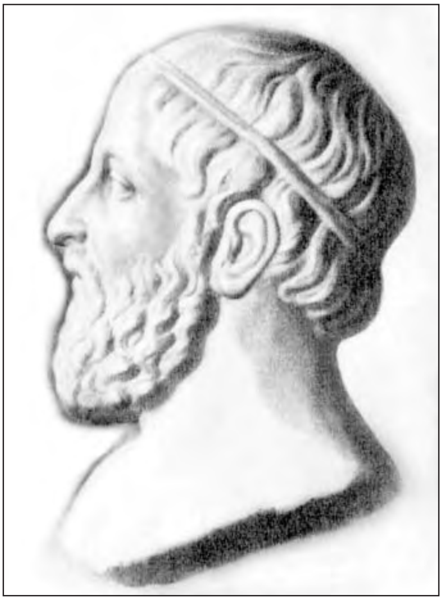
Xenophanes, an Ionian who had moved to Italy, represents a new generation of thinkers. He was a skeptic who trusted only his own observations about the world. He interpreted the new natural explanations of the universe that had challenged the older Hesiodic mythopoeic construct as the abandonment of the old, often immoral, anthropomorphic gods, who dressed in clothes and spoke Greek. He posited a single spiritual creator-god who controls the universe without effort, by pure thought. In this monotheism, Xenophanes was alone among the Greeks.

Insightfully, Xenophanes said human knowledge about the universe is limited and the whole truth may never be known. He taught that natural events have natural, not divine, causes. The rainbow is only a colored cloud. The sea is the source of all waters, winds, and clouds. From sea fossils found in rocks, his cosmogony deduced a time when land was under water. Civilization was the work of men, not gods.

Pythagoras

Pythagoras, an Ionian mathematician in southern Italy, had noticed that the sounds of lyre strings varied according to their length and that harmonies were mathematically related. He saw that proportion can be visually perceived in geometrical figures. From these notions he and his followers described a cosmos structured on a mathematical model. Instead of adopting Anaximander's "justice" or Heraclitus of Ephesus's *logos* (a sort of primordial reason or order identified with speech or the word) as the dominant organizing principle, the Pythagoreans preferred numerical harmony. Pythagoras thus added a dimension to the ancient concepts of due proportion and the golden mean that pervaded Greek thought. These concepts are seen in Greek sculpture and architecture and as moral principles in lyric and dramatic poetry and historical interpretations, where *hybris* (hubris, or excess) and *sophrosyné* (moderation) were fundamental principles of human behavior.

Inevitably, Greek physical philosophy began to investigate the process of knowing. Number is unchanging; ten is always ten. In a world of apparently infinite diversity and flux, numbers, as opposed to objects of experience, can



Pythagoras. (Library of Congress)

be known perfectly. Although the Pythagoreans went too far in trying to explain everything by numbers, they taught that a nature based on mathematical harmony and proportion was knowable.

Heraclitus

Heraclitus argued that change, though sometimes imperceptible, is the common element in all things. All change, he said, takes place along continuums of opposite qualities, such as the hot-cold line or dry-moist line. His contribution, however, was his idea of *logos* as the hidden organizing principle of the cosmos. *Logos* maintains a protective balance (the golden mean again) among all the oppositional tensions in the world.

Parmenides and Democritus

Parmenides and Democritus contributed logic to the Greek discovery of the cosmos. In the mid-fifth century, Democritus reasoned to a world built of the smallest thinkable indivisible particles, atoms. Parmenides—struck by the constant flux of the physical world and seeking, as Pythagoras, an unchanging object of knowledge that mind can grasp—saw existence, or Being, as the common element of things in the cosmos. He proposed the logic that while things change, Being itself cannot change, for nothing and no place exists outside of the sphere of Being, so nothing could enter or leave. He is thus the most metaphysical of the philosophers, initiating ideas that would only be completed by Plato and Aristotle, the greatest of the philosophers.

Impact

The significance of the Ionian philosophers is that, within little more than a century after breaking with mythopoeic interpretations of the world, they had asserted its atomic makeup, conceived human evolution, discovered induction and logic, and practiced a curiosity about all natural phenomena. This was one of history's great intellectual revolutions—the origins of scientific speculation.

See also Galen's Medicine; Greek Astronomy; Greek Medicine; Scientific Method: Aristotle; Scientific Method: Bacon.

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—Daniel C. Scavone

SEAFLOOR SPREADING

THE SCIENCE: Harry Hammond Hess's idea of seafloor spreading as the reason for continental drift had the same impact on geology that Charles Darwin's evolution theory had on biology.

THE SCIENTISTS:
Harry Hammond Hess (1906-1969), American geologist
Alfred Lothar Wegener (1880-1930), German scientist-explorer
Robert S. Dietz (1914-1995), American geologist
Matthew F. Maury (1822-1891), U.S. Navy officer and oceanographer

A GEOPHYSICAL "FAIRY TALE"

The Princeton University professor Harry Hammond Hess is noted for his scientific contributions to the field of geology, specifically for his groundbreaking *History of the Ocean Basins* (1962), in which he proposed seafloor spreading as the long-sought-after mechanism for Alfred Lothar Wegener's theory of continental drift, which he had proposed fifty years before. The elements of seafloor spreading, the splitting of the original Pangaea supercontinent into several continental-size plates, and movement of those plates to their present positions are collectively known as "plate tectonics."

Yet the hostility of the geologic community toward previous seafloor spreading hypotheses kept Hess from publishing his theory. Robert S. Dietz, working for the Navy, published virtually identical ideas and coined the phrase "seafloor spreading" in a 1961 article, "Continent and Ocean Basin Evolution by Spreading of the Seafloor," published in *Nature*.

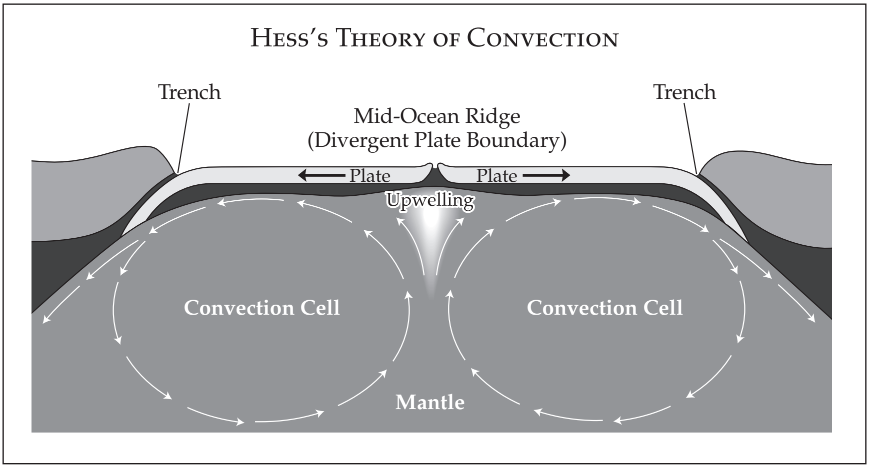
World War II (1939-1945) delayed research into the question, and from the 1930's to the mid-1950's, continental drift remained a theory held with great passion by a minority of geologists. As late as 1966, the University of Hamburg physicist Pascual Jordan described the theory as the geophysicists' "favorite fairy tale."

The Mid-Atlantic Ridge

Postwar advances in technology, in methodology, and in the new science of paleomagnetism (the study of the direction and intensity of the Earth's magnetic field through geologic time) lent support to Wegener's theory. The U.S. Navy directed its interest to the ocean floor, and other seagoing nations also initiated active research programs that led to the International Geophysical Year (July, 1957, to December, 1958), the first multinational research effort. This effort focused on almost every area of geologic research and led scientists to realize that the Earth, particularly the ocean, was very different from what they had previously imagined. One of the most curious features was the Mid-Atlantic Ridge, which spans the Atlantic Ocean from north to south. Understanding the feature led to an understanding of plate tectonics.

Matthew F. Maury, director of the U.S. Navy's Department of Charts and Instruments, had first recognized the Mid-Atlantic Ridge in 1850 while measuring ocean depths aboard the USS *Dolphin*. Maury named it the "Dolphin Rise" and published a map of it in his *The Physical Geography of the Sea* (1855). Data from the HMS *Challenger* expedition (1872-1876) supplemented Maury's map, but the details of the Mid-Atlantic Ridge remained vague. In 1933, German oceanographers Theodor Stocks and Georg Wust produced the first detailed map of the ridge, noting a valley that seemed to be bisecting it. Later, in 1935, geophysicist Nicholas H. Heck found a strong correlation between earthquakes and the Mid-Atlantic Ridge.

The idea of a seismically active ridge received further support in 1954. That year Jean P. Rothé, director of the International Bureau of Seismology in Strasbourg, mapped a continuous belt of earthquake epicenters from Iceland through the mid-Atlantic around South Africa, through the Indian Ocean, and on to the African Rifts and the Red Sea. In 1956, Maurice Ewing



In 1960, Harry Hammond Hess proposed that seafloor spreading, powered by convection currents within the Earth's mantle, might be the cause of continental "drift." The idea of continental drift became the theory of plate tectonics, which is accepted by most earth scientists today.

and Bruce C. Heezen continued the German technique of echo sounding at the Lamont Geological Observatory and found that the Mid-Atlantic Ridge was more than 64,000 kilometers long and, more important, it had a rift valley along the entire crest.

In 1961, Ewing and Mark Landisman discovered that this ridge system extends throughout all the world's oceans, is seismically and volcanically active, and is mostly devoid of sediment cover. The question of whether the ridge system was covered with sediment—and the amount and age of that sediment—was important: It would reveal clues to the age of the ridge itself. Ivan Tolstoy and Ewing first characterized the sediment cover in 1949, describing a main ridge of thin sediment and flanks of thick sediment. The age of the sediments increased as one moved from the ridge toward the continents, the oldest age being only about sixty-five million years old.

Central to the interpretation of this underwater mountain range was the early 1950's paleomagnetic research of Patrick M. S. Blackett and his student, Keith Runcorn, at the University of Manchester. Their studies of fossil magnetism suggested that in the geologic past, the inclination, the declination, and even the polarity of the Earth's magnetic field had been very different from current orientations. The seemingly chaotic data formed a consistent pattern only upon assuming that the continents had moved relative to the magnetic poles and to one another. Magnetic studies of the seafloor by other oceanographers revealed a symmetrical, zebralike pattern about the midoceanic ridge in 1957.

A BOLD NEW SYNTHESIS

The period between 1960 and 1965 was one of great uncertainty and multiple directions for geologists. In 1960, Hess synthesized the oceanic data of the 1950's into a bold new theory. Hess's theory was so novel and radical that he did not attempt to publish it in the usual professional journals but included it in a 1960 report to the Office of Naval Research. Hess also widely circulated reprints among his colleagues.

In his 1960 report, Hess proposed that the midoceanic ridges were the locations of upwelling "mantle convection cells": that is, areas of the Earth's mantle that progressively moved the seafloor outward from the ridge and eventually under the continents. The mantle is part of the molten core of the Earth. Hess suggested that different parts of it (cells) may spin like wheels, driven by changes in temperature (convection) between the lower and upper parts of the mantle.

IMPACT

This driving mechanism brought together the divergent data of post-World War II research into one coherent theory. It explained the rift valley in the middle of the ridge, the correlation of the ridge with earthquake epicenters, the continuation of the ridge throughout the oceans, the thin sediment in the middle of the ridge and its thickening toward the edges, and the symmetrical paleomagnetic zebra patterns. In addition, the energy of the mantle convection currents was sufficient to drive the continents.

In 1966, in recognition of his scientific breakthrough, Hess received the Geological Society of America's Penrose Medal, the geologist's equivalent of the Nobel Prize. By 1967, seafloor spreading was the dominant theory, and virtually all earth scientists began to reinterpret their data in the light of the new theory.

See also Continental Drift; Earth's Core; Earth's Structure; Geomagnetic Reversals; Hydrothermal Vents; Mid-Atlantic Ridge; Plate Tectonics; Radiometric Dating.

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—*Richard C. Jones and Anthony N. Stranges*

SMALLPOX VACCINATION

THE SCIENCE: English physician Edward Jenner was the first person to establish the scientific legitimacy of smallpox vaccinations through his experiments and research publications. His campaign to popularize the procedure led to its worldwide use and effectively protected millions from an often fatal disease.

THE SCIENTISTS:
Edward Jenner (1749-1823), English physician
James Phipps (1788-1808), first person to be vaccinated by Edward Jenner
Benjamin Jesty (1736-1816), English farmer who vaccinated his family against smallpox in 1774
William Woodville (1752-1805), head of the London Smallpox and Inoculation Hospital
George Pearson (1751-1828), physician at St. George's Hospital in London

VARIOLATION

In eighteenth century England, smallpox was a leading cause of death, and traditional methods of treating it were largely ineffective. The practice of variolation was introduced to England from the Ottoman Empire in 1721 and gained general acceptance after some successful trials. This procedure involved inoculating patients with puss from smallpox sores in hopes of giving them a mild case of the disease and future immunity. However, the risks of a patient developing a serious, possibly lethal, case of smallpox and even creating an epidemic were significant, and there was a clear need for a safer and more effective method of protection from the disease.

Jenner and Cowpox

Edward Jenner. (Library of Congress)

Edward Jenner, a physician in Berkeley, England, in the county of Gloucestershire, began variolating patients using a refined procedure developed by Robert Sutton in 1768. Jenner found that his patients who in the past had contracted cowpox, a relatively mild disease, did not react to the smallpox virus. This finding was consistent with the conventional wisdom in rural areas that cowpox conferred an immunity to smallpox, which had been supported in reports to the Medical Society of London in the mid-1760's by several physicians, including at least two from Gloucestershire. In fact, a farmer in Yetminster, England, named Benjamin Jesty successfully protected his wife and two sons from a smallpox epidemic by vaccinating them with the puss from the udders of cows suffering from cowpox in 1774. Jenner, however, always maintained that he was unaware of these earliest documented smallpox vaccinations.

By the early 1780's, Jenner's interest in the connection between cowpox and smallpox immunity led him to distinguish between two similar but distinct diseases, "spontaneous," or genuine, cowpox, which created an immunity from smallpox, and "spurious," or false, cowpox, which did not. In May of 1796, a young woman named Sarah Nelmes came to Jenner to be treated for cowpox. On May 14, Jenner vaccinated James Phipps, an eight-year-old boy, by placing fluid from a sore on Nelmes' hand into two small incisions on the boy's arm. A week later, Phipps developed the symptoms of cowpox, including infected sores, chills, head and body aches, and loss of appetite. The child recovered quickly, and, on July 1, 1796, Jenner variolated Phipps using fluid from smallpox pustules, and he had no reaction. Jenner inoculated the boy several more times in this manner with the same results.

Arm to Arm

In late 1796, Jenner submitted a paper to be considered for publication in *Philosophical Transactions of the Royal Society*, England's premiere scientific journal. The manuscript described the cases of thirteen former cowpox sufferers who exhibited no reaction when variolated by Jenner, as well as his experiments with Phipps. The Council of the Royal Society rejected the article, and berated Jenner in scathing terms, characterizing his findings as being unbelievable, and "in variance with established knowledge," and advising him that advancing such wild notions would destroy his professional reputation. Jenner was undaunted and began experimenting again in the spring of 1798, when cowpox broke out again in Gloucestershire. Through these studies he learned that cowpox could be transferred from one patient to another by using the puss from the sores of one vaccinated person to vaccinate another, and so forth. This discovery of "arm-to-arm vaccination" made a natural outbreak of cowpox unnecessary as a source of vaccine.

In June of 1798, Jenner independently published the findings from all of his research to date, including reports of the cases from his first manuscript and nine other patients he had vaccinated beside Phipps. This seventy-five-page book was titled *An Inquiry into the Causes and Effects of the Variolae Vaccinae, a Disease Discovered in Some of the Western Counties of England, Particularly Gloucestershire, and Known by the Name of the Cow Pox*. The word *variolae* is "smallpox" in Latin, and *vaccinae* is from *vaca*, which is Latin for "cow." In his inquiry, Jenner described the process now called "anaphylaxis," the body's allergic reaction to a foreign protein after a previous exposure, and coined the term "virus" to describe the mechanism of cowpox transmission.

The Fight for Vaccination

The London medical establishment's initial reaction to Jenner's publication was extremely negative. Just as in 1796, some prominent physicians questioned the validity of Jenner's findings. Others, who were profiting handsomely from variolation, attacked Jenner for fear of losing their lucrative monopoly on protecting the public from smallpox. Jenner had rejected the suggestion that he could become personally wealthy from his discovery, and he planned to share it with all of England and the world. After the publication of his findings Jenner tried for three months to find people who would agree to be vaccinated in order to demonstrate the effectiveness of the procedure. He did not find a single volunteer because of the public attacks on his professional competence.

Instead, Jenner pursued his goal of popularizing vaccination indirectly, through London physicians to whom he provided vaccine. For example, the director of the London Smallpox and Inoculation Hospital, William

Woodville, vaccinated some six hundred people in the first half of 1799. Based on vaccinations that he performed in 1799, George Pearson of St. George's Hospital replicated Jenner's findings, and tried to take credit for the procedure. Woodville, who caused several cases of smallpox and at least one death by inadvertently contaminating some vaccine with the smallpox virus, blamed Jenner's procedure in order to protect his own reputation. However, a nationwide survey conducted by Jenner that documented cases of immunity to smallpox by former cowpox sufferers, clearly validated his work.

By late 1799, vaccination had gained widespread acceptance, and the procedure was being performed not only by physicians, but also by schoolteachers, ministers, gentlemen farmers, and others in all parts of the country. Jenner continued to report the results of his research on vaccination through publications such as *The Origin of the Vaccine Inoculation* (1801). In recognition of his achievements, Parliament awarded Jenner £10,000 in 1802 (the equivalent of more than $500,000 today) and an additional £20,000 in 1807. Oxford, Harvard, and Cambridge Universities honored him as well.

Impact

Edward Jenner's work on refining and promoting the use of smallpox vaccinations, before the development of antibiotics, was a major breakthrough in preventive medicine. Countless lives were undoubtedly saved in Great Britain during the years immediately following Jenner's efforts, given the high mortality rates during earlier smallpox epidemics. Furthermore, his successful lobbying for a government-sponsored national vaccination program eventually led to the passage of the Vaccination Act in 1840, which provided for the free vaccination of infants and made variolation illegal. Subsequent laws made vaccination mandatory, with severe penalties for noncompliance. By 1871, 97.5 percent of England's population reportedly had been vaccinated.

Jenner's method of preserving vaccine for up to three months enabled him to share his vaccination procedure with the world. As a result, an estimated 100,000 people had been vaccinated worldwide by the end of the eighteenth century. Shortly thereafter, Benjamin Waterhouse, a professor at the Harvard School of Medicine, used vaccine from England to perform the first vaccinations in the United States on his young son and servants. Jenner also shipped vaccine to President Thomas Jefferson, who had eighteen of his relatives vaccinated and established the National Vaccine Institute, with Waterhouse as its director, to spread vaccination throughout the country. In addition, mass vaccination programs were initiated in all Spanish colonies in North and South America and Asia by King Charles IV of Spain, in India by the British governor general, for the French army by Napoleon, and in numerous other countries. These programs were all undertaken in the early 1800's using Jenner's vaccine.

By 1967, although smallpox had completely disappeared from North America and Europe, there were still 10-15 million cases reported in the world annually. The World Health Organization initiated an effort to eradicate smallpox worldwide. The campaign was declared a success in 1980. Jenner's work is credited not only with the defeat of smallpox but also with helping to establish the science of immunology, which has produced vaccines against numerous lethal and debilitating diseases.

See also Anesthesia; Antisepsis; Aspirin; Contagion; Diphtheria Vaccine; Germ Theory; Hybridomas; Immunology; Penicillin; Polio Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Streptomycin; Vitamin C; Vitamin D; Yellow Fever Vaccine.

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—*Jack Carter*

SOLAR WIND

THE SCIENCE: Eugene N. Parker predicted the existence of the solar wind, which was confirmed by a Soviet satellite in 1959.

THE SCIENTISTS:

Eugene N. Parker (b. 1927), American physicist
Ludwig Biermann (1907-1987), German astrophysicist
Sydney Chapman (1889-1970), English mathematician and physicist
Subrahmanyan Chandrasekhar (1910-1995), Nobel laureate in physics
K. I. Gringauz (b. 1925), the principal investigator for the Soviet satellite that detected the existence of the solar wind

A STREAM OF CHARGED PARTICLES

When the idea of the solar wind was first proposed, the notion of a steady stream of charged particles emanating from the Sun at supersonic speeds was hard to accept. Even when the solar wind was confirmed by satellite, it continued to be dismissed by some as impossible. Some events that are now known to be caused by the solar wind were quite familiar by the 1950's. For example, the auroras, both at the North Pole (aurora borealis) and at the South Pole (aurora australis), had been observed for centuries. The fact that the tail of a comet always points away from the Sun, no matter in which direction the comet is moving, was known. Magnetic storms, which affect the Earth's magnetic field and induce voltages in telegraph and power lines, had been observed. For each of these occurrences, scientists knew that the Sun was responsible, or at least involved, but did not know how.

In 1957, Eugene N. Parker was an assistant physics professor at the University of Chicago. He had been studying the origin of Earth's magnetic field, the atmosphere of the Sun, and cosmic rays. Ludwig Biermann, director of the Max Planck Institute for Astrophysics in Munich, was visiting the University of Chicago that same year. Biermann told Parker of his studies of comet tails. Comets are essentially chunks of rock dust and ice, "dirty snowballs." As a comet nears the Sun, solar heat vaporizes the ice, which releases dust particles, and both vapor and dust create a tail. Solar radiation ionizes the atoms in the tail, making it one of the most spectacular sights in the evening sky.

TAILING THE COMET

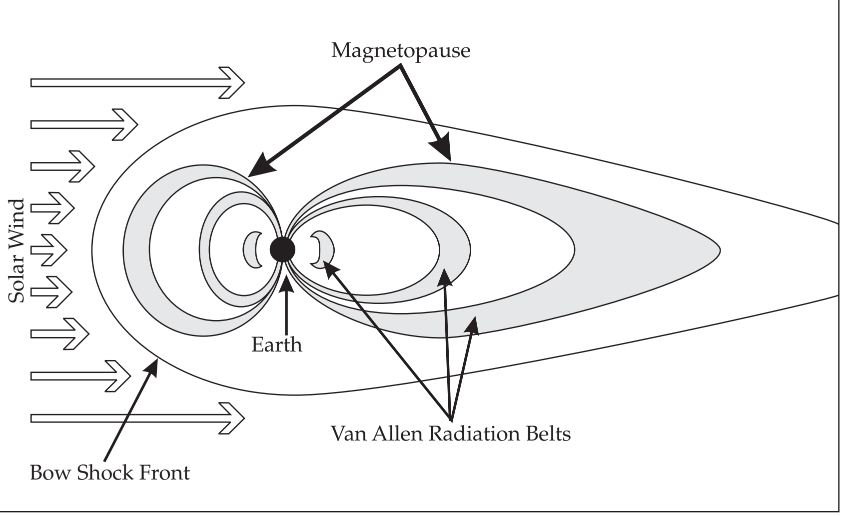
Biermann was interested in why comet tails always point away from the Sun, even when that means that the tail is pointing in the same direction in which the comet is moving. It was thought that the Sun's electromagnetic field exerted radiation pressure on the comet, thereby pushing the tail away from the Sun. Astronomers also believed that this pressure, while very small, was still stronger than the tail of a comet.

Yet the dust and gas in the tail were not merely being carried away from the comet—they were being blown away with great force. Further research by Biermann showed that a comet's tail did not have enough surface area for solar radiation to have that effect. He concluded that there was only one other explanation: "solar corpuscular radiation," the discharge of particles from the Sun at the time of a "solar flare" (the sudden eruption of hydrogen gas on the Sun's surface). This corpuscular radiation evidently was shot out from the Sun at an average velocity of 500 kilometers per second. Such bursts were known to cause auroras and magnetic storms. The rest of the time, however, interplanetary space was thought to be empty.

Parker was influenced by Biermann's theories. Taking hold of the observation that the tail of a comet always points away from the Sun, the fact that auroras are always present, and other cosmic observations, Parker agreed that interplanetary space must continually be filled with solar corpuscular radiation. Now he needed to determine why it was there and why it was moving so forcefully.

Shortly after a discussion with Biermann, Parker was in Boulder, Colorado, where he had been invited to give a lecture at the High Altitude Observatory. He had an opportunity to learn of the work of Sydney Chapman on the solar corona. The corona is an envelope of thin, hot gas that surrounds the Sun. Chapman showed Parker some calculations indicating that the outer atmosphere of the Sun, the corona, extends out into space, past the orbit of Earth. The high temperature of the corona was causing it to

Effect of the Solar Wind on Earth's Magnetosphere



expand slowly upward against the gravitational field of the Sun. It gradually increased in speed until it reached supersonic velocity.

Chapman's conclusion not only was novel and interesting but also appeared to be inescapable. A little more thought, however, seemed to indicate a conflict with Biermann's equally inescapable conclusion that solar corpuscular radiation continually fills interplanetary space. The two could not possibly exist together. Parker, however, believed that solar corpuscular radiation and the extended solar corona described the same phenomenon. They both were, as he came to name it, the "solar wind."

In 1958, Parker wrote a paper titled "Dynamics of the Interplanetary Gas and Magnetic Fields." He reconciled the work of Chapman and Biermann and included equations showing supersonic velocities for the solar wind of several hundred kilometers per second. With the publication of Parker's paper in the *Astrophysical Journal*, all that remained to be accomplished was an actual "sighting." Instruments designed by Soviet scientist K. I. Gringauz and carried aboard a Luna satellite were the first to detect a gas moving past the Earth faster than 60 kilometers per second—a supersonic velocity that confirmed Parker's prediction.

IMPACT

The discovery of the solar wind has given the correct explanation for the auroras, magnetic disturbances, and the behavior of comet tails and has added to our knowledge of stars. Most stars have their own stellar winds, similar to the solar wind.

Traditionally, stars have been seen as tranquil objects, shining for billions of years and eventually dying. It has been learned that a star is very active. For example, it has been established that the luminosity of the Sun varies by one part in six hundred, and there is evidence from other Sun-type stars that it could vary at times by one part in one hundred, in the space of a few years. A decrease in luminosity of that magnitude would cause the polar ice caps to advance, thus producing a small "ice age." In fact, there is evidence that the Sun's luminosity has fluctuated recently: The Little Ice Age began in the thirteenth century and ended in the middle of the eighteenth century. The Little Ice Age affected global agricultural output, leading to hardship in China and in Europe. Killing frosts in the North American Great Plains were commonplace each summer.

Understanding the solar wind shows scientists that the Sun is losing mass at the rate of about 1 million tons per second. That, however, is not a problem. Because of the immense size of the Sun, the loss it has experienced has amounted to only one ten-thousandth of its original mass.

See also Cassini-Huygens Mission; Extrasolar Planets; Halley's Comet; Magnetism; Nebular Hypothesis; Oort Cloud; Planetary Formation; Pluto; Stellar Evolution; String Theory; Van Allen Radiation Belts; Very Long Baseline Interferometry; X-Ray Astronomy.

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—*John M. Shaw*

SPACE SHUTTLE

THE SCIENCE: Circling above the globe, the world's first reusable spacecraft opened the future to payloads and experimenters to whom space was previously inaccessible.

THE ASTRONAUTS:

Joe H. Engle (b. 1932), U.S. Air Force colonel and STS 2 commander
Richard H. Truly (b. 1937), Navy captain and STS 2 pilot
John W. Young (b. 1930), STS 1 commander who became the first person to fly into space six times when he became commander of the STS 9 mission
Robert L. Crippen (b. 1937), Navy captain and STS 1 pilot

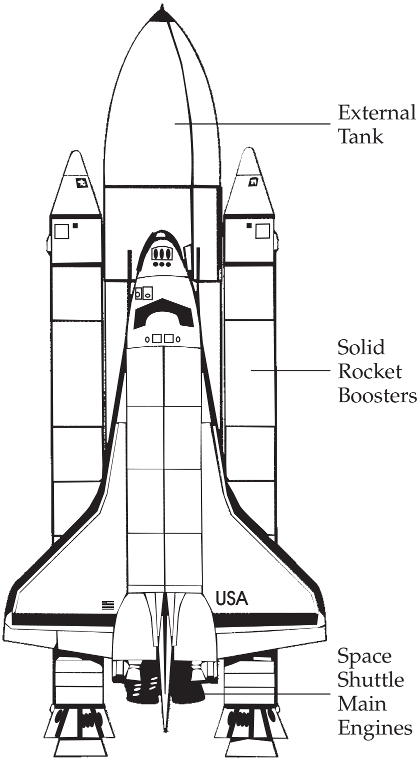
FUNDING AND DEVELOPMENT

After the success of the lunar landings in 1969, the National Aeronautics and Space Administration (NASA) wanted to send astronauts to Mars, build a fifty-person Earth-orbiting space station serviced by a reusable ferry (space shuttle), and build a second space station orbiting the Moon.

At $8 to $10 billion per year, Congress rejected the proposal as too expensive. NASA proposed two other programs, each one simpler and less expensive, but Congress refused to finance either of them. By the spring of 1971, NASA was determined to secure appropriations for at least the space shuttle, which would be the first step if any of the other programs were approved.

NASA turned to the Department of Defense (DOD). Under NASA's plan, the DOD would provide a large portion of the funding for the shuttle; in return, the shuttle would be used for military as well as scientific missions. The shuttle also would become the only launch vehicle in NASA's fleet, thereby replacing expendable boosters and saving billions of dollars. Congress approved this proposal, and plans were drawn for a shuttle system.

THE SHUTTLE CONFIGURED FOR LAUNCH



Budgetary cuts forced NASA to reduce the shuttle program—formally known as the Space Transportation System (STS)—to the four-part system it became. Basically, the shuttle system consists of an orbiter, to which are attached three main engines to be used during launch; a large, external fuel tank for the engines; and a pair of strap-on solid rocket boosters to get the stack off the launch pad. The orbiter could be reused, as could the major components of the solid rocket boosters, which would parachute back into the ocean after running out of fuel. Only the external fuel tank would have to be discarded.

By 1977, a series of drop tests were done using an orbiter that was identical to later flight versions but that was incapable of spaceflight. *Enterprise* (named for the starship from the television series *Star Trek*) was placed on top of a modified Boeing 747 airliner and released. This allowed the glide characteristics of the orbiter to be determined and gave shuttle pilots hands-on experience with landing at speeds close to those expected on orbital missions.

CAN THEY DO IT TWICE?

On December 29, 1980, the first operational space shuttle, *Columbia*, was rolled to Launch Complex 39A at the Kennedy Space Center in preparation for its first flight. This was to be a piloted flight, and it marked the first time that a piloted space vehicle would be flown without the benefit of robotic test flights in space—another result of budgetary limits.

The STS 1 mission blasted off on April 12, 1981, twenty years to the day after the first astronaut, Yuri Gagarin, had been launched into space by the Soviet Union. The STS 1 commander was John W. Young; the pilot was Robert L. Crippen. The two-day "shakedown cruise" showed that the systems worked and that the orbiter could convert from rocket to orbiter to glider without enormous problems. The only major concept yet to be tested was that of reusability. The only way to find out was to fly *Columbia* a second time.

The STS 2 mission was scheduled to be launched on November 4, 1981. The STS 2 commander was Joe H. Engle; the pilot was Richard H. Truly. A problem with one of *Columbia*'s auxiliary power units (APUs), however, could not be corrected in time to meet the launch deadline for the day. The launch was pushed back to November 12. At 59 seconds past 10:09 A.M. eastern standard time, the era of the reusable shuttle vehicle began. The launch proceeded normally, and *Columbia* was placed into a 222-kilometer-high orbit above Earth. The mission was supposed to last five days but was shortened to a little more than two days after a fuel cell failure less than five hours into the mission. During the shortened mission, more than 90 percent of the high-priority flight tests were completed successfully. The Development Flight Instrumentation, used to monitor *Columbia*'s systems during the flight, showed that the orbiter functioned as planned. The Remote Manipulator System's 15-meter robot arm was first flown on this mission. On later missions, it would be used to handle large payloads.

Columbia landed at Edwards Air Force Base on November 14 at 6:23 P.M. Pacific time. The space shuttle had been proved to be reusable.

IMPACT

In a throwaway society where nearly everything is disposable, the idea of building a spacecraft that could be used many times over was pure science fiction until the space shuttle. Prior to the Space Transportation System, a satellite or probe was launched into space and, if it arrived at its destination successfully, kept operating until it ran out of fuel or lost electrical power. Then it was discarded for a newer model.

Space shuttle Atlantis *takes a ride home after landing at Edwards Air Force Base in 1998.* (NASA/DFRC)

By building a vehicle that could carry large payloads to and from low-Earth orbit, it was possible to retrieve those old satellites and either repair them or bring them back to Earth. Doing so would save the space program a great deal of money. The ideal and most economical craft for this job was one that reused all or most of its parts: the space shuttle.

The space shuttle program continued to enjoy a number of achievements in the years that followed *Columbia*'s historic flight. Sadly, the entire U.S. space program was dealt a severe blow with the fiery explosion of the *Challenger* spacecraft and the tragic loss of its entire crew, including the first civilian astronaut, on January 28, 1986. NASA identified the problem and corrrected it, returning to flight in 1988 with STS-26 and completing many more missions—increasingly to service the growing International Space Station (ISS). When a second accident killed the seven-member crew of *Columbia* on February 1, 2003, during the reentry of STS-107, NASA was forced into another hiatus to determine what had caused small pieces of the heat-resistant foam tiles to peel from the shuttle upon liftoff and again put measures in place to correct the problem: The return-to-flight mission, STS 114, lifted off in July of 2005 with unprecedented cameras and procedures in place to inspect the orbiter in space as it also delivered supplies to the ISS.

As the shuttle fleet aged and with two of the orbiters lost, NASA continued its plans to complete the shuttle's obligations to the ISS. It also made plans for a new fleet of crew transfer vehicles to replace the shuttle program, whose lifetime was expected to end around 2010. In the meantime—more than a quarter century and many successful launches later—the space shuttle remained NASA's primary source for piloted space exploration. Counted among its many successes are the deployment of the Hubble Space Telescope and Chandra X-Ray Observatory; the Galileo, Ulysses, and Magellan probes; and the early stages of construction of the International Space Station.

See also Cassini-Huygens Mission; Earth Orbit; Galileo Mission; International Space Station; Mars Exploration Rovers; Moon Landing; Voyager Missions; Wilkinson Microwave Anisotropy Probe.

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—*Russell R. Tobias*

SPECTROSCOPY

THE SCIENCE: Joseph Fraunhofer discovered that sunlight, when passed through a glass prism or a grating, produced a spectrum of colors that contained numerous dark lines. Later investigators showed that these lines were due to specific chemical elements.

THE SCIENTISTS:

Joseph Fraunhofer (1787-1826), skilled glass maker, inventor of the spectroscope, and discoverer of numerous dark lines in the spectrum of sunlight

Gustave Kirchhoff (1824-1887) and

Robert Bunsen (1811-1899), German scientists who used the spectroscope to show that each chemical element emits a unique pattern of spectral lines

Thomas Young (1773-1829), British scientist who first determined the wavelength of light waves by passing them through two narrowly spaced slits

William H. Wollaston (1766-1818), British scientist who observed seven dark lines in the solar spectrum shortly before Fraunhofer's independent discovery

MISSING WAVELENGTHS

In 1704, the renowned British physicist Sir Isaac Newton published a book entitled *Opticks* (*Optics*, 1706). In it he described his wide-ranging investigations into the properties of light. He measured the angular dispersion of sunlight into a spectrum of colors by using a triangular glass prism. He also gave a mathematical explanation for the creation of the rainbow from the refraction of sunlight by water droplets in the atmosphere.

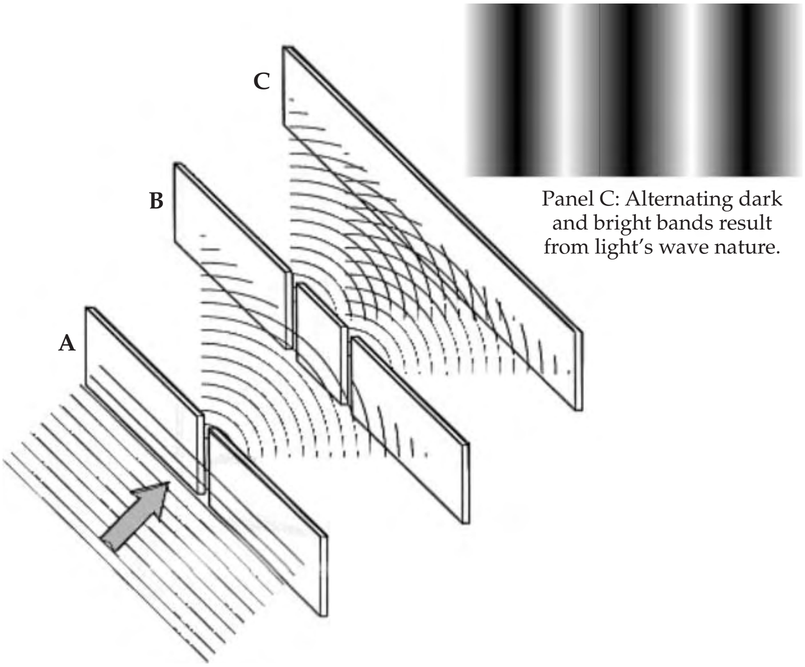
About a hundred years later, the British scientist William H. Wollaston saw something in the spectrum of sunlight that neither Newton nor anyone else had noted before. He was using a narrow slit for the sunlight to enter a dark room, where it struck a prism. The resulting spectrum was observed from ten feet away. At that distance, the colors from red to violet were greatly spread out. Wollaston noticed that the continuous spectrum of the Sun had some narrow, dark lines in it. Whereas an ordinary light source viewed through a prism emits a truly continuous spectrum of colors, sunlight appears to have some missing wavelengths. He reported finding seven dark lines but had no explanation for what caused them.

FRAUNHOFER'S SPECTROSCOPE

Twelve years after Wollaston's discovery, Joseph Fraunhofer independently rediscovered the dark lines in the spectrum of the Sun. He devised a special apparatus, the spectroscope, that enabled him to catalog more than five hundred dark lines, now called Fraunhofer lines in his honor. The spectroscope had a lens that could be pointed at the Sun or any other source of light, followed by a narrow slit. The incoming light beam struck a prism made of flint glass that produced a relatively large angular separation of colors. The spectrum was viewed through an eyepiece attached to a platform that could be rotated, allowing the angle of view to be measured with high precision. The most prominent dark lines were given letter names. Fraunhofer noted that the so-called D line in the solar spectrum exactly matched the angle of sodium light that had been observed previously. However, he was not able to interpret the significance of this observation.

Thomas Young, another British scientist, earlier had shown that a light

YOUNG'S DOUBLE-SLIT EXPERIMENT



Young's double-slit experiment displayed the wave nature of light.

beam, when passed through two slits that are very close together, produced an interference pattern of bright and dark images on a screen. He explained this pattern using the wave theory of light: when two waves are in step, their amplitudes will add to produce a brightness, but when they are half a wavelength out of step, their amplitudes will cancel to produce darkness. Young developed a mathematical formula that used the distance between the two slits and the angles of maximum brightness to calculate the wavelength of the light. Fraunhofer improved on Young's double slit by making a grating, consisting of a large number of closely spaced parallel slits. He wound a thin metal wire back and forth between two threaded screws. By advancing from one thread to the next one, he obtained a closely spaced mesh of wires.

Fraunhofer replaced the prism in his spectroscope with such a grating. The angular separation of colors, or dispersion, was not much better than his result had been with the prism. To improve his observations further, he needed to make the slits in the grating even closer together. As part owner of a glassworks company, Fraunhofer had access to a machine shop. A new grating was made by scribing hundreds of evenly spaced parallel lines on a piece of glass. Light came through the spaces to form a spectrum with high dispersion. With this device, he was able to measure the wavelength of yellow light from a sodium flame with a precision that agrees within one percent of the modern accepted value.

Fraunhofer was not an academic scientist. He was skilled in making glass lenses for optical instruments. He used the solar dark lines as fixed calibration points to measure how the index of refraction of glass varied throughout the spectrum. He learned how to combine lenses of different glass composition into an achromatic system that gave the sharpest possible images. He became famous throughout Europe as the premier supplier of lenses for large telescopes.

EMISSION SPECTRA

Gustave Kirchhoff, a physicist, and Robert Bunsen, a chemist (of Bunsen burner fame), were colleagues at the University of Heidelberg in Germany. In the 1850's, they were studying the spectra of flames that contained various chemicals, such as sodium, potassium, and copper salts. Using a grating in a spectroscope, they observed that each element had a unique spectrum of bright lines. These emission spectra provided them with an unambiguous identification, like a fingerprint, for each element.

Kirchhoff and Bunsen were aware of Fraunhofer's work, thirty-five years earlier, on dark lines in the spectrum of sunlight. In trying to under-

CHEMICAL FINGERPRINTS

In 1860, Gustave Kirchhoff, a physicist, and Robert Bunsen, the chemist for whom the Bunsen burner is named, described the characteristic spectra of some specific elements and speculated on the wide variety of applications of this knowledge:

It is known that several substances have the property of producing certain bright lines when brought into the flame. A method of qualitative analysis can be based on these lines, whereby the field of chemical reactions is greatly widened and hitherto inaccessible problems are solved. . . . The lines show up the more distinctly the higher the temperature and the lower the luminescence of the flame itself. The gas burner described by one of us [Bunsen] has a flame of very high temperature and little luminescence and is, therefore, particularly suitable for experiments on the bright lines that are characteristic for these substances. . . .

In this time-consuming, extensive research, which need not be presented here in detail, it came out that the variety of the compounds in which the metals were used, the differences in the chemical processes of the flames, and the great difference between their temperatures had no influence on the position of the spectral lines corresponding to the individual metals. . . .

Kirchhoff and Bunsen went on to describe their spectroscopic experiments and their outcomes with sodium, lithium, potassium, strontium, calcium, and barium, as well as their conclusions:

Spectrum analysis should become important for the discovery of hitherto unknown elements. If there should be substances that are so sparingly distributed in nature that our present means of analysis fail for their recognition and separation, then we might hope to recognize and to determine many such substances in quantities not reached by our usual means, by the simple observation of their flame spectra. We have had occasion already to convince ourselves that there are such now unknown elements. . . .

Spectrum analysis, which, as we hope we have shown, offers a wonderfully simple means for discovering the smallest traces of certain elements in terrestrial substances, also opens to chemical research a hitherto completely closed region extending far beyond the limits of the Earth and even of the solar system. Since in this analytical method it is sufficient to see the glowing gas to be analyzed, it can easily be applied to the atmosphere of the Sun and the bright stars.

Source: Gustav Kirchhoff and Robert Bunsen. “Chemical Analysis by Observation of Spectra.” *Annalen der Physik und der Chemie* (Poggendorff) 110 (1860): 161-189.

stand these lines, Kirchhoff created a crucial experiment. Using a laboratory lamp, he showed that it had a true continuous spectrum with no dark lines. Then he placed a sodium flame between the lamp and the grating. This time the continuous spectrum had a dark line in the yellow region, just at the known wavelength of sodium. Evidently, sodium vapor was absorbing its particular wavelength out of the continuous spectrum.

Kirchhoff and Bunsen proposed the idea that atoms of the chemical elements have distinct "absorption spectra" that match their emission spectra. They were able to show that three prominent Fraunhofer dark lines in the solar spectrum exactly matched the emission wavelengths of potassium. They came to the conclusion that light from the surface of the Sun was being absorbed at fixed wavelengths by sodium, potassium, and other atoms in the Sun's outer atmosphere.

Impact

The Fraunhofer dark lines have led to some interesting results. Sir John Lockyer, a British astronomer, in 1868 speculated that a prominent dark line in the solar spectrum, which did not match any element known on earth, might be due to a new element found only on the Sun. He named it helium, after the Greek word for the Sun. Some thirty years later, helium gas eventually was found deep in mine shafts. Helium became a valuable resource for various technological applications, including lighter-than-air balloons.

Fraunhofer dark lines are found in the spectra not only of the Sun but also of all stars. Astronomers can use a telescope to focus on one star at a time and can record its spectrum on photographic film. In some cases, the Fraunhofer lines show a shift toward a longer wavelength—that is, toward the red end of the spectrum. Such a "redshift" comes about when a star is moving away from the Earth at high speed. This phenomenon is like the drop in frequency that one hears when an ambulance with a siren is traveling away from the listener. The redshift in the Fraunhofer lines from distant stars is the primary evidence for an expanding universe.

Spectroscopy was extended to other parts of the electromagnetic spectrum as new instrumentation became available. For example, infrared spectra are the primary means to obtain information about the structure of molecules. Gamma-ray spectroscopy has become a highly developed method of analysis that can detect impurities in materials as small as a few parts per billion. Fraunhofer's spectroscope was the starting point for many practical applications in analytical chemistry, astronomy, medical research, and other technologies.

See also Buckminsterfullerene; Expanding Universe; Galaxies; Gamma-Ray Bursts; Inflationary Model of the Universe; Isotopes; Lasers; Optics; Radioactive Elements; Schrödinger's Wave Equation; Speed of Light; Superconductivity; Superconductivity at High Temperatures; Thermodynamics: First and Second Laws; Thermodynamics: Third Law; Water; Wave-Particle Duality of Light; X Radiation; X-Ray Crystallography; X-Ray Fluorescence.

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—*Hans G. Graetzer*

SPEED OF LIGHT

THE SCIENCE: In 1676, Ole Rømer's measurement of the speed of light was the first clear demonstration that light travels with a finite velocity. Although his value was off by about 25 percent, his method was correct in principle. A more accurate value was obtained fifty years later by James Bradley using another astronomical method.

THE SCIENTISTS:

Ole Rømer (1644-1710), Danish astronomer whose study of Jupiter's moons helped determine the speed of light

Galileo Galilei (1564-1642), Italian physicist and astronomer who made one of the first attempts to measure the speed of light

Christiaan Huygens (1629-1695), Dutch physicist and astronomer who assisted Rømer in calculating the speed of light

James Bradley (1693-1762), third Astronomer Royal in England, whose measurements of the aberration of starlight led to the first accurate measurement of the speed of light

Gian Domenico Cassini (1625-1712), Italian astronomer and first director of the Paris Observatory

BEYOND INFINITY

Before the seventeenth century, scientists believed that the speed of light was infinite. In about 1607, Galileo attempted to measure the speed of light with the aid of an assistant on a hilltop at some distance away with a covered lamp. When the assistant saw Galileo uncover a similar lamp, he then uncovered his lamp and Galileo tried to observe the time for the light to travel to the assistant and back again. He concluded that the speed of light was either instantaneous or extremely rapid.

The first observations showing that the speed of light is finite were made by the Danish astronomer Ole Rømer in Paris in 1675. Using the new pendulum clock invented in 1657 by Christiaan Huygens, a fellow foreign member of the Royal Academy of Sciences, Rømer determined that the 42.5-hour period of Jupiter's moon Io had an orbital period that was a maximum of 13 seconds longer when the Earth was moving away from Jupiter and 13 seconds less time when it was approaching (42.5 hr. ± 13 seconds). He recognized that this phenomenon occurred because the light took longer to reach the Earth as it moved away from Jupiter and shorter as the Earth moved toward Jupiter in each 42.5-hour orbit of Io.

RØMER'S CALCULATIONS

To determine the range of variations in the orbital period, Rømer observed consecutive eclipses of Io as it passed behind Jupiter, noting the times when it emerged from each eclipse. Since these emergences of the Moon from eclipses were not instantaneous events, there were some errors in his measurements. From these variations, he calculated that light would take about 22 minutes to cross Earth's orbit (compared with a modern value of about 16 minutes). On November 22, 1675, Rømer read a paper to the science academy, in which he announced that an eclipse of Jupiter's moon Io would occur about 10 minutes later than the time predicted from the average orbital period as measured in 1668 by Gian Domenico Cassini, director of the Paris Observatory and also a foreign member of the science academy.

Working with the aid of Huygens, Rømer combined the 22-minute time for light to cross Earth's orbit with the diameter of Earth's orbit as determined by Cassini in 1671, a value that was 7 percent too small. By taking the ratio of the distance to the time, he found the speed of light to be about 230 million meters per second, or about three-fourths of the modern value of nearly 300 million meters per second.

Rømer published his discovery in a short paper entitled "Demonstration touchant le mouvement de la lumière trouvé" (demonstration concerning the discovery of the movement of light) in the *Journal des Savants* on December 7, 1676. At the request of the Danish king, Rømer returned to Denmark in 1681 as royal mathematician and professor of astronomy at Copenhagen University.

Bradley's Calculations

The first accurate measurement of the speed of light was made some fifty years after Rømer's measurements by the English astronomer James Bradley in 1728, also using an astronomical method. Bradley was trying to find evidence for the Earth's motion around the Sun by measuring the annual stellar parallax, the shifting angle of the stars that should result from Earth's motion in a six-month period. Rømer also had attempted to measure this parallax, but he had failed to detect any change. Although Bradley also failed to measure any parallax, he did notice a relatively large shift in angle of one second of arc in just three days and in the wrong direction to qualify as the annual parallax.

According to some accounts, Bradley's explanation of the anomalous star angles he observed occurred to him while sailing on the Thames River and noticing how a steady wind caused the wind vane on the mast to shift relative to the boat as it changed directions. He reasoned that the apparent shift in star angles resulted from the orbital motion of the Earth relative to the constant speed of light. This "aberration of starlight" is similar to the apparent angle of vertically falling raindrops relative to a moving observer. The angle of stellar aberration is given approximately by the ratio of the Earth's forward orbital speed to the speed of light. Careful measurements of this angle combined with the known speed of the Earth allowed Bradley to obtain a value of 295 million meters per second for the speed of light, slightly too small (but by less than 2 percent).

Bradley's precise measurements of stellar aberration not only improved the value for the finite speed of light but also provided the first direct evidence for the motion of the Earth as suggested by the Copernican theory some two hundred years earlier. Further careful measurements of star angles by Bradley revealed in 1732 the nodding motion of the Earth's axis, called nutation, resulting from variations in the direction of the gravitational pull of the Moon. For these achievements, he was named the third Astronomer Royal in England. His value for the speed of light was not corrected until terrestrial measurements were begun in mid-nineteenth century France, when the original method of Galileo was improved by using reflected light and rapid timing by rotating wheels.

IMPACT

Even though Ole Rømer's value for the speed of light was about one-quarter too small, his method was correct and revealed that light has a finite speed. By showing that light travels nearly one million times faster than sound, Rømer provided evidence that eventually showed that light cannot consist of a mechanical propagation like sound, but is actually an electromagnetic wave as demonstrated in the nineteenth century.

OLE RØMER: HEAT AND LIGHT

Ole Rømer was born in Åarhus, the largest city in Jutland, Denmark, on September 25, 1644, and studied astronomy in Copenhagen. He assisted in determining the exact location of Tycho Brahe's observatory on the island of Hveen in 1671 and then went to Paris in 1672. He remained for nine years at the new Paris Observatory of the Royal Academy of Sciences, making careful observations of the moons of Jupiter. In 1675, he discovered an inequality in the motion of the moon Io, the closest and fastest of the four large moons of Jupiter discovered by Galileo in 1610.

In addition to calculating the speed of light, Rømer played a key role in the development of the modern thermometer, paving the way for Daniel Fahrenheit's work. Rømer was particularly interested in creating a reproducible thermometer, so that experiments and observations from widely differing locales could be compared. Due to problems with hand-blowing the hollow glass tubes that were used in making thermometers, it was impossible to make them physically identical. As a result, it was necessary to find some other way to determine when they all indicated the same temperatures. Rømer's solution was to calibrate each thermometer against known reference points (such as the melting point of ice and the boiling point of water) so that it would be possible to have all the thermometers measuring temperature equally even if they were not structurally identical. It remained to assign numerical values to the various points on his scale. Rømer experimented with a number of different scales, setting various numbers for the reference points. Rømer still had not settled upon a workable scale when Daniel Fahrenheit arrived to discuss questions of measurement with him.

Historians of science would subsequently argue intensely about the extent of Rømer's role in inspiring Fahrenheit's work in thermometers and temperature scales, until the discovery of a letter in an archive in Leningrad (St. Petersburg, Russia). In the letter, Fahrenheit recounts experiments that he and Rømer performed together, which led him to an interest in improving the mechanism of both thermometers and barometers.

Bradley's improved method for measuring the speed of light began a quest for precision that finally revealed the true nature of light and gave the first direct evidence for the motion of the Earth. Terrestrial measurements a century after his work gave the most accurate values for the speed of light and revealed that light travels more slowly in water than in air, confirming the wave nature of light. When electromagnetic studies showed that light is propagated by electric and magnetic fields, the speed of the resulting electromagnetic waves could be calculated from electric and magnetic constants as measured in the laboratory, and the result matched the observed speed of light. In Albert Einstein's theory of relativity, the speed of light is seen as one of the fundamental constants of the universe.

See also Cepheid Variables; Diffraction; Gravitation: Einstein; Inflationary Model of the Universe; Lasers; Optics; Photoelectric Effect; Quantized Hall Effect; String Theory; Superconductivity at High Temperatures.

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—*Joseph L. Spradley*

SPLIT-BRAIN EXPERIMENTS

THE SCIENCE: The fact that the two halves of the human brain can function separately, and the ways they interact, were demonstrated by Roger W. Sperry and his colleagues in a series of brilliant experiments.

THE SCIENTISTS:

Roger W. Sperry (1913-1994), neurophysiologist who won the 1981 Nobel Prize in Physiology or Medicine

Michael S. Gazzaniga (b. 1939), graduate student

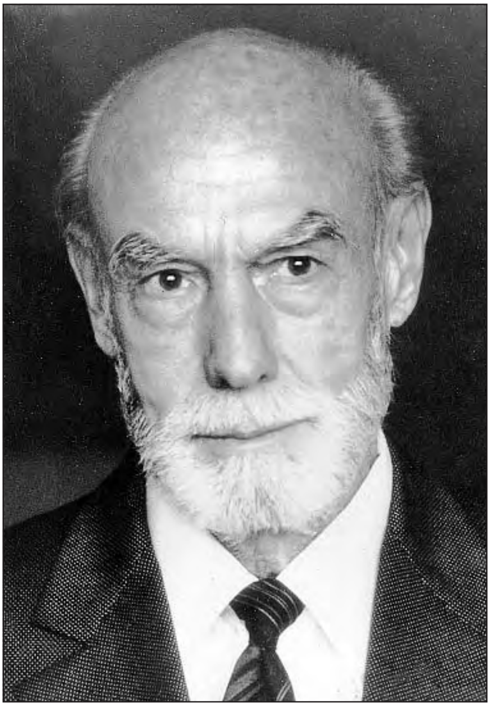
Ronald Myers (b. 1929), graduate student

SPLITTING THE BRAIN

The nature of the human body is such that many of its parts come in two halves. The halves of these paired organs—such as lungs, kidneys, and eyes—generally perform similar or identical functions. It was long assumed that the two halves of the brain likewise have a single function. Scientists were therefore surprised to discover not only that the two halves of the brain perform different activities but also that, in certain cases, each half can function independently.

In the early 1950's, Roger W. Sperry began to research the function of the corpus callosum. This narrow bundle of nerve cells, containing some 200 million neurons, connects the two halves of the brain. At the University of Chicago, with a graduate student, Ronald Myers, Sperry severed the corpus callosum in a cat. He covered up the cat's right eye, forcing it to see only through its left eye, and taught the cat a simple task. Things seen by the left eye are stored in the right half of the brain. By forcing the cat to use its left eye, Sperry was making sure that all learning would be stored in the right half only. Yet when its left eye was closed and right eye open (which forced the cat to use the left half of the brain and any learning stored there), it was unable to perform the same task. Sperry concluded that the information absorbed through the left eye could not pass between the two halves when the corpus callosum was cut. The right half could, however, learn the task all by itself. It was as if the cat had two separate brains, each of which could function independently when separated from the other.

There was reason to doubt that these findings would be relevant to human brains. The corpus callosum had been cut in a number of humans as a last resort in controlling severe epilepsy. Doctors reasoned that if the connection between the two halves was


Roger W. Sperry. (The Nobel Foundation)

cut, an epileptic seizure occurring in one half of the brain would leave the other half unaffected. The surgery not only proved to be effective in limiting the spread of epileptic seizures but also, for reasons still unknown, actually decreased the frequency of such seizures. Fortunately for the patients, there were no obvious changes in personality, intelligence, or mental functioning. This, however, suggested to scientists that the corpus callosum had no important function in humans.

Right Brain, Left Brain

More careful behavioral studies were begun by Michael S. Gazzaniga, a graduate student, in Sperry's laboratory. His first subject was a forty-eight-year-old war veteran whose corpus callosum had been severed to control his epilepsy. The experimental procedure was simple: A picture of some everyday object was flashed in front of one eye or the other, and the subject was asked to report what he saw. A normal person would report having seen an object no matter which eye was involved, but Gazzaniga's subject reported seeing only objects viewed by his right eye (and perceived by the left hemisphere). When a picture was flashed before his left eye (and perceived by the right hemisphere), he denied having seen anything. The right hemisphere was not "blind," it simply could not "speak": When the subject was asked to point to an object he had seen, he was able to do so, indicating that his right hemisphere had, in fact, perceived the object.

Sperry and Gazzaniga thus solved the problem of the elusive function of the corpus callosum. When a normal person sees an object in the left visual field, the right hemisphere, which obtained the information, sends it through the corpus callosum to the left hemisphere, which can then verbalize a response about what the individual saw. The corpus callosum thus allows communication between the two hemispheres. For the subject in the experiment, this had been impossible because of the severed connection.

Although the right hemisphere was initially considered inferior because it lacked the verbal ability of the left hemisphere, subsequent research showed that the right hemisphere can understand the vocabulary of a ten-year-old. Although unable to direct the mouth to speak, the right hemisphere could direct the left hand to move plastic letters so as to spell out the answers to certain questions.

Gazzaniga tested split-brain patients in another study, in which they were required to arrange a set of blocks to match a design in a picture. The left hand (guided by the right half of the brain) was superior at this task. The scientists concluded that the right hemisphere is important for spatial skills. In related work, Doreen Kimura, studying normal individuals, showed that the left hemisphere is better at interpreting verbal information, while the right hemisphere is better at identifying melodies.

IMPACT

The acceptance of the idea of hemispheric specialization had some positive effects in the general population, since people gained a better understanding of nonverbal forms of intelligence. Intelligence tests, which had traditionally measured what have come to be considered left-brain activities, are placing more emphasis on measuring and appreciating types of intelligence that operate in the right brain.

Sperry's studies also had some impact on the understanding of certain disorders. Dyslexia, for example, is a disorder that makes it difficult to learn to read. Children who suffer from dyslexia tend to show less than the usual right-hemisphere specialization for spatial relations. The idea that reading disorders are biologically based and not the result of the children's misbehavior has led to more flexibility in dealing with these disorders.

Split-brain research raises certain philosophical considerations: Is the split brain also a split mind? Are there two separate consciousnesses in a single individual? Controversy about the meaning of split-brain research continues long after the research was first announced in the 1960's. For stimulating this controversy, Sperry was awarded the Nobel Prize in Physiology or Medicine in 1981.

See also Manic Depression; Pavlovian Reinforcement; Psychoanalysis; REM Sleep.

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—*Judith R. Gibber*

SPONTANEOUS GENERATION

THE SCIENCE: Lazzaro Spallanzani was among the first to show experimentally that living organisms—such as maggots in rotting meat—could not simply appear out of nowhere. Though his work was not considered conclusive on the subject, it represented the beginnings of a modern view of biology.

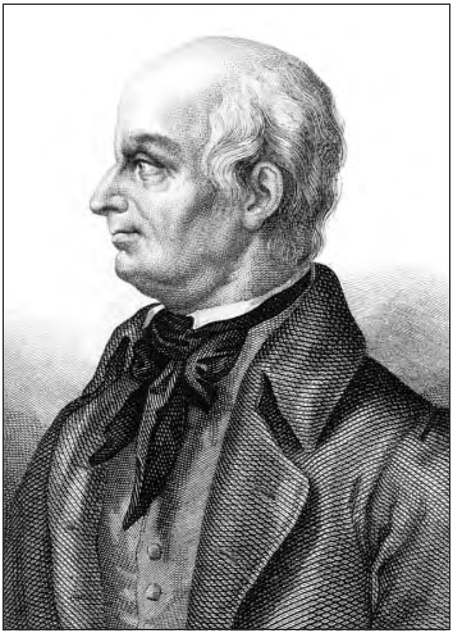
THE SCIENTISTS:
Lazzaro Spallanzani (1729-1799), Italian biologist
Francesco Redi (1626-1697), Italian physician
Georges-Louis Leclerc, Comte de Buffon (1707-1788), French naturalist and author of the first comprehensive natural history
John Tuberville Needham (1713-1781), Catholic priest and collaborator with Buffon

LIFE FROM NONLIFE?

Naturalists before the eighteenth century had observed many instances of what seemed to them to be the "spontaneous generation" of life. Meat left out would sprout maggots, and frogs could similarly emerge from apparently simple mud. There was no mystery associated with these seeming miracles, however. Indeed, spontaneous generation made perfect sense to those, now called "vitalists," who believed in a Creator who had the ability to produce life from abiotic matter. If life had first originated in this manner, the reasoning went, life could appear again through similar means. There were also nonreligious explanations for the phenomenon. The ancient Greek philosopher Aristotle, during the fourth century B.C.E., believed that humidity provided a form of life force to dry objects. Later naturalists argued that mud could produce frogs or eels and even had recipes for the formation of life.

The first significant experiments to address the subject of spontaneous generation were carried out by Franceso Redi in 1668. An Italian physician and member of del Cimento Academy, Redi designed a series of experiments in which putrefying meat was placed in vessels. Some vessels were covered with gauze or were completely sealed, while others served as uncovered controls. Redi observed that only meat that was accessible to flies developed maggots. The French physicist René-Antoine Ferchault de Réaumur, more famous for development of an alcohol thermometer, would later directly observe flies depositing eggs in food.

The debate over spontaneous generation continued for more than a cen-



Lazzaro Spallanzani. (Library of Congress)

tury, and the development of the microscope, resulting in the discovery of microscopic "animalcules" by Antoni van Leeuwenhoek, only added to the debate. Leeuwenhoek's work established that an entire world of living things existed beyond the ability of the human eye to see. Even if it were established that the organisms of the visible world were incapable of spontaneous generation, therefore, it might still be the case that microscopic animalcules could appear spontaneously. Support for this view could be found in experiments carried out by the British clergyman John Tuberville Needham in 1745. Since it was known by then that heat could kill microorganisms, Needham boiled chicken broth and placed it in sealed vessels. Despite this treatment, microorganisms would still appear in the broth.

Needham later went to Paris, where he met and began a collaboration with the comte de Buffon. Buffon was well noted for his contributions to the growing field of comparative anatomy in the massive work *Histoire naturelle, générale et particulière* (1749-1789; *Natural History, General and Particular*, 1781-1812). Though many of Buffon's views on the similarities of species and the age of the Earth were still controversial at the time of their publication, he was well enough respected that his support for Needham's views lent credibility to the arguments in favor of spontaneous generation.

HEATING THE DEBATE

Lazzaro Spallanzani had a differing interpretation of Needham's results, however: He believed that the broth had been contaminated before being sealed. His criticism of Needham's techniques formed the basis for a 1765 dissertation on the subject. He also, more importantly, devised a set of practical tests to confirm his hypothesis that Needham's samples must have been contaminated. Spallanzani's experimental procedure was relatively simple: He boiled his samples for varying periods to ensure that nothing survived and then sealed the mixture in an airtight container. Beginning with a duration of forty-five minutes, Spallanzani tested various boiling periods, observing whether anything would still grow in the broth after each test.

Spallanzani determined that extensive boiling prevented microorganisms from growing, resulting in the medium remaining sterile. To refute the potential counter-argument that boiling destroyed a "life force" that had existed in the broth and that was necessary for spontaneous generation to occur, Spallanzani sealed his vessels with semipermeable barriers. He created seals with pores of various sizes, and he observed that the number of organisms that returned to the boiled broth was a function of the pore size. The implication of this result was that contamination from air had been the source of growth in Needham's experiments.

Spallanzani also observed that there existed several classes of organisms that differed in their sensitivity to heat. One class, probably protozoa, was highly sensitive to heat, and Spallanzani labeled this class "superior animalcula." On the other hand, the class he named "lower class animalcula," probably bacteria, was less sensitive. Thus, a nonrigorous application of heat in an experiment might kill only the more sensitive microscopic organisms, leaving the less sensitive ones to "appear spontaneously" afterward.

Despite these results, Spallanzani's experiments did not resolve the issue of spontaneous generation in the minds of all scientists. The experiments' results admitted of different interpretations, especially after Joseph Priestley discovered oxygen in 1774. When it was discovered that oxygen itself was driven from Spallanzani's experimental vessels during the heating process, some scientists argued that this newly discovered gas was necessary to activate the "vital force" that caused life to appear from nothing. It would remain for Louis Pasteur in the 1860's to resolve the argument to the satisfaction of the entire scientific community. After all, spontaneous generation had been believed to exist, in one form or another, for at least two thousand years. Such an entrenched belief could not be eliminated with anything less than utterly conclusive proof.

The theory explained quite efficiently an otherwise mysterious phenomenon that, in the days before preservatives and refrigeration, was extremely common—the sudden appearance of maggots, flies, or other biological contaminants on seemingly clean foods. The advances in experimental design in the sciences during the sixteenth and seventeenth centuries allowed naturalists to test the theory. Among the first to do so was Francesco Redi. However, despite Redi's initial results, which seemed to demonstrate that infestation of maggots in meat resulted from flies, not decay, the belief in spontaneous generation continued for years. Even Redi himself was not completely convinced that spontaneous generation was impossible.

IMPACT

Spallanzani's work, following from Redi's, was carried out during a period in the eighteenth century in which science was undergoing significant advancement. The development of the microscope in the previous century had allowed the observation of the very small. The significance of such observations when applied to germs or contamination, however, was still misunderstood. Nevertheless, Spallanzani continued the earlier experiments of Redi on the subject by demonstrating that if water was sterilized in a sealed container, spontaneous formation of life could not occur.

Where Redi's experiments, important in their use of biological controls, had demonstrated that relatively large forms of life would not spontaneously appear, Spallanzani showed that even microscopic organisms could be eliminated through the use of heat. In the process, he brought an experimental approach to the study of such organisms, complementing the scientific approach to the macroscopic world developed by the comte de Buffon. Nicolas Appert, a French cook, several decades later would apply Spallanzani's approach in developing a method of canning as a way to preserve food.

In the immediate wake of Spallanzani's experiments, however, the debate concerning spontaneous generation was not yet settled. Criticism of Spallanzani's experiments centered on the lack of a formal, scientifically rigorous understanding of the nature of life—a lack not fully corrected even today. Various vitalist arguments about a "life force" that made generation possible complicated matters tremendously: If this hypothetical force was itself intangible, it would be difficult or impossible to prove that it had not been altered by heat, the lack of air, or other effects of Spallanzani's experiments.

Moreover, as a result of the state of experimental design in the 1760's, Spallanzani himself never came to the conclusion that microorganisms were present in the air. The fact that there was a gas called oxygen in the air, indeed the fact that the air was composed of a mixture of different gases, was new information added to the debate in the 1770's. As a result, one could still not rule out the possibility that it was the presence of oxygen that was required for spontaneous generation to occur.

It would be nearly one hundred years before Louis Pasteur ended the debate with what became known as the "swan-neck" flask experiment. In this experiment, Pasteur placed the experimental sample in a flask that remained unsealed, but he created a curved neck for the flask that allowed air to enter normally but kept microorganisms out; the solution under such circumstances remained sterile. Still, Spallanzani's work remained an important step in the evolution of biological knowledge.

See also Cell Theory; Contagion; Fossils; Germ Theory; Lamarckian Evolution; Microscopic Life; Photosynthesis.

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—*Richard Adler*

STELLAR EVOLUTION

THE SCIENCE: Henry Norris Russell used the color-luminosity relationship of stars to work out a theory of how stars change over time.

THE SCIENTISTS:

Henry Norris Russell (1877-1957), American astronomer who discovered the color-luminosity relationship and codeveloped the Hertzsprung-Russell diagram that led to his theory of stellar evolution

Ejnar Hertzsprung (1873-1967), Danish astronomer and photographer, who established that there is a relationship between a star's color and its luminosity

Sir Joseph Norman Lockyer (1836-1920), British astronomer who developed a theory of stellar evolution later elaborated by Russell

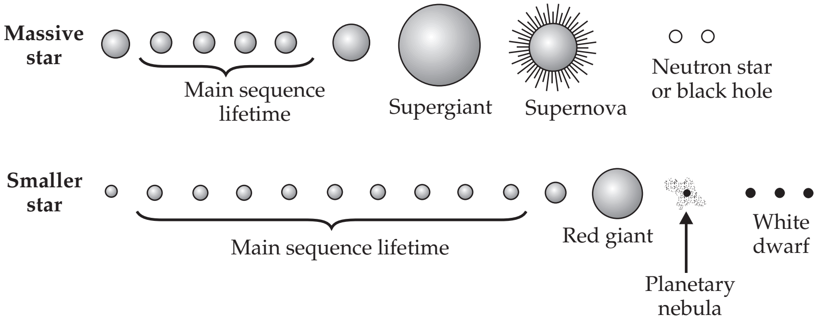
A STARRY GARDEN

Sir William Herschel described the starry sky as a garden, wherein one sees stars in varying stages of their lives, as in a garden or a forest one sees plants and trees in varying stages of early growth, maturity, and death. The assumption of seeing stars of different ages and that stars change as they age was an important prerequisite for the formation of theories of stellar evolution. The advent of increasingly sophisticated techniques for classifying stars in the late nineteenth and early twentieth centuries brought a wealth of data on spectral types from which a theory of stellar evolution could be built.

CLASSIFICATION SYSTEMS

Sir Joseph Norman Lockyer, working in the late 1800's, used the simple classification systems of Angelo Secchi and Hermann Karl Vogel—which placed stars in one of four categories—to develop a scheme for stellar evolution. This scheme was based on current theory regarding the energy source for stars and the physical forces shaping their life histories. At the time, physicists believed that a star's radiation was heat and light, which was released as the star contracted under the force of gravity. A star was believed to form when enough interstellar matter accumulates in one place to begin to exert gravitational attraction on itself and to form a sphere. The star then begins to contract inward under the force of gravity and to heat up and to shine. Eventually, the collapse is halted when a critical density is reached, and the star begins to cool off and die. Lockyer used the spectral classes of the time to identify a sequence of stages through which it was believed that all stars pass.

LIFE OF A MASSIVE VS. SMALLER STAR

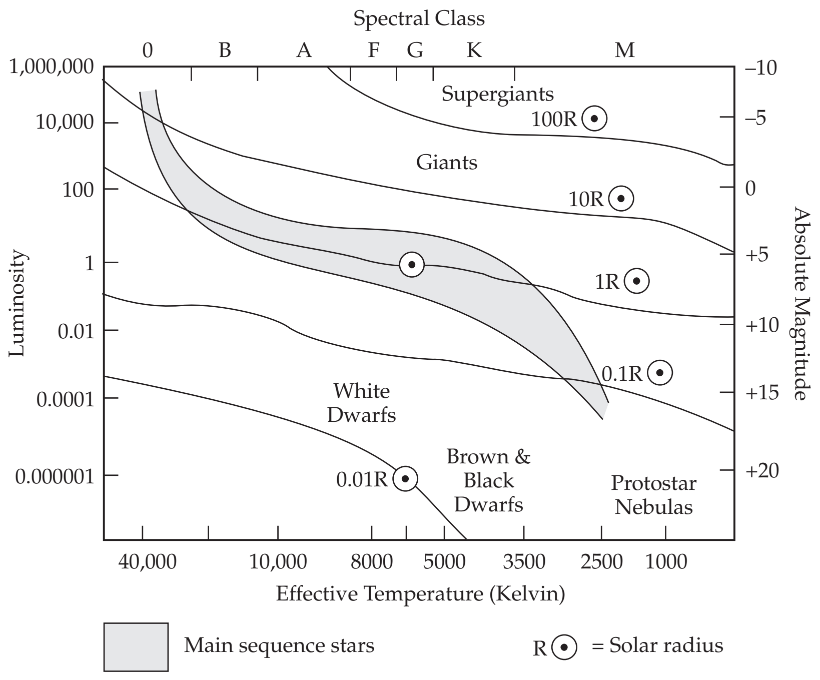


Henry Norris Russell had at his disposal a more sophisticated system of classification, involving seven classes of stars. Also, many more stars had been classified while Russell was conducting his research. This was largely the result of a program carried out at Harvard College Observatory under the direction of Edward Charles Pickering at the beginning of the twentieth century, in which stars were given classifications based on their spectra. A star's spectrum, or the bands of color and darkness produced when its light is spread out by a prism or grating, contains dark lines that can be used to classify stars. The researchers at Harvard College Observatory looked at thousands of such spectra and classified their associated stars, producing massive catalogs of information on stellar types. Russell was able to use this information in developing his scheme of stellar evolution.

THE HERTZSPRUNG-RUSSELL DIAGRAM

Because stars cannot be directly examined in the laboratory, astronomers are forced to deduce their characteristics from things that can be ob-

A HERTZSPRUNG-RUSSELL DIAGRAM



served, such as their spectral type or their brightness. Russell was faced with the question of how to identify a star's characteristics and thus its stage of evolution by its visible characteristics. A star's spectral type was almost universally believed at the time to be linked to its surface temperature and its color, and the different types were the result of differing temperatures; however, no consensus had been reached on the cause of differences in brightness. Russell showed that differences in brightness were a result of variations in density. Thus, spectral type was related to surface temperature and color, and brightness was related to density.

Russell plotted data on spectral types versus data on the absolute brightness (luminosity) of stars (that is, a star's true brightness, after its brightness as seen from Earth is corrected for its distance). In 1913, he produced a plot of spectral type versus brightness. Ejnar Hertzsprung had made a similar diagram in 1911. This type of plot is known today as a Hertzsprung-Russell, or H-R, diagram. Russell then used this plot to view the relationship between brightness (and density) and spectral type (and color and temperature).

Russell presented his diagram to the Royal Astronomical Society on June 13, 1913, and to the American Astronomical Society in Atlanta, Georgia, on December 30, 1913. He also offered his interpretation of the diagram, in terms of stellar evolution.

Main and Giant Sequence Stars

Most stars fell either on a diagonal band stretching across the plot (the "main sequence") or on a horizontal strip across the top of the plot (the "giant sequence"). The names given to these two sequences were based on work by Hertzsprung and others which determined that the stars on the giant sequence were much larger than the stars on the main sequence.

On the main sequence, stars vary in brightness and color, with stars ranging from bright blue ones to dim red ones. On the giant sequence, stars have a fairly constant brightness but vary in type (color). These two groups or sequences of stars were explained by Russell in terms of the age of stars in each sequence. He used the idea that a star's evolution is driven by gravity alone, and that a star begins its life as cool, red, dim, and diffuse, and grows increasingly dense, bright, and hot (with an associated color change) as it contracts. Once it has contracted as far as it can so that no more gravitational energy is available to it, it begins to cool off and become less bright and more red.

Russell hypothesized that the large red stars at one end of the giant sequence are the youngest of stars and that they represent the earliest stages in a star's life, when stars are very diffuse and just beginning their gravitational collapse. As a star collapses, it becomes more dense and begins to change color and spectral type as it moves across the giant sequence; it eventually brightens and leaves the giant sequence for the main sequence. At its hottest point, which Russell believed to be the midpoint of its life, the star was at the top of the main sequence among the brightest and bluest stars. As it then began to cool, while continuing to become denser, it slid down the main sequence from being a hot blue star to being a yellow star like the Sun and finally to being a dim red star, very dense and near the end of its life.

Thus, this track, along the giant sequence and down the main sequence, was thought to be a path of increasing density and increasing age. There were two sorts of red stars: young, diffuse, large ones of increasing temperature and old, dense, small ones of decreasing temperature. A red star could therefore be at either end of its lifetime; Hertzsprung had demonstrated earlier that the spectra of the two types of red stars were different, and thus enabled astronomers to tell whether a red star was old or young.

Russell presented a concise and straightforward scheme of stellar evolution, which neatly fit the known data in terms of the accepted explanation for why stars shine and how they form, exist, and die. He was able to use his diagram to illustrate succinctly the life-stages of a star as he hypothesized them. His work on the temperature and density of stars, as related to spectral type and brightness, was confirmed by later work. Although his evolutionary scheme later required major revision, it was still an important step in the understanding of the "garden" of varying stars we see.

Impact

Hertzsprung-Russell (H-R) diagrams were used by many astronomers immediately after Russell first presented one in 1913, and they are an important tool in astrophysics today. Walter Baade was able to compare H-R diagrams for groups of stars to show that there are, in fact, two populations of stars (one much older than the other) and that each type has its own distinct H-R diagram. This work had important cosmological implications. The H-R diagrams of clusters of stars in the Milky Way have been studied by Robert Julius Trumpler, Bengt Georg Daniel Strömgren, and Gerard Peter Kuiper, among others, to work out theories of stellar formation and evolution.

The discovery that nuclear fusion powers stars for most of their lifetimes, rather than gravitational collapse, brought about drastic revisions in Russell's scheme. Russell's work was important, however, in that it was an early attempt to deduce, from observable quantities, the life cycles of stars. His use of the diagram was a key step in the developing science of astrophysics. Astronomers' knowledge of the causes of a star's observable properties, as plotted on the diagram, changed as they learned of nuclear fusion and nuclear science. However, the method of using the H-R diagram as a clue to a star's properties and life cycle has remained the same. Russell pioneered a practice that continues today.

In his explanation of how the H-R diagram reveals the evolution of stars, Russell gave at least a hint of what was to be discovered later about nuclear power fueling the stars. He suggested that perhaps there is a type of energy release related to radioactivity, which could counteract the gravitational pull inward for a brief period and give a star a longer lifetime than it would have had otherwise. He thought this would not be an important enough effect to change the overall life cycle of the star as he described it.

Today, however, it is known that while a star starts to form because a cloud of material collapses under the influence of gravity, eventually conditions become hot enough in the center of the forming star that nuclear fusion begins to occur. The star then lives out most of its life cycle in one spot on the main sequence, its gravitational pull inward balanced by the pressure outward resulting from energy being released in nuclear fusion. Gravity becomes important again at the end of the star's lifetime, where its fate is determined by the amount of mass it contains. (This is also the factor that determines how long the star lives and where on the main sequence it appears, that is, its brightness and color.)

Much has been learned about such exotic objects as white dwarfs, neutron stars, and black holes, which are the end products of evolution for various masses of stars. Without the H-R diagram, and the foundation of knowledge it offers for the understanding of the interrelationships among a star's density, brightness, temperature, and spectral type, astronomers could not have arrived at their current understanding.

See also Big Bang; Black Holes; Brahe's Supernova; Cassini-Huygens Mission; Cepheid Variables; Chandrasekhar Limit; Copernican Revolution; Extrasolar Planets; Galactic Superclusters; Galaxies; Hubble Space Telescope; Neutron Stars; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; X-Ray Astronomy.

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—*Mary Hrovat*

STEM CELLS

THE SCIENCE: Stem cells, which can be manipulated to create unlimited amounts of specialized tissue, may be used to treat a variety of diseases and injuries that have destroyed a patient's cells, tissues, or organs. Stem cells could also be used to gain a better understanding of how genetics works in the early stages of cell development and may play a role in the testing and development of drugs.

THE SCIENTISTS:

Ernest Armstrong McCulloch (b. 1926?) and
James Edgar Till (b. 1931?), Canadian cellular biologists at the Ontario Cancer Institute who won the 2005 Lasker Award for their pioneering research in proving the existence of stem cells

James Thomson (b. 1958), developmental biologist at the University of Wisconsin, Madison, who first isolated embryonic stem cells in 1998

TYPES OF STEM CELLS

Stem cells are defined by their ability to renew themselves, their lack of differentiation, and their ability to diversify into other cell types. There are three major classes of stem cells: totipotent, pluripotent, and multipotent. Totipotent cells can differentiate to become all of the cells that make up an embryo, all of the extraembryonic tissues, and all of the postembryonic tissues and organs. Pluripotent cells have the potential to become almost all of the tissues found in an embryo but are not capable of giving rise to supporting cells and tissues. Multipotent cells are specialized stem cells capable of giving rise to one class of cells.

A fertilized egg, or zygote, is totipotent. The zygote first divides into two cells about one day after fertilization and becomes an embryo. The embryonic cells remain totipotent for about four days after fertilization. At that point, the embryo consists of about eight cells. As the cells of the embryo continue to divide, they form a hollow sphere. The approximately fifty to one hundred cells on the inner side of the sphere are pluripotent and will continue developing to form the embryo, while the cells on the outer surface will give rise to the extraembryonic tissues, such as the placenta and the umbilical cord.

Multipotent stem cells are found in a variety of tissues in adult mammals and are sometimes referred to as adult stem cells. They are specialized stem cells that are committed to giving rise to cells that have a particular function. Identities of some multipotent stem cells have been confirmed. Hematopoietic stem cells give rise to all the types of blood cells. Mesenchymal stem cells in the bone marrow give rise to a variety of cell types: bone cells, cartilage cells, fat cells, and other kinds of connective tissue cells such as those in tendons. Neural stem cells in the brain give rise to its three major cell types: nerve cells (neurons) and two categories of nonneuronal cells, astrocytes and oligodendrocytes. Skin stem cells occur in the basal layer of the epidermis and at the base of hair follicles. The epidermal stem cells give rise to keratinocytes, which migrate to the surface of the skin and form a protective layer. The follicular stem cells can give rise to both the hair follicle and the epidermis.

Stem cells in adult mammalian tissues are rare and difficult to isolate. There is considerable debate concerning the plasticity of stem cells in adults. Plasticity is the ability of multipotent cells to exhibit pluripotency, such as the capacity of hematopoietic stem cells to differentiate into neurons.

BEHAVIOR IN CELL CULTURE

During the 1980's, researchers first established in vitro culture conditions that allowed embryonic stem cells to divide without differentiating. Embryonic stem cells are relatively easy to grow in culture but appear to be genetically unstable; mice cloned from embryonic stem cells by nuclear transfer suffered many genetic defects as a result of the genetic instability of the embryonic stem cells. As embryonic stem cells divide in culture, they lose the tags that tell an imprinted gene to be either turned on or turned off during development. Researchers have found that even clones made from sister stem cells show differences in their gene expression. However, these genetic changes, while having defined roles in fetal development, may have little significance in therapeutic uses, because the genes involved do not serve a critical role in adult differentiated cells.

Unlike embryonic stem cells, adult stem cells do not divide prolifically in culture. When these stem cells do divide in culture, their division is unlike that of most cells. Generally, when a cell divides in culture, the two daughter cells produced are identical in appearance as well as in patterns of gene expression. However, when stem cells divide in culture, at least one of the daughter cells retains its stem cell culture while the other daughter cell is frequently a transit cell destined to produce a terminally differentiated lineage. The genes expressed in a stem cell and a transit cell are significantly different. Therefore a culture of adult stem cells may become heterogeneous in a short time.

Potential Therapeutic Issues

Although stem cells have significant use as models for early embryonic development, another major research thrust has been for therapeutic uses. Stem cell therapy has been limited almost exclusively to multipotent stem cells obtained from umbilical cord blood, bone marrow, or peripheral blood. These stem cells are most commonly used to assist in hematopoietic (blood) and immune system recovery following high-dose chemotherapy or radiation therapy for malignant and nonmalignant diseases such as leukemia and certain immune and genetic disorders. For stem cell transplants to succeed, the donated stem cells must repopulate or engraft the recipient's bone marrow, where they will provide a new source of essential blood and immune system cells.

In addition to the uses of stem cells in cancer treatment, the isolation and characterization of stem cells and in-depth study of their molecular and cellular biology may help scientists understand why cancer cells, which have certain properties of stem cells, survive despite very aggressive treatments. Once the cancer cell's ability to renew itself is understood, scientists can develop strategies for circumventing this property.

Research efforts are under way to improve and expand the use of stem cells in treating and potentially curing human diseases. Possible therapeutic uses of stem cells include treatment of autoimmune diseases such as muscular dystrophy, multiple sclerosis, and rheumatoid arthritis; repair of tissues damaged during stroke, spinal cord injury, or myocardial infarction; treatment of neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS, commonly called Lou Gehrig's disease) and numerous neurological conditions such as Parkinson's, Huntington's, and Alzheimer's diseases; and replacement of insulin-secreting cells in diabetics.

Stem cells may also find use in the field of gene therapy, where a gene that provides a missing or necessary protein is introduced into an organ for a therapeutic effect. One of the most difficult problems in gene therapy studies has been the loss of expression (or insufficient expression) following introduction of the gene into more differentiated cells. Introduction of the gene into stem cells to achieve sufficient long-term expression would be a major advance. In addition, the stem cell is clearly a more versatile target cell for gene therapy, since it can be manipulated to become theoretically any tissue. A single gene transfer into a pluripotent stem cell could enable scientists to generate stem cells for blood, skin, liver, or even brain targets.

Ethical Issues

Stem cell research, particularly embryonic stem cell research, has unleashed a storm of controversy. One primary controversy surrounding the use of embryonic stem cells is based on the belief by opponents that a fertilized egg is fundamentally a human being with rights and interests that need to be protected. Those who oppose stem cell research do not want fetuses and fertilized eggs used for research purposes. Others accept the special status of an embryo as a potential human being yet argue that the respect due to the embryo increases as it develops and that this respect, in the early stages in particular, may properly be weighed against the potential benefits arising from the proposed research.

Another ethical issue concerns the method by which embryonic stem cells are obtained. Embryonic stem cells are isolated from two sources: surplus embryos produced by in vitro fertilization and embryos produced by somatic cell nuclear transfer (SCNT), often referred to as therapeutic cloning. In SCNT, genetic material from a cell in an adult's body is fused with an enucleated egg cell. With the right conditions, this new cell can then develop into an embryo from which stem cells could be harvested. Opponents argue that therapeutic cloning is the first step on the slippery slope to reproductive cloning, the use of SCNT to create a new adult organism. Proponents maintain that producing stem cells by SCNT using genetic material from the patient will eliminate the possibility of rejection when the resulting stem cells are returned to the patient.

IMPACT

Stem cell research, along with advances in genetics and cloning, gave impetus to a national policy on the use of stem cells. On August 9, 2001, President George W. Bush announced that federal funds could be used to support research using a limited number of human embryonic stem cell lines (about sixty) that had been derived before that date. However, there were no restrictions placed on the types of research that could be conducted on mouse embryonic stem cell lines and no federal law or policy prohibiting the private sector from isolating stem cells from human embryos. Several states introduced legislation to encourage research on stem cells taken from human embryos.

Neither reproductive cloning nor therapeutic cloning was forbidden by law in the United States. Congress has debated legislation in this area, however: One bill was proposed to ban both types of cloning, while an alternative proposal would ban only reproductive cloning. A number of states already have laws that ban human cloning for reproductive purposes, while a small number of states forbid cloning of embryos for stem cells as well.

The impact of policies to ban research must be weighed seriously in the global environment. On one hand, limits must be set and societal values must be debated in open public discussion. On the other, in a world in which national policies are imposed on scientific research, it is important to take into account the implications of different limitations—or lack of limitations—across the globe and how the dynamics of such different policies and laws may affect our society.

See also Chromosomes; Cloning; DNA Fingerprinting; DNA Sequencing; Double-Helix Model of DNA; Evolution; Gene-Chromosome Theory; Genetic Code; Human Evolution; Human Genome; Mendelian Genetics; Mitosis; Oncogenes; Population Genetics; Recombinant DNA Technology; Ribozymes; Viruses.

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—*Lisa M. Sardinia*

STONEHENGE

THE SCIENCE: English physician William Stukeley spent summers between 1719 and 1724 examining Stonehenge, Avebury, and related sites, producing exceptional notes but wrongly believing that Druids built the monuments. Nevertheless, his systematic method of investigation became a model for archaeological fieldwork.

THE SCIENTISTS:

William Stukeley (1687-1765), English antiquarian and archaeologist
John Aubrey (1626-1697), English antiquarian who discovered Avebury

EARLY THEORIES

The Wiltshire prehistoric sites of Avebury and Stonehenge are significant both in their construction and in the way they are situated in the landscape. Stonehenge is the ruin of a single building. An earthen embankment surrounded by a circular excavation ditch defines the site, although additional megaliths and earthworks lie outside the circle. In contrast with the compact area of Stonehenge, Avebury is a complex that covers several square miles, with a main circular bank and ditch and lined with megaliths, delimiting the original 30-acre site. In the eighteenth century, stones were dispersed among houses, gardens, and fields, making the layout difficult to discern. Avebury was not recognized as a human-made complex until 1649, when antiquarian John Aubrey discovered it during a hunting trip.

Although the site at Avebury had gone undetected, speculation about Stonehenge abounded for centuries. Noticed since medieval times, there were conflicting theories about its origin. In the early 1600's, poet and antiquarian Edmund Bolton credited its construction to the legendary first century military and rebel leader, Queen Boudicca. English architect Inigo Jones, who made the first known architectural study of the site, believed that it was a temple built by the Romans. Later in the seventeenth century, Walter Charleton, physician to King Charles II, claimed it was built by Danes. Aubrey, after his discovery of Avebury, investigated both monuments and believed that they were of Druid origin.

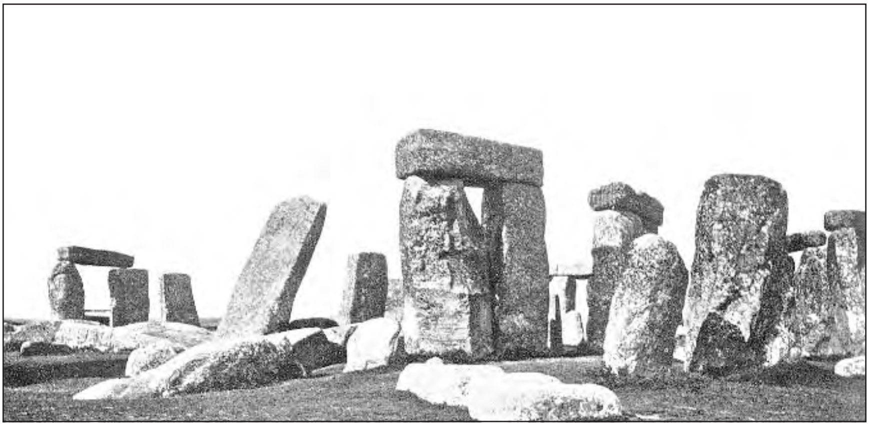
STUKELEY'S FIELDWORK

William Stukeley first visited Stonehenge and Avebury (which he called, collectively, Abury) in 1719. Although he was a trained physician, he pursued studies in theology, science, and antiquities. A member of the Society of Antiquaries and a fellow of the Royal Society, he was a colleague of the most gifted individuals of eighteenth century England. He explored the English countryside observing and recording ancient monuments.

Stukeley was familiar with Aubrey's then unpublished *Monumenta Britannica: Or, A Miscellany of British Antiquities* (1980-1982), which recorded Aubrey's theories along with his observations and measurements of Avebury and Stonehenge. Like Aubrey, Stukeley believed that the monuments were built in pre-Roman times. Furthermore, he felt that his theory could be proven. He speculated that compilation of data about the circles and other ancient sites could provide information not obtainable from written sources.

There are few particulars about Stukeley's visits to Avebury and Stonehenge in 1719 and 1720, but from 1721 to 1724, after he decided to develop a typology of ancient monuments, he detailed his studies. Although Aubrey's work provided an underacknowledged precedent, it was not as encompassing as the project undertaken by Stukeley. Each summer he conducted fieldwork, living on site. His techniques of observation, accurate measurement, and detailed recording accompanied by carefully executed drawings have led to Stukeley being recognized as the foremost figure in eighteenth century English archaeology.

Close observation was a key element in developing his typological study, as was evident in his *Itinerarium curiosum: Or, An Account of the Antiquitys and Remarkable Curiositys in Nature or Art* (1724). Here he noted common building characteristics, such as placement of upright stones in a circular pattern on elevated ground with a surrounding ditch, a surrounding plain,



Stonehenge. (Library of Congress)

and an avenue of approach. Through this typology he wanted to show that Stonehenge and Avebury had the same provenance as other stone temples in England.

Much of his work was without precedent. He developed a vocabulary to describe his findings; he coined the term "trilithon," for example, to describe two upright stones supporting a lintel. He pioneered the field of astroarchaeological studies by being the first to note that Stonehenge was astronomically aligned: The site's assumed entrance marks the point of sunrise on the summer solstice. In 1721 he was the first to discern a raised area, which he called the "avenue," extending from the entrance to Stonehenge toward the River Avon; although the lining stones were gone, he measured placement intervals after observing sockets remaining in the uncultivated ground. Also, in 1723, he discovered at Stonehenge a shallow enclosure of parallel ditches measuring 2 miles in length; he called this the "cursus," speculating that it was an ancient racetrack. At Avebury he discovered similar stone-lined constructions leading toward West Kennet and Beckhampton.

To establish his typology, Stukeley needed measurements from many ancient sites. He stressed precision, believing valid conclusions could be drawn only from accurate comparisons. In 1723 he and Lord Winchelsea took two thousand measurements at Stonehenge, attempting to detect a common, indigenous standard of measurement, which Stukeley called "Druid's cubit," to prove pre-Roman origins of megalithic sites. Through reading and correspondence he also compiled measurements of stone circles located outside the sphere of Roman occupation.

In addition to recording his observations and measurements, Stukeley developed excavation techniques, which he compared to anatomical dissection. In 1722 and 1723 he and Lord Pembroke excavated Bronze Age barrows around Stonehenge. Stukeley's careful technique surpassed anything undertaken prior to that time. He noted that stratigraphy had the potential to establish chronology. He studied construction of barrows and their funerary contents, made precise notes, and carefully drew a cross-section diagram, which was the first such visual record in British archaeology.

Drawings and diagrams played an important role in his fieldwork. From 1721 to 1723 he diagramed the main circles within the great ditch at Avebury and also indicated the avenue of standing stones leading toward West Kennet. The avenue terminated in a double circle of standing stones called the "sanctuary" by local villagers. Stukeley then recorded what remained of the sanctuary and marked discernible sites of destroyed stones.

It has been suggested that the ongoing destruction at Avebury and Stonehenge induced Stukeley to prepare records before the monuments were lost. In the Middle Ages, megaliths often were regarded as pagan relics and were buried. In the eighteenth century, the Avebury site was used as a quarry for building stone. Stukeley also noted that visitors hammered off pieces of the monuments for souvenirs. The owner of Avebury Manor destroyed part of the site's embankment to build a barn. Each year, cultivation further eliminated features of the prehistoric landscape.

After he was ordained into the Church of England in 1729, Stukeley became increasingly conjectural in interpreting the past. Responding to the perceived threat of Enlightenment secularism, he romanticized Druids and postulated that the Church of England was prefigured in their ancient religion. In three works—*Palaeographia sacra: Or, Discourses on Monuments of Antiquity that Relate to Sacred History* (1736); *Stonehenge: A Temple Restor'd to the British Druids* (1740); and *Abury: A Temple of the British Druids* (1743)—he mixed religious speculation with his scientific fieldwork.

IMPACT

William Stukeley's writing reflected the dual nature of thought in the eighteenth century, which incorporated rational-scientific as well as religious-romantic ideas. His linking of Avebury and Stonehenge with Druidism became an enduring fallacy that was expressed in the Romantic tradition in English literature of the late eighteenth and early nineteenth centuries. Poetry by Thomas Gray and William Collins reflected a Druidical revival, as did works by the artist and poet William Blake.

Because Stukeley's scientific studies were intermingled with his Druidic theories, the accuracy of his field surveys has been questioned. Subsequent studies at Stonehenge and Avebury, however, have validated his work, which has provided a valuable record of historic sites before they were subjected to additional ravages of agricultural and economic development. Early aerial photography of the 1920's corroborated Stukeley's observations of the avenue at Stonehenge. Excavations in 1930 confirmed the existence of Avebury's sanctuary, which was destroyed shortly after Stukeley's documentation. The frontispiece to *Abury* provided accurate site information that was used in Alexander Keiller's excavations of 1934 to 1938. The Beckhampton Avenue stones at Avebury no longer exist, but recent excavations substantiate Stukeley's findings.

Stukeley was a key figure in bridging antiquarianism and the emerging science of archaeology. His pioneering work, although based on Aubrey's early techniques, provided the most thorough, systematic studies of Avebury and Stonehenge attempted before the nineteenth century. His careful observations, measurements, and diagramed descriptions were significant components in the development of the field of archaeology. He compiled enough data to recognize these structures as representing a larger group of monuments scattered across Britain. He correctly conceived of these sites as prehistoric sanctuaries. At a time when scholars still used Old Testament chronologies for establishing historical dates, he set about proving that native Britons created the monuments in pre-Roman times. He was among the first to recognize their historic value and to express concern over their preservation. Contemporary analysis of Stukeley's detailed records reveals how much has been lost from the sites in the past two centuries, either taken or destroyed, or both. Historians and archaeologists are indebted to Stukeley for charting the course and following the traces.

See also Dead Sea Scrolls; Pompeii; Rosetta Stone; Troy.

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—*Cassandra Lee Tellier*

STRATOSPHERE AND TROPOSPHERE

THE SCIENCE: Based on experimental balloon measurements of atmospheric temperature versus height, Léon Teisserenc de Bort discovered the stratosphere's and troposphere's vertical layering on the basis of thermal inversion.

THE SCIENTISTS:

Léon Teisserenc de Bort (1855-1913), French physicist and meteorologist
Richard Assmann (1845-1918), German physicist and meteorologist

TEMPERATURE AND ALTITUDE

The details of the rate of change of atmospheric temperature versus height have been of basic importance for many years in trying to determine and predict the processes governing weather. For example, the variation of wind with height also depends upon vertical temperature variation.

Until 1883, the body of air above the Earth's surface was considered generally a uniform body. Then, violent eruption of the volcano Krakatoa in the Java Sea in 1883 produced abnormally high atmospheric concentrations of dust, implying the existence of higher-level global temperature and wind patterns. William Morris Davis's *Elementary Meteorology* (1894) is representative of knowledge of the upper atmosphere before large-scale kite and balloon sondings. Davis simply divided the Earth into geosphere (rock), hydrosphere (water), and atmosphere (air). An empirical formula for atmospheric temperature gradient was developed by Austrian meteorologist Julius Ferdinand von Hann in 1874, based on indirect atmospheric measures such as astronomical observations of the duration of twilight and of meteor burns. Davis proposed that successive isobaric (equipressure) surfaces were separated by greater and greater distances indefinitely, out into space. The general distribution of temperature with elevation was simply illustrated as a nearly linear decreasing function.

BALLOON ASCENTS

Manned balloon ascents to measure upper air temperature were first undertaken by John Jeffries and François Blanchard in 1784 and subsequently by Jean-Baptiste Biot and Joseph-Louis Gay-Lussac in 1804, and continued in England in 1852. Factors influencing balloon performance included the excess of buoyancy forces over balloon gross weight (including human observers) and the maximum size to which the balloon's silk or India rubber envelope would expand in response to decreasing atmospheric pressure. These factors control both maximum ascent ceiling and ascent rate. The need for light gases, such as hydrogen or helium, is to keep the balloon's envelope sufficiently distended. The buoyancy force, which arises from Archimedes' principle, is equal to the air mass displaced by the balloon. As the balloon rises, the air density falls by a factor of about ten for every 10 kilometers of ascent; therefore, the balloon's envelope expands in exact proportion to falling density.

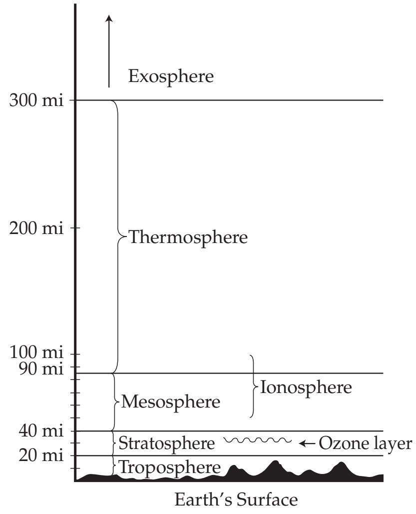
Prior to 1890, balloon observations were, for the most part, limited to heights of only a few kilometers by human oxygen consumption, recording mainly local rather than regional or global temperature behaviors. The first attempts at global isothermal charts were published by Hann in Vienna and Alexander Buchan in Edinburgh in 1887 and 1889, respectively. To overcome the human limitation, kites were first employed by Cleveland Abbe in studying winds under a thunder cloud at the Blue Hill Observatory in Massachusetts. Nevertheless, for technical reasons, the maximum heights attained by kites were only about 8 kilometers.

Because of proven dangers to human life in high ascents, small free rubber balloons carrying recently developed self-recording temperature and pressure recorders were first deployed in 1893 by French aeronomist Georges Besançon and were rapidly adopted elsewhere for meteorological observations. When atmospheric visibility is sufficiently good, larger meteorological balloons could be followed visually by theodolites to obtain supplementary wind direction data. Theodolites are grid-mounted survey telescopes permitting measurement of height and angular motion. These various observations demonstrated that to at least about 9,000 meters, temperature decreased in a fairly uniform fashion at a rate of about 1 degree Celsius per every 180 meters risen.

Teisserenc de Bort's Sondings

After extensive work in Europe and North Africa with the French government undertaking barometric and other weather observations, in 1897, Léon Teisserenc de Bort founded his own private aeronomic observatory at Trappes near Paris. Earlier, Teisserenc de Bort had pioneered self-recording temperature and barometric pressure sensors; the physicist Richard Assmann developed the first self-recording hygrometer to measure atmospheric humidity. Using hydrogen-filled balloons specially designed for rapid and near vertical ascents, Teisserenc de Bort named his surveys "soundings" or "sondings," in analogy to bathymetric depth soundings by sonde-line or acoustic sound at sea. A critical factor was sufficient protection of thermometers from direct solar radiation, as well as recorders that could respond to changing temperature faster than the balloon would rise.

In April, 1898, Teisserenc de Bort, using his improved apparatus, began a long series of regular balloon sondings from Trappes, France. Among other details, he soon discovered unusual temperature records, first believed to be instrument errors, of constant or even increasing temperature conditions from the extreme upper limits of his balloon's ascents. After precluding instrument error and repeating many measurements, in 1899, he published a report indicating that temperatures at heights above 0.1 atmospheric pressure (100 millibars) cease to decline with altitude but remain constant over a specific height interval, thereafter slowly increasing.



LAYERS OF THE EARTH'S ATMOSPHERE

In his papers of 1904 in the noted French journal *Comptes rendus physique* and his own *Travaux scientifiques de l'observatoire de météorologie de Trappes*, Teisserenc de Bort gave mean temperatures versus height measured at Trappes between between 1899 and 1903. Out of 581 balloon ascents, 141 attained temperature "isothermal" and "inverted" measurements at height records of 14 kilometers or more. His data showed that there is a slow temperature decrease up to about 2 kilometers above sea level. This is followed by a more rapid decrease up to about 10 kilometers. A very slow or total lack of decrease was measured between 11 and 14 kilometers (with an ambient temperature of about –55° Celsius). He called this the "thermal" zone or boundary.

Teisserenc de Bort's observations were almost concurrently confirmed by Assmann's independent series of ascents from Berlin. Assmann and Artur Berson, beginning in 1887, undertook a more extensive series of upper atmospheric soundings, under the aegis of the Prussian Meteorological Office and Aeronautical Section of the German Army, and later as an independent scientific station at Lindenberg. The details of their seventy ascents between 1887 to 1889 were the first published aeronometric measurements of temperature for several locations, in 1900, and thereafter published regularly in the German journal *Das Wetter*. From a particularly long series of kite soundings from Berlin between October, 1902, and December, 1903, Assmann showed that atmospheric temperature is much more variable at 6 or 7 kilometers height than at ground surface. The effects of diurnal and seasonal changes on upper-level temperatures were also measured. Following the systematic planned simultaneous ascents from many European cities between 1895 and 1899, Assmann assembled a data base of more than one thousand of his own observations, with 581 of Teisserenc de Bort, and others from England, Holland, and the Soviet Union, enabling him to compute monthly and annual temperature and wind velocity averages of many altitudes between 0 and 11 kilometers over central Europe. Assmann also argued that at about 12 kilometers, the upper limit for cirrus clouds, temperature remains constant and later increases slowly. The atmospheric region above these heights of constant temperature was called the stratosphere, the lower region nearest the ground was called the troposphere, and the transition zone was called the tropopause. The mesosphere and thermosphere are above the stratosphere.

IMPACT

Meteorologic sonding heights of more than 25 kilometers were achieved in France and Belgium between 1905 and 1907. The Fifth Conference of the International Committee on Scientific Aeronautics at Milan in 1906 saw an increasing number of measurements confirming the temperature results of Teisserenc de Bort and Assmann, notably kite ascents from 1904 to 1905 from the Soviet Union. These data established that above a height that geographically varied from about 18 kilometers near the equator to about 11 kilometers at 50° north latitude to only about 6 kilometers at the poles, atmospheric temperature remained approximately constant over a certain level. (The English meteorologist W. Dines subsequently showed that the stratosphere is high and cold over high pressure and low and warm over low pressure.)

As soon as diverse independent observations had established the troposphere/ tropopause/stratosphere, many efforts were made to explain rigorously the occurrence of stationary upper-level discontinuities on the basis of the rapidly developing hydrothermodynamics of Vilhelm Bjerknes, Ludwig Prandtl, and others—initially, however, with only very limited success. Finally, W. Humphreys in the United States (*Astrophysical Journal*, vol. 29, 1909) and F. Gold in England (*Proceedings of the Royal Society*, vol. 82, 1909) published what became essentially the generally accepted explanation. In both approaches, it was recognized that it is necessary to consider the thermodynamic balance between absorbed and reemitted solar radiation. Humphreys' account is less mathematical but equivalent to Gold's. Briefly, since the average annual temperature in the atmosphere at any location had been shown experimentally not to vary greatly, Humphreys concluded that the absorption of solar radiation is equal basically to the net outgoing reradiation by Earth (discovered previously by S. Langley), using a simple thermodynamic "blackbody" model. Humphreys concluded that the isothermal/tropopause zone marks the limit of vertical thermal convection and, from this, correctly deduced that the above-lying layers are warmed almost entirely by direct solar radiation (later shown to be dependent upon atmospheric ozone). The increasing temperature trend was shown later to be caused directly by the heat released during the interaction between incoming ultraviolet radiation and atmospheric ozone molecules.

Further direct and indirect studies of the stratosphere and troposphere continued by a variety of means. In studies of ground versus air waves from earthquakes by Emil Wiechert in 1904, and later during World War I, it was noted that loud noises could be heard occasionally at distances ranging from 150 kilometers to more than 400 kilometers from their source, even when observers near the source could barely hear the sounds. Between 1928 and 1931, H. Benndorf, P. Duckert, and O. Meissner made recordings of seismic-acoustic wave propagation in atmospheric temperature inversions associated with the troposphere. Sound waves are bent gradually or refracted resulting from the increased velocity of sound in air resulting from a gradient of rising temperature at about 35 to 60 kilometers height. These observations provided another method of estimating temperature then inaccessible to aircraft, balloon, and kite soundings. In 1926, G. Dobson and F. Lindemann employed data from hundreds of meteor burn observations to extrapolation temperature, pressure, and chemical observations to heights of up to 160 kilometers, confirmed by V-2 flights during and after World War II.

Subsequent studies of the stratosphere by Earth-orbiting satellites include the mapping of the (polar) jet streams and the twenty-six-month quasi-biennial cycle. The original motivation and basis for these and other studies, however, remain the methods and results of Teisserenc de Bort and Assmann.

See also Atmospheric Circulation; Atmospheric Pressure; Chlorofluorocarbons; Global Warming; Ionosphere; Ozone Hole; Van Allen Radiation Belts; Weather Fronts.

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—*Gerardo G. Tango*

STREPTOMYCIN

THE SCIENCE: Selman Abraham Waksman searched for an antibacterial substance in soil microorganisms, discovering eighteen antibiotics, including streptomycin, the first drug effective against tuberculosis.

THE SCIENTISTS:

Selman Abraham Waksman (1888-1973), Soviet-born American soil microbiologist and winner of the 1952 Nobel Prize in Physiology or Medicine
René Dubos (1901-1982), French-born American microbiologist
William Hugh Feldman (1892-1974), American pathologist

CURING COWS

Some microbiologists in the late nineteenth century believed that a struggle for survival occurred in the microbial world. They thought that microbes might contain substances that inhibited the growth of other microbes. There were attempts to isolate chemotherapeutic agents from such microbial substances as molds and bacteria, but the field was abandoned in the early twentieth century until the reawakening of interest in such agents by René Dubos in the 1930's.

Dubos was a student of Selman Abraham Waksman, whose area of expertise was the population of microorganisms that inhabit the soil. Waksman specialized in one type of soil microbe, the actinomycetes, organisms intermediate between bacteria and fungi. His research included a study on how the tubercle bacillus fared when introduced into soil. From 1932 to 1935, Waksman established that the germ could not survive because of the antagonism of soil microbes. The finding substantiated the fact that pathogenic germs do not survive when introduced into soil. At the time, his finding did not seem to lead to anything new; it was only another example of microbes inhibiting other microbes.

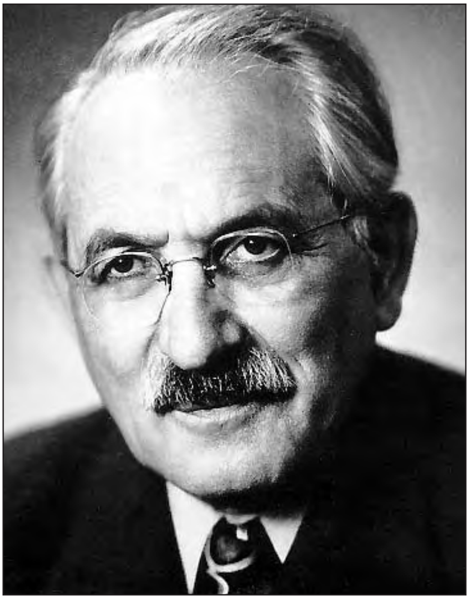
Dubos wondered what would happen if soil were enriched with pathogenic germs. He pondered if perhaps their presence would encourage soil microbes antagonistic to them to flourish. In February, 1939, Dubos announced that he had tracked down such an antagonistic microorganism, *Bacillus brevis*, and from it had isolated two antibacterial substances, tyrocidine and gramicidin. The latter proved to be the first true antibiotic drug, attacking pneumococcus, staphylococcus, and streptococcus germs. Too toxic for human therapy, it became useful in treating animals. It aroused public interest when, at the 1939 New York World's Fair, sixteen of the Borden cow herd developed a streptococcal udder infection and gramicidin cured twelve of the cows of the bacteria.

Curing Tuberculosis

Dubos's discovery alerted scientists to the possibility of finding other powerful drugs in microorganisms, and the central figure in exploiting this field was Waksman. He seized on Dubos's work and converted his research on soil actinomycetes into a search for the antibacterial substances in them. The actinomycetes proved to be the most fertile source for antibiotics. Waksman coined and defined the term "antibiotic" in 1941 to describe the novel drugs found in microbes. He developed soil enrichment methods and discovered eighteen antibiotics between 1940 and 1958. He cultured thousands of soil microbes in artificial media and screened them for activity. The promising ones were then chemically processed to isolate the antibiotics.

Streptomycin was the most important of Waksman's discoveries. In September, 1943, with his students Elizabeth Bugie and Albert Schatz, he isolated a soil actinomycete, *Streptomyces griseus*, which contained an antibiotic he named "streptomycin." It was antagonistic to certain types of bacteria. His report appeared in January, 1944, and two months later, another article claimed that streptomycin was active against the deadly tubercle germ, *Mycobacterium tuberculosis*.

In the 1940's, tuberculosis was not fully under control. There was no



Selman Abraham Waksman. (The Nobel Foundation)

cure, only prolonged bed rest and a regimen of nutritious food. The tubercle germ could invade any organ of the body, and in its various forms, the disease took a horrifying toll. A diagnosis of tuberculosis entailed lifelong invalidism, and patients died because the available treatment was so limited.

As the search for a cure progressed, the medical world took notice of the clinical tests conducted by William Hugh Feldman and H. Corwin Hinshaw at the Mayo Clinic. They had been investigating the chemotherapy of tuberculosis since the 1930's. Many scientists believed that such therapy was unattainable, but Feldman and Hinshaw refused to accept this verdict. They worked with sulfa drugs and sulfones and found some effect in suppressing the growth of tubercle bacilli, but not their eradication. Feldman had visited Waksman before the discovery of streptomycin and indicated a desire to try any promising antibiotics.

When Waksman found antitubercular effects in 1944, he wrote at once to Feldman to offer streptomycin for his studies. Feldman and Hinshaw had developed a practical system to determine the ability of a drug to slow the course of tuberculosis in guinea pigs. They used streptomycin on guinea pigs inoculated with the tubercle germ. In December, 1944, they issued their first report. The tests revealed streptomycin's ability to reverse the lethal course of the inoculations, and they concluded that it was highly effective in inhibiting the germ, exerting a striking suppressive effect, and was well tolerated by the animals.

Feldman and Hinshaw were now ready to test human patients. Hinshaw enlisted two physicians from a nearby sanatorium. On November 20, 1944, and for the next six months, a twenty-one-year-old woman with advanced pulmonary tuberculosis received streptomycin. In June of 1945, she was discharged, her tuberculosis arrested; she married eventually and reared three children.

This happy ending was followed by many more. Feldman and Hinshaw deserve the credit for proving that streptomycin could be used against tuberculosis. They demonstrated its value in carefully conducted trials. Some observers believe that they should have shared the 1952 Nobel Prize with Waksman.

IMPACT

Waksman did more than discover a major antibiotic. His work encouraged others to attempt to isolate new antibiotics by means of screening programs similar to those he devised. The 1950's witnessed a large increase in the number of antibiotics, and antibiotics became a large industry with total production of more than nine million pounds in 1955.

Streptomycin was not perfect. As early as 1946, reports appeared on the resistance of bacilli to the drug. Such resistant strains could be responsible for the failure of therapy. New drugs came to the rescue; Swedish investigators found that a drug consisting of para-aminosalicylic acid would inhibit the tubercle bacillus, although not as effectively as streptomycin. In 1949, the Veterans Administration combined the two drugs. After that, "combination" therapy proved to be the key to the future of chemotherapy, as the combination delayed the appearance of resistant strains. By 1970, using available drugs, and by the judicious use of combinations, physicians could achieve recovery in nearly all cases of pulmonary tuberculosis.

See also Anesthesia; Antisepsis; Aspirin; Contagion; Diphtheria Vaccine; Germ Theory; Hybridomas; Immunology; Penicillin; Polio Vaccine: Sabin; Polio Vaccine: Salk; Schick Test; Smallpox Vaccination; Viruses; Yellow Fever Vaccine.

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—*Albert B. Costa*

STRING THEORY

THE SCIENCE: The theory of cosmic strings provided a workable explanation of how matter formed into stars, galaxies, and clusters.

THE SCIENTISTS:
Tom Kibble (b. 1932), English physicist
Neil Turok, English physicist
Andreas Albrecht (b. 1927), American quantum chemist
Edward Witten (b. 1951), American physicist

THE MOMENT AFTER CREATION

According to the "big bang" theory, the universe began with a colossal explosion fifteen to twenty billion years ago. Modern advances in particle physics and other branches of the physical sciences have allowed scientists to formulate theories that describe the events immediately following the big bang. According to one theory, from the moment of creation until a point some 10^{-43} second later, all four of the forces of nature consisted of one "superforce." The universe consisted of energy; there were no elementary particles. Physicists refer to this state as one of symmetry. In other words, the universe at that time would have appeared to have the same properties in all directions. As minute increments of time passed, the symmetry was broken as individual forces began to appear. First came gravity, and then the strong nuclear force. At about 10^{-12} second, the weak force and electromagnetism began to exist as independent forces. The appearance of these forces made possible first the formation of elementary particles and then, within minutes, the first atomic nuclei. After much expansion and cooling of the universe, the first atoms were formed. Physicists estimate that this latter event took place about 700,000 years after the initial explosion in which the universe was created.

Prior to the formation of the first atoms, the vast number of free electrons in the universe interacted with light emitted at the instant of the big bang. After most of the electrons had become involved in the formation of atoms, matter and light were decoupled and the universe became transparent to radiation. At this juncture, reduced light pressure allowed bits of matter to form larger masses.

LIKE CRACKS IN ICE

According to the first theories of galactic formation, gravitational forces acting in the early universe caused matter to form lumps. These lumps, in turn, attracted great clouds of dust, and from these huge rotating masses, individual stars were born. Stars that were formed close to one another remained gravitationally bound and formed huge multibillion-star assemblages called galaxies. Individual galaxies were attracted by gravity to form clusters, and clusters were bound to superclusters.

The problem with this theory is that it does not explain why or how matter formed into lumps in the first place. Since cosmic radiation—the remnant of the big bang fireball—is the same in intensity from all parts of the sky, it is difficult to accept the idea that there may have been irregularities in the explosion that could have caused some unevenness in the distribution of matter.

In 1976, physicist Tom Kibble, working at the Imperial College in London, was considering the possible effects of modern theories of unified fields on the universe. He was particularly concerned with that fraction of a second after the big bang when the forces (fields) began to assume their separate identities. His mathematical model suggested that shortly after the big bang, the rapidly cooling universe developed flaws that appeared to be stringlike in nature. This rapid cooling of the universe would produce what is called a "phase transition," which is analogous to the cracks and other flaws that are formed when water is frozen into ice. Kibble's strings were described as slender strands of highly concentrated mass-energy. These remnants of the original fireball, according to the theory, are much thinner in diameter than a proton and as long as the known universe. A segment of a cosmic string 1.6 kilometers long would weigh more than the entire Earth. This large mass suggests that strings must have been formed early in the history of the universe, when there was an excess of energy.


Tom Kibble. (Imperial College of Science, Technology, and Medicine)

IMPACT

Computer simulations conducted by Neil Turok and Andreas Albrecht indicate that as the universe expanded and rapidly cooled immediately after the big bang, defects in space-time formed long, continuous chains. Within these chains or strings, symmetry still exists. The forces of nature exist as one force, and as a result, there are no atomic particles. As the universe expands, the strings evolve. Rapid vibrations within any one string may cause portions of that string to overlap. When this occurs, the loop that has been formed breaks away from the string. These loops may be of any size, from microscopic to several light-years across.

According to the theory of cosmic strings, the loops undergo rapid oscillations. These oscillations, the speed of which may approach the speed of light, cause the emission of gravitational waves. These waves, which were predicted by Albert Einstein's general theory of relativity, are ripples in the fabric of space-time. As a string radiates this energy, it eventually shrinks and disappears. It has been estimated that a loop of cosmic string 1,000 light-years in circumference would radiate away in 10 to 100 million years.

Scientists wonder whether any strings remain in the universe. Researchers working on string theory have determined that the smallest loop that could have been formed in the primeval universe and could still exist must have had an initial diameter of at least one million light-years. It is also theorized that any currently existing strings would be widely dispersed, perhaps as much as one billion light-years from Earth.

A modification of cosmic string theory by Edward Witten suggests that strings might be superconductors of electricity. It has been calculated that currents as great as 100 quintillion amperes could be induced. The flow of electrical current produces a magnetic field, so strings should be surrounded by intense fields. Particles trapped and accelerated within these fields would glow. The observation of radiation from these particles might one day provide the first evidence of the existence of cosmic strings.

See also Big Bang; Black Holes; Brahe's Supernova; Cassini-Huygens Mission; Cepheid Variables; Chandrasekhar Limit; Copernican Revolution; Cosmic Microwave Background Radiation; Cosmic Rays; Expanding Universe; Extrasolar Planets; Galactic Superclusters; Galaxies; Galileo Mission; Gamma-Ray Bursts; Gravitation: Einstein; Greek Astronomy; Halley's Comet; Heliocentric Universe; Herschel's Telescope; Hubble Space Telescope; Inflationary Model of the Universe; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mars Exploration Rovers; Mass Extinctions; Mayan Astronomy; Moon Landing; Nebular Hypothesis; Neutron Stars; Oort Cloud; Planetary Formation; Pluto; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Saturn's Rings; Solar Wind; Speed of Light; Stellar Evolution; Van Allen Radiation Belts; Very Long Baseline Interferometry; Voyager Missions; Wilkinson Microwave Anisotropy Probe; X-Ray Astronomy.

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—*David W. Maguire*

SUPERCONDUCTIVITY

THE SCIENCE: John Bardeen, Leon N. Cooper, and John Robert Schrieffer were the first physicists to explain how some metals, as they approach absolute zero (–237.59° Celsius), lose their resistance to electricity.

THE SCIENTISTS:

John Bardeen (1908-1991), American physicist
Leon N. Cooper (b. 1930), American physicist
Fritz Wolfgang London (1900-1954), American physicist
Heinz London (1907-1970), American physicist
Heike Kamerlingh Onnes (1853-1926), Dutch physicist
John Robert Schrieffer (b. 1931), graduate student in physics

A SCIENTIFIC MIRACLE

When an electric current is run through a piece of metal, a considerable amount of the energy is lost to what is called "electrical resistance." Different metals have different resistances. In 1911, Heike Kamerlingh Onnes, a Dutch physicist who later won a Nobel Prize in Physics, made a startling discovery. He found that when the temperature of mercury was lowered almost to absolute zero (–273.15° Celsius), it seemed to lose all of its electrical resistance. Kamerlingh Onnes had discovered superconductivity. For the next fifty years, scientists would repeat this experiment with other metals with the same results, but no one was able to explain it.

John Bardeen first became interested in superconductivity in 1938, when he read David Shoenberg's new book *Super-Conductivity*. He had already heard of the report given by Fritz London and Heinz London to a meeting of the Royal Society that established a link between superconductivity and quantum mechanics, something else that physicists were only beginning to understand. By 1940, Bardeen had begun to formulate his own explanation for superconductivity. Unfortunately, his thinking was sidetracked by World War II. Between 1941 and 1945, Bardeen worked at the Naval Ordnance Laboratory, doing research on the transistor. He was awarded his first Nobel Prize for this research in 1956.

Bardeen resumed his study of superconductivity in 1950, after some new discoveries helped to explain how electricity works. These discoveries turned out to be some of the missing pieces in the puzzle of superconductivity, though the puzzle still seemed almost impossible to solve. Bardeen decided that the only way to solve the puzzle was to break it up into smaller, less difficult pieces. In 1951, having become a professor of physics and engineering at the University of Illinois at Urbana-Champaign, he asked Leon N. Cooper, who had a doctorate in physics from Columbia University, to help him with some of the problems. In 1956, they were joined by John Robert Schrieffer, one of Bardeen's graduate students.

It was already known that twenty-six metals and ten alloys (combinations of metals) are superconductors at different temperatures. The highest temperature at which any of them became superconductors was –214.44° Celsius. As yet, there was no real evidence that superconductivity had to take place at such extremely low temperatures. Although using liquid nitrogen is a fairly cheap way to bring temperatures down close to absolute zero, Bardeen and his coworkers knew that superconductivity would never be truly practical unless it could be achieved at higher temperatures.

Cooper Pairs

As early as 1950, Bardeen had understood that the key to understanding superconductivity lay in the way in which electrons move and interact with one another. Earlier theories had supposed that superconductivity involved atomic vibration. Bardeen suggested possible ways of measuring the change in electrical resistance when superconducting temperatures had been reached. Until this time, there had been no instruments sensitive enough to measure this resistance.

By 1956, Cooper, Bardeen's assistant, had finally taken the first step toward solving the puzzle. He discovered that free electrons (electrons that are not bound to any one molecule) are attracted to each other in pairs during superconductivity. These pairs are often called "Cooper pairs." After a year of working with this discovery, Bardeen and his coworkers finally came up with a successful model for understanding superconductivity. They published this model in February, 1957, and followed it with supporting evidence for the next six months.

One way to view their model is to think of the electrons as people in a crowded railroad station. The people are squeezed together so tightly that they bump into anything that gets in their way—mostly other people. This is how electrons move when there is little or no current running through a metal.

When a current is introduced, it is as though the people on one side of the station were suddenly pushed very hard. The people in their immediate vicinity are pushed very hard as well, but the people who are farther away feel the push only slightly, and the people on the other side of the station may not feel anything. If electrons are weakly paired, however, as the Cooper pairs are, the resistance to any one pair from all the electrons that are not a part of that pair goes down about one hundred times. It is this state that comes close to superconductivity. Bardeen and his coworkers also discovered that besides lacking resistance, superconductors can also prevent magnetic fields from entering them.

Impact

For centuries, people have been seeking a way to use perpetual motion to create energy without using fuel. When Bardeen proposed his theoretical explanation of superconductivity, scientists began to think that the search was almost over. When the theory was announced, scientists immediately started to devise ways to put superconductivity to use. They thought of electrical power lines made of superconductive wire. Without any electrical resistance to stop much of the electricity from reaching the end of the line, electrical power plants would be much cheaper and more efficient. Scientists also suggested superfast trains that would be built on top of powerful magnets and hover over superconductive "rails." They imagined computers running hundreds of times faster than had been possible before the development of superconductors. These ideas and many more were made possible by the theory set forth by Bardeen, Cooper, and Schrieffer. Many ideas have already been put to work, and others, still unthought of, will be developed in the years to come.

See also Buckminsterfullerene; Electron Tunneling; Kelvin Temperature Scale; Liquid Helium; Quantized Hall Effect; Superconductivity at High Temperatures; Thermodynamics: Third Law.

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—*R. Baird Shuman*

SUPERCONDUCTIVITY AT HIGH TEMPERATURES

THE SCIENCE: K. A. Müller and J. G. Bednorz found a ceramic material that "superconducted" (conducted electricity without resistance) at a temperature much higher than those at which other materials could act as superconductors.

THE SCIENTISTS:
Karl Alexander Müller (b. 1927), Swiss physicist
Johannes Georg Bednorz (b. 1950), German physicist
Heike Kamerlingh Onnes (1853-1926), Dutch physicist

THE DISCOVERY OF SUPERCONDUCTIVITY

At the end of the nineteenth and the beginning of the twentieth century, when modern physics was being created, scientists found that the world did not behave in extreme conditions in the same way that it behaved in ordinary conditions. For example, Albert Einstein discovered that objects moving at speeds close to the speed of light contracted in length. Similarly, Heike Kamerlingh Onnes found that matter behaved in unusual ways at extremely low temperatures. By the first decade of the twentieth century, all gases except helium had been liquefied, and in 1908, using an elaborate device that cooled helium gas by evaporating liquid hydrogen, Kamerlingh Onnes succeeded in liquefying helium. He was then able to use this liquid helium to cool various materials down to temperatures near absolute zero. In 1911, he discovered, to his surprise, that when mercury was immersed in liquid helium and cooled to 4 Kelvins (four degrees above absolute zero), its electrical resistance disappeared. When its temperature rose above 4 Kelvins, mercury lost this property of "superconductivity."

During the decades after Kamerlingh Onnes's discovery, scientists found that other metals and many metal alloys were superconductors when they were cooled to temperatures near absolute zero, but they found no superconductor with a "transition temperature" (the temperature at which superconductivity occurs) higher than 23 Kelvins. They were, however, able to deepen their understanding of superconductivity. For example, in 1933, Karl Wilhelm Meissner, a German physicist, discovered that superconductors expel magnetic fields when cooled below their transition temperatures. This property and the property of resistanceless current flow became the defining characteristics of superconductivity.

Despite these and other discoveries, it was not until 1957 that a satisfactory theory of superconductivity was published. In that year, John Bardeen, Leon N. Cooper, and J. Robert Schrieffer, working at the University of Illinois, used the idea of bound pairs of electrons (Cooper pairs) to explain superconductivity. They showed how the interaction of these electrons with the vibrations of ions in the crystalline lattice of the metal caused the electrons to attract rather than repel one another, and because the movements of neighboring Cooper pairs are coordinated, the electrons could travel unimpeded. Despite these theoretical and experimental advances, however, scientists had been able to achieve only a transition temperature of 23 Kelvins for a niobium-germanium alloy.

The Discovery

Great discoveries are often made by taking risks, and Alex Müller and Georg Bednorz, working at the International Business Machines (IBM) Corporation's laboratory near Zurich, Switzerland, chose to investigate complex metal oxides for superconductivity rather than the usual metals and alloys. Although other scientists had shown that some metal oxides superconducted at very low temperatures, most metal oxides turned out to be insulators (nonconductors). From 1983 to 1985, Bednorz and Müller combined metal oxides to create new compounds to test for superconductivity. More than a hundred compounds turned out to be insulators before Bednorz and Müller heard about a ceramic compound of lanthanum, barium,

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copper, and oxygen that French chemists had made but had failed to test for superconductivity. Bednorz discovered that this compound was indeed a superconductor, and they were able to shift its superconductivity to temperatures as high as 35 Kelvins, twelve degrees above the previous record.

Bednorz and Müller had established that their ceramic material carried electrical current without resistance, but they realized that for a material to be a genuine superconductor, it also had to exhibit the Meissner effect—that is, it had to prevent magnetic fields from entering its interior. In 1986, their tests showed that their material exhibited the Meissner effect. Their results were soon confirmed at several other laboratories, which led to a frantic search among physicists for materials with even higher transition temperatures. When this search led to amazing successes, it became clear that Bednorz and Müller had made a revolutionary breakthrough. In 1987, a little more than a year after their discovery, they received the Nobel Prize in Physics for their work.

Impact

After Bednorz and Müller's discovery, other researchers made compounds that superconducted at even higher temperatures, the most famous of which was yttrium-barium-copper oxide, a material that superconducted at almost 100 Kelvins, a temperature higher than that of liquid nitrogen (77 Kelvins). The discovery of this compound's transition temperature led to a flurry of activity among physicists, since it meant that liquid nitrogen—instead of the inconvenient and much more expensive liquid helium—could now be used to study superconductivity. About a year later, researchers at IBM's Almaden Research Center in San Jose, California, announced that they had found a thallium-calcium-barium-copper oxide with a transition temperature of 125 Kelvins.

Because substances with no electrical resistance could have many profitable applications, businessmen, engineers, and government officials were fascinated by these high-temperature superconductors. Corporations and governments invested heavily in their development (about $450 million worldwide in 1990). Politicians and businessmen were convinced of the potential of superconductors in electronics (especially high-speed computers), transportation (especially levitating trains), and power generation and distribution. Several difficulties quickly arose, however, that tempered the initial promise of superconductors. Complex metal oxides are not easily formed into wire, for example, which would be required for many applications. Researchers have tried various ways to solve this problem, but so far they have been unsuccessful. Nevertheless, it seemed almost certain that high-temperature superconductors would eventually transform the way many people live and work.

See also Buckminsterfullerene; Electron Tunneling; Kelvin Temperature Scale; Liquid Helium; Quantized Hall Effect; Superconductivity; Thermodynamics: Third Law.

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—*Robert J. Paradowski*

THERMODYNAMICS: FIRST AND SECOND LAWS

THE SCIENCE: The formulation of the second law of thermodynamics by Rudolf Clausius, along with his insights into the first law of thermodynamics, established the foundation for modern thermodynamics.

THE SCIENTISTS:

Rudolf Julius Emmanuel Clausius (1822-1888), German physicist and mathematician
Sadi Carnot (1796-1832), French physicist
Benoît-Paul-Émile Clapeyron (1799-1864), French engineer
Pierre-Simon Laplace (1749-1827), French physicist and mathematician
Siméon-Denis Poisson (1781-1840), French physicist and mathematician
James Joule (1818-1889), British physicist
Julius von Mayer (1814-1878), German physician and physicist
Hermann von Helmholtz (1821-1894), German physicist
William Thomson, Lord Kelvin (1824-1907), Scottish physicist and mathematician
Ludwig Boltzmann (1844-1906), Austrian physicist

CALORIC THEORY

The mid-nineteenth century was a time of great interest in thermodynamics, the study of the relationship between heat and other forms of energy. Around 1842, James Joule and Julius von Mayer discovered the first law of thermodynamics, or conservation of energy: Although energy can be changed into different forms, the total energy of an isolated system remains the same. This theory was confirmed by Hermann von Helmholtz in 1847.

In 1850, Rudolf Clausius published a paper in the German *Annalen der Physik* that analyzed the relationship between heat, work, and other thermodynamic variables. Prior to the appearance of Clausius's paper in 1850, the theory of heat, known as the caloric theory, was based on two fundamental premises: the heat in the universe is conserved, and the heat in a material depends on the state of the material. Pierre-Simon Laplace, Siméon Poisson, Sadi Carnot, and Benoît Clapeyron had all developed thermodynamical concepts and relationships that were based upon the assumptions of the caloric theory. By reformulating the first law of thermodynamics using the concept of the internal energy of a system, Clausius showed in his 1850 paper that both assumptions of the caloric theory of heat were incorrect. He

Rudolf Clausius. (Library of Congress)

stated additionally that the natural tendency is for heat to flow from hot bodies to cold bodies and not the reverse. This was the first published statement of what became known as the second law of thermodynamics.

Although the idea seems rather obvious for heat flow that occurs through the process of conduction, the principle stated by Clausius goes much further by asserting that no process whatever can occur that is in conflict with the second law. His 1850 paper was monumental in the development of thermodynamics. It replaced the caloric theory of heat with the first and second laws of thermodynamics, laying the foundation for modern thermodynamics.

Efficiency of Heat Engines

Between 1850 and 1865, Clausius published an additional eight papers that applied and clarified the second law of thermodynamics. One of his first applications was to the efficiency of a heat engine. A heat engine is any device that absorbs heat from a higher-temperature source, or reservoir, converts part of that energy into useful work, and dumps the rest to a lower-temperature reservoir.

Steam engines are a prime example. In 1824, Carnot had derived an equation for the efficiency of a simple heat engine based strictly on the conservation of energy. In the 1850's, Clausius determined the restrictions on the efficiency of a heat engine by also invoking the second law of thermodynamics in the calculation of efficiency. He showed that the upper limit to the thermal efficiency of any heat engine is always less than one. He concluded that it is impossible to construct any device that will produce no effect other than the transfer of heat from a colder to a hotter body when it operates through a complete cycle. The consequence is that heat energy can not be converted completely into mechanical energy by any heat engine.

Irreversibility

Through his applications of the second law to heat engines and other thermodynamic systems, Clausius deduced that processes in nature are irreversible, always proceeding in a certain direction. This is analogous to time only moving forward and not in reverse. Since it is impossible for a heat engine or any other system to convert the heat that it absorbs completely into mechanical work, the system can not return to the same state in which it began. Clausius concluded that the disorder of the system and its surroundings had increased. In a heat engine, for example, the particles that constitute the system are initially sorted into hotter and colder regions of space. This sorting, or ordering, is lost when the system performs work and thermal equilibrium is established.

ENTROPY

In 1865, Clausius published a paper in which he coined the term "entropy" to describe the concept of increasing disorder when processes occur in nature. Becauce the key word in the first law of thermodynamics was "energy," Clausius looked for a similar word to characterize the second law. He finally settled on the word entropy, which originates from a Greek word meaning "transformation." Clausius determined an equation that related entropy to heat and temperature. He then used entropy as a quantitative measure to determine the disorder or randomness of a system.

In his 1865 paper, he restated the second law of thermodynamics in essentially the following form: The change in the entropy of a system interacting with its surroundings always increases. Every event that occurs in the world results in a net increase in entropy. Although energy is con-

THE LAWS OF THERMODYNAMICS

FIRST LAW, CONSERVATION OF ENERGY: Energy is neither created nor destroyed; it simply changes from one form to another. Although energy can be changed into different forms, the total energy of an isolated system remains the same. (James Joule and Julius von Mayer)

SECOND LAW, ENTROPY AND IRREVERSIBILITY: Energy available after a chemical reaction is less than that at the beginning of a reaction; energy conversions are not completely efficient. Also, the natural tendency is for heat to flow from hot bodies to cold bodies and not the reverse. (Rudolf Clausius, Sadi Carnot, Lord Kelvin)

THIRD LAW, NERNST HEAT THEOREM: It is impossible to reach a temperature of absolute zero; close to that temperature, matter exhibits no disorder; if one could reach absolute zero, all bodies would have the same entropy, or zero-point energy. (Walther Nernst) served, an increase in entropy means a reduction in available ordered energy for doing work in the future. Elucidated this way, the second law of thermodynamics is of utmost importance because it imposes practical restrictions on the design and operation of numerous important systems, including gasoline and diesel engines in motorized vehicles, jet engines in airplanes, steam turbines in electric power plants, refrigerators, air conditioners, heat pumps, and the human body.

Impact

Because energy conversion is an essential aspect of human technology and of all plant and animal life, thermodynamics is of fundamental importance in the world. The work of Clausius in formulating the second law of thermodynamics laid the framework for modern thermodynamics. The practical significance of his formulation of the second law was recognized on several occasions during his lifetime. He was elected to the Royal Society of London in 1868, received the Huygens Medal in 1870, the Copley Medal in 1879, and the Poncelet Prize in 1883.

Lord Kelvin, who was also instrumental in the development of thermodynamics, pointed out that the principles of heat engines were first correctly established by applying Clausius's second law of thermodynamics and his statement of the first law of thermodynamics. The contributions of Clausius to thermodynamics also formed the basis for future interpretations of the second law of thermodynamics by Ludwig Boltzmann and others in terms of probability, which led to the development of the field of statistical mechanics.

The field of modern thermodynamics and statistical mechanics that evolved from the work of Clausius and other prominent scientists provides immense insights into how the everyday world works, with applications to engineering, biology, meteorology, electronics, and many other disciplines. The operation of engines and the limits on their efficiencies, the operation of refrigerators and the limits on their coefficients of performance and energy efficiency ratings (EER), the function of semiconductors in solid-state circuits as a function of temperature, and the analytical aspects of the human body operating as a thermodynamic engine or fuel cell as it extracts some of the energy released when sugars are metabolized into carbon dioxide and water—all are based on Clausius's formulation of the second law of thermodynamics and his statement of the first law of thermodynamics. Energy-conversion research and the development of alternative energy resources, including solar energy systems, biomass systems, and nuclear power plants, are also dependent on an understanding and application of Clausius's insights into thermodynamic processes and the fundamental laws that govern them.

See also Boyle's Law; Kinetic Theory of Gases; Thermodynamics: Third Law.

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—*Alvin K. Benson*

THERMODYNAMICS: THIRD LAW

THE SCIENCE: Walther Nernst showed that it is impossible to reach a temperature of absolute zero and that, close to that temperature, matter exhibits no disorder. Together, these two statements are known as the third law of thermodynamics.

THE SCIENTISTS:
Walther Nernst (1864-1941), German physicist
Sir James Dewar (1842-1923), English physicist
Heike Kamerlingh Onnes (1853-1926), Dutch physicist

Reaching Very Low Temperatures

Beginning in the 1870's, scientists were able to achieve temperatures lower than –100° Celsius by allowing gases to expand rapidly. At such low temperatures, the gases themselves often became liquid and could be used to cool other materials to similar temperatures. Work in this area led to the idea of "absolute zero," which was the lowest temperature possible. That temperature was –273° Celsius (0° Celsius is the temperature of an ice-water mixture). During the next thirty years, physicists such as Sir James Dewar tried to see how closely they could approach absolute zero. In trying to reach absolute zero, Dewar invented new equipment for cooling gas and for storing it after it had been liquefied.

Scientists also studied the properties of matter at such very low temperatures, and in doing so they came to two conclusions. First, the closer one approached absolute zero, the more difficult it became to go any lower. This was the result of a combination of practical problems. For example, the colder a sample of matter became, the more rapidly heat leaked into it and warmed it up. Also, at very low temperatures, the liquid gases that were used in the cooling process actually froze into solids, thereby becoming useless in any further cooling. The second conclusion was quite unexpected: At these extremely low temperatures, many properties of matter and energy changed in ways that seemed to contradict existing ideas.

Approaching Absolute Zero

Physicists began asking what led to such dramatic changes, and they also wondered whether it was possible to achieve absolute zero. More than any other physicist of his generation, Walther Nernst was able to provide important answers to these questions. Together, some of these answers became known as the third law of thermodynamics.

To understand the third law of thermodynamics, it is necessary to consider the first two laws. Thermodynamics is the study of a number of forms of energy, including heat energy, mechanical energy, and the energy associated with the orderliness of things. This last kind of energy is called "entropy." More exactly, entropy reflects the degree of disorder that exists; a decrease in orderliness produces an increase in entropy. An example of order is the way in which molecules are arranged in a crystal. An example of disorder is the chaotic way that molecules are scattered in a gas. The first law of thermodynamics states that different forms of energy have to add up: If one kind of energy increases, another kind must decrease. The second law, which is concerned with entropy, states that, in any process, some energy is lost through an increase in disorder. The third law also says something about entropy: As temperature approaches absolute zero, entropy also approaches zero. Thus, at absolute zero, all disorder vanishes.

Walther Nernst was a great experimentalist and an even greater theoretical physicist, and his development of the third law enabled him to combine the two talents. He made ingenious heat measurements at different

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temperatures close to absolute zero. He also thought deeply about his results and reached a conclusion of great importance. He realized that, at lower and lower temperatures, the total energy of a system becomes more and more nearly equal to its heat energy. In such a case, the total energy is the sum of heat energy and entropic energy. Therefore, if the total energy and heat energy become equal, entropy cannot exist.

This conclusion was astonishing to most of Nernst's contemporaries, who believed that at absolute zero all energy, and not just entropy, became zero. In fact, a certain amount of energy remained at absolute zero. Also, if entropy was zero, then the system was completely ordered. This makes sense, since at zero, even gases would exhibit a solid, crystalized state.

There was also, however, an additional consequence of zero entropy. Nernst realized that, in the process of achieving low temperatures by means of gas expansion, the drop in temperature resulted from converting heat energy into entropy. Therefore, the closer one approached zero (where entropy became zero), the more difficult it became to perform this conversion, and no number of steps could ever reach absolute zero. Thus, the third law makes two statements that seem to be different but are, in fact, closely related: First, as absolute zero is approached, entropy also approaches zero; second, it is impossible to reach absolute zero.

IMPACT

Nernst's work indicated that quite unexpected things happened at temperatures approaching absolute zero. During the next few years after Nernst's discoveries, additional surprises were in store, many of which were discovered in the laboratory of Kamerlingh Onnes in the Netherlands. For one thing, it was discovered that the electrical resistance of certain metals falls suddenly to zero at a specific temperature, a result that had not been predicted by existing theories. Such "superconductivity" has led to a new understanding of the way in which matter is constructed.

Superconductivity has become important in such practical applications as the efficient transmission of electrical power and the construction of powerful magnets that do not dissipate their power in useless heat. Also, when helium gas is liquefied (at approximately 2° Celsius), it proves to flow much more easily than other "normal" liquids do; this phenomenon is called "superfluidity."

The list of unexpected phenomena that manifest at very low temperatures is a long one, and it will probably grow longer. Some of the most significant advances in physics have come from studies of extremely low temperatures, and Walther Nernst's insights continue to provide important guidance to low-temperature physicists.

See also Boyle's Law; Kinetic Theory of Gases; Thermodynamics: First and Second Laws.

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—*John L. Howland*

TROY

THE SCIENCE: Restlessly energetic, ruthlessly self-promoting, wealthy businessman and amateur archaeologist Heinrich Schliemann's excavations of ancient Troy made him a legendary figure.

THE SCIENTISTS:
Heinrich Schliemann (1822-1890), sensational excavator
Frank Calvert (1828-1908), first identifier of site of Troy

A SELF-MADE SELF-PROMOTER

Son of a lowly schoolmaster and clergyman in the north German area of Mecklenburg-Schwerin, Heinrich Schliemann mythologized much of his own life. Apparently his childhood was harsh and his schooling minimal, destining him for a career in trade. He was, however, bright and industrious, a voracious reader with an early flair for languages; he supposedly learned a dozen or so through his years.

He learned business clerking in Amsterdam and at twenty-two joined a major mercantile firm. Sent to Russia, he became a very successful commodities dealer in St. Petersburg. Following family footsteps to California during the gold rush, Schliemann opened a bank there to trade in prospectors' gold. Back in St. Petersburg, Schliemann married a Russian woman, with whom he had three children. During the Crimean War (1853-1856), he profited enormously from dealings in wartime commodities. He made another fortune in cotton and other products during the American Civil War. Several rounds of international travel and the frequenting of museums had stimulated his interest in past cultures. On one tour, he carried off a stone from the Great Wall of China, fascinated by the structure.

Homeric Studies

Sufficiently wealthy to retire from business by age forty-one, Schliemann hungered to enter some area of scholarly endeavor. In Paris he pursued some formal studies, making intellectual contacts, reading widely, and developing a taste for antiquities. The science of archaeology was still in its infancy, and Schliemann was drawn to it as much as a collector as for scholarly discovery. Beginning a new tour of Mediterranean lands in early 1868, Schliemann studied early archaeological undertakings in Rome and Pompeii. It was the world of early Greece, however, to which he was most attracted.

Like any well-read person of the day, he was deeply familiar with the Homeric epics, and like a good Romantic of his time he was prepared to accept them as factual accounts—even though serious scholars had long rejected them as a pack of legends. Identifying himself with the wandering Odysseus, Schliemann proceeded to the Ionian island of Ithaca, where he made his first primitive venture into some archaeological digging, on what he imagined was the site of Odysseus's palace.

Hungering for new sites and objects, Schliemann stopped in Athens, where a local scholar suggested the Troad at the Dardanelles, the northwestern corner of Asia Minor, in the heartland of the Ottoman Empire (now in Turkey). Schliemann was directed to the hill of Pinarbashi (Bunarbashi), which some antiquarians thought was the site of ancient Troy, and he was advised to consult a local expert, the Englishman Frank Calvert, then American vice-consul for the region. Making his way there in

August of 1868, Schliemann initially avoided Calvert, reconnoitering and then undertaking some ill-defined and fruitless excavations at Pinarbashi. Only when about to leave did he meet Calvert. The latter had spent years exploring the area's topography and sites. First interested in Pinarbashi, he had come to reject it as the site of Troy, which he now firmly believed was the hill called Hisarlik. He had even purchased a portion of the hill and wanted to excavate it himself but lacked financial means.

Hisarlik: Undisciplined Excavations

Calvert gave Schliemann a crash-course in what Hisarlik represented. Calvert recognized that this wealthy enthusiast had the means to do what he himself could not afford to do, while Schliemann recognized a golden opportunity at hand. In proposing a partnership with Schliemann, however, Calvert not only shared his dream but sacrificed it to an opportunist whose character he had not understood.

While months were spent in correspondence and securing permissions from the local Turkish authorities, Schliemann began consolidating his standing. He published a book exaggerating his work on Ithaca but staking his claims as a serious archaeologist. With that he secured an honorary doctorate from the University of Rostock, thus acquiring an instant scholarly stature that Calvert, the gentleman-antiquarian, lacked. Moreover, in a quick trip to the United States, Schliemann took out American citizenship, which he used deviously to obtain a divorce from the Russian wife who had refused to follow him in his adventures. Thus freed to extend his philhellenism, Schliemann found himself a new Athenian bride in Sophia Engastromenou, all of seventeen years old to his forty-seven.

In April, 1870, Schliemann began serious excavations at Hisarlik. From the start, he engaged in constant duplicity, breaking agreements with Calvert and practicing forms of digging that were clear vandalism by modern archaeological standards. Ignoring Calvert's advice, he had large

The Mask of Agamemnon, from one of the Trojan excavations.

trenches dug, culminating in a huge north-south gash across the hill. The successive campaign years turned up numerous finds that reinforced the identification with Troy. However, Schliemann was quite unprepared for the complex layering of strata in his quest to identify the Troy of Homer's King Priam. Further conflicts developed over Schliemann's cheating Calvert out of his share of treasures, and there was even a rupture between them when Calvert argued in print against reckless interpretations of the site that Schliemann was circulating in his orgy of self-serving publicity.

Priam's Treasure

The climax of Schliemann's excavations came on May 31, 1873, when Schliemann came upon a body of copper and gold objects, including jewelry. This trove he proclaimed Priam's treasure, reporting that it was recovered with the help of his wife. In fact, Sophia was back in Athens at the time. Some critics have even speculated that the "treasure" was a plant—objects Schliemann had purchased on the black market and sequestered on the site for "discovery." Defying his contract with the Turkish government, Schliemann smuggled these objects out to Athens, to install them in his home there for exhibition and photography. A picture of his wife bedecked in "Helen's Jewels" was circulated worldwide as the peak of Schliemann's self-promotion. These treasures eventually found their way to Berlin, from which they were carried off into obscurity by the Russians after World War II; in 1993 it was finally revealed that they were preserved at Moscow's Pushkin Museum.

Schliemann faced fury and long legal actions from Constantinople, and only after a financial settlement was he allowed further access to Troy. In 1874, Schliemann published in book form his excavation reports, in which he consolidated his fame as the discoverer of Homer's Troy, in the process burying any credit due Calvert. Indeed, in his autobiographical writings, Schliemann even appropriated from Calvert the story that he had nourished since childhood about his determination to find and reveal Homer's Troy.

On the basis of his sensational work at Troy, Schliemann was allowed to conduct excavations in Greece at Mycenae in 1876, where he cleared the grave circle and discovered its famous burial masks. In 1878-1879, after an uneasy reconciliation with Calvert, Schliemann pursued new excavations at Troy. He also ventured some further "Homeric" explorations at Ithaca (1878), Orchomenos (1881), and Tiryns (1884-1885), while continuing his prolific outpouring of writings and publications. A celebrity of worldwide standing and now one of the great men of Greece, he built a grand mansion in downtown Athens for himself and Sophia; it still stands.

Still, the perplexities of Troy drew him, and, with Calvert's collaboration, Schliemann undertook new explorations of the area in 1882. He continued involvement with the site, attending an international conference held there in 1889 to clarify the identity of Hisarlik. His plans for further investigations in 1890 were cut short unexpectedly by his death during a visit to Naples. Schliemann's remains were brought back to Athens and buried in a grandiose neoclassical mausoleum on a hilltop in the city's main cemetery.

IMPACT

The tangled explication of the various layers of Hisarlik's settlements was resumed by Schliemann's assistant, Wilhelm Dörpfeld, and continue to the present day, all on a more scientific scale. Schliemann did demonstrate that the stories of the Trojan War corresponded to tangible evidence and that Hisarlik was the site of the ancient Troy, but his brutal excavation techniques ironically destroyed much of what remained of the city of the Trojan War. Acclaimed as "the father of archaeology," Schliemann awakened a broad public to this new science, but his methods now evoke horror, while his shameful suppression of Calvert's role is now evident.

See also Dead Sea Scrolls; Pompeii; Rosetta Stone; Stonehenge.

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—*John W. Barker*

UNIFORMITARIANISM

THE SCIENCE: James Hutton's "dynamic equilibrium"—the theory that Earth's formation was the result of a cyclic process of erosion and uplift which, in turn, was the result of the compounding of the ordinary action of water and heat in geologic time—laid the foundation for Charles Lyell's uniformitarian geology and established the "deep time" necessary to Charles Darwin's evolutionary theory.

THE SCIENTISTS:

James Hutton (1726-1797), a Scottish natural philosopher
John Playfair (1748-1819), a Scottish geologist and mathematician, and chief popularizer of Hutton's theory
Sir James Hall (1761-1832), Scottish geologist and chemist
Abraham Gottlob Werner (1750-1817), a professor at Freiburg Mining Academy
George-Louis Leclerc, Comte de Buffon (1707-1788), a French naturalist

HUTTON'S DURABLE EARTH

On March 7, 1785, members of the Royal Society of Edinburgh assembled to hear a much-anticipated paper. Its author, James Hutton, was ill that day and had chosen his closest friend, the renowned philosophical chemist Joseph Black, to deliver the first part of a new theory in a work titled "Concerning the System of the Earth, Its Durability and Stability." Four weeks later, on April 4, Hutton had recovered sufficiently to present the second part of his theory. In July, he privately printed and circulated an abstract of the paper. Eventually, in 1788, the full ninety-five-page manuscript from which Hutton's papers had been drawn was published in the first volume of the *Transactions* of the Royal Society as "Theory of the Earth: Or, An Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe."

Hutton's paper was written in the context of a well-established consensus in eighteenth century geological science. The French naturalist Georges-Louis Leclerc, the comte de Buffon, had provided a general framework for the consensus in the initial volumes of his *Histoire naturelle, générale et particulière* (1749-1789; *Natural History, General and Particular*, 1781-1812), and again in his *Époques de la nature* (1778; the epochs of nature). According to Buffon, the Earth originated as solar matter. As Earth cooled, a universal ocean covered its surface. Sedimentation of materials suspended in this primitive ocean produced rock strata, which were exposed as the ocean receded.

In the 1780's, Abraham Gottlob Werner, a professor at the Freiburg Mining Academy in Saxony, supplemented Buffon's cosmogony with a stratigraphy that distinguished four mineralogical groups according to the order in which they had settled out of the universal ocean. Most primitive were chemical precipitates such as granite. Settling out next, at lower elevations, were heavier materials such as limestone, followed by basalts at still lower elevations and sand and other alluvial deposits. Werner's stratigraphy would potentially accommodate a great variety of geological phenomena and gain widespread acceptance. Indeed, when professor of natural history John Walker offered the first series of lectures in geology at the University of Edinburgh in 1781, it was Werner's stratigraphy that he introduced.

Plutonism Joins Neptunism

What the audience for Hutton's Royal Society paper heard was an audacious departure from the Wernerian consensus. To be sure, Hutton's theory acknowledged that water was one of the primary agents in geological change. During the 1750's and 1760's, Hutton had been a highly innovative agricultural improver on his Berwickshire estate and knew well the power of erosion. However, for Hutton, water's geological effect was destructive. The action of water could not explain dramatic features of the Earth's topography such as mountain ranges, nor could it adequately explain the presence of unconformities in rock strata.

For these phenomena, Hutton required a more constructive force. A graduate of the University of Edinburgh in 1743, Hutton had had a longtime interest in chemistry and, during the 1740's, he had even invented an improved method of producing the ammonium chloride used in soldering metals. In 1768, Hutton leased his farm and returned to Edinburgh. It was at this time that Hutton developed his friendship with Joseph Black, a pioneer in the study of heat, and Black's former student, James Watt, the inventor of the modern steam engine. These friendships soon suggested to Hutton a second agency in geological change. Subterranean heat, he began to argue, drove the terrestrial machine.

Hutton was combining the so-called Neptunian consensus with a new Plutonism: As does the sea, the underworld could rise and fall. The origins of this conception of dynamic equilibrium again lay in Hutton's own past. As an undergraduate at the University of Edinburgh, Hutton had studied with Colin Maclaurin, one of the eighteenth century's most effective popularizers of Sir Isaac Newton's ideas. In the autumn of 1744, Hutton had begun to study medicine at Edinburgh; in 1747, he had transferred to the University of Paris; and, in 1748, he had enrolled in the center of medical Newtonianism at the University of Leiden, where he completed his medical degree with *Dissertatio physico-medica inauguralis de sanguine et circulatione microcosmi* (1749; *James Hutton's Medical Dissertation*, 1980).

Just as a balance of centrifugal and gravitational forces produced the solar system in Newtonian astronomy, and just as systolic and diastolic forces circulate the blood (or just as the piston pushes and pulls in Watt's double-acting steam engine), uplift complemented erosion in Hutton's system of the Earth. As water dissolved rock, the products of sedimentation accumulated, generating intense heat and pressure. The intense heat and pressure, in turn, caused rapid expansion and uplift. Even as old continents become new oceans, old oceans become new continents.

Dynamic Equilibrium = Uniformitarianism

Hutton's argument had profound implications for eighteenth century geology. Whereas Buffon conceived the history of the Earth proceeding in one direction of greater cooling and erosion, Hutton did for matter in time what Newton had done for matter in space and conceived the laws of motion in terms of reciprocal action and reaction. Whereas Neptunism implied catastrophism, the assumption that the geological processes of the past were of a qualitatively greater magnitude than the geological processes of the present, Hutton's dynamic equilibrium implied a uniformitarianism, in which the observed geological processes of the present were the key to understanding the geological processes of the past. Also, whereas catastrophism offered a way to reconcile biblical accounts of the Creation and the Flood, Hutton entirely ignored Genesis as a source of geological knowledge.

"Deep" Time

Finally, Hutton undercut Werner's stratigraphy. In the years after 1785, Hutton traveled to sites across Scotland—most famously, to the unconformity at Siccar Point—to gather evidence for his theory. This evidence indicated that granite had not originated as an aqueous precipitate but had crystallized from molten magmas. It also revealed that granite, which Werner had made the oldest rock, was in some cases intruded upward into sedimentary strata. Conversely, the evidence also showed the ancient volcanic origin of basalts. By recognizing the igneous origin of many rocks, Hutton reconfirmed that the forces of geological change acted uniformly in past and present. He also reconfirmed that geological processes did not work in one direction and, therefore, no inherent limit could be set regarding Earth's geological history. In short, Hutton had discovered deep time. "We find," Hutton famously concluded in his 1788 paper, "no vestige of a beginning, —no prospect of an end."

IMPACT

James Hutton extended the Scottish tradition of conjectural history to the economy of nature. From the perspective of deep time, cycles of dissolution and composition succeeded one another in a spontaneous and, ultimately, benevolent order. As if by an invisible hand, the nearly imperceptible action of heat and water shaped the grandest features of the physical environment. Still, for all the assurance of durability and stability, Hutton's theory faced intense criticism in the years after 1788. The specter of the French Revolution rendered Hutton's defense of design an invitation to atheism, his understanding of nature's uniformity an incitement to political turbulence.

In 1795, a very ill Hutton attempted to rebut these charges in the two sprawling volumes. Most responsible for keeping Huttonian geology before a scientific public, however, were his two companions on the trip to Siccar Point in 1788, the chemist and geologist James Hall and the mathematician John Playfair. Under the pressure of criticism, Hutton's geology underwent its own reconstruction. In a series of ingenious experiments between 1798 and 1805, Hall proved aspects of Hutton's theory, demonstrating, for example, the thermal metamorphosis of limestone into marble. In 1802, geologist Playfair published *Illustrations of the Huttonian Theory of the Earth*. Beautifully presented in compelling prose, Playfair's illustrations were no longer organized as mere proofs of an a priori theory but as the empirical foundation for a historical narrative.

It was Hall's experimental and Playfair's empirical Huttonianism, that, in 1830, provided the precedent for the scientific uniformitarianism of British geologist Charles Lyell's *Principles of Geology* (1830-1833). It was the same Huttonianism that, in 1859, provided two crucial elements to the variational evolution of Charles Darwin's *On the Origin of Species by Means of Natural Selection*: the notion that evolutionary change could take place by an incremental accumulation of small variations and the discovery of time that allowed this slow agency to work.

See also Continental Drift; Earth's Core; Earth's Structure; Fossils; Geologic Change; Geomagnetic Reversals; Hydrothermal Vents; Mass Extinctions; Microfossils; Plate Tectonics; Radiometric Dating; Seafloor Spreading.

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—Charles R. Sullivan

VAN ALLEN RADIATION BELTS

THE SCIENCE: James Van Allen pioneered the use of artificial satellites for Earth studies, which led to the discovery of electrically charged particles trapped within the Earth's magnetic field.

THE SCIENTISTS:

James Van Allen (b. 1914), American physicist and naval officer

REACHING TOWARD SPACE

Until the late 1950's, studies of the Earth's magnetic field could be performed only from the Earth's surface. This hindered the understanding of how the field is generated, as well as the determination of the field's shape and strength and the volume of space that it occupies. This changed, however, with the development of artificial satellites. The V-2 rockets used by the Germans during World War II (1939-1945) to destroy English cities could reach an altitude of 100 kilometers. Although they did not reach the speeds necessary to place a satellite in orbit, they were a step in the right direction. After the war, captured German scientists and rockets provided the basis for the United States' space efforts.

James Van Allen started studying cosmic rays as an undergraduate. He received his Ph.D. in 1939. During the war, he served as a naval officer and worked on a proximity fuse for artillery shells. This device used a radar signal that emanated from the shell once the shell had reached its target, triggering the fuse that caused the shell to explode. Van Allen worked to miniaturize the electronic components needed for the small confines of the shell.

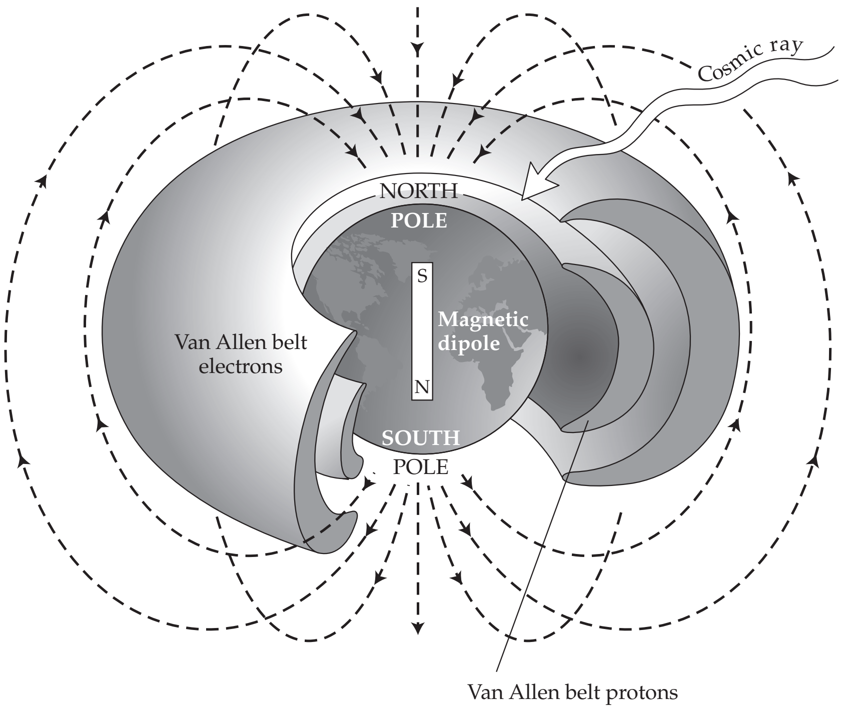
After the war, Van Allen worked to reduce the instrument packages being sent aloft in the captured V-2 rockets. These rockets could go higher because they were now lifting smaller payloads, but they were still not capable of placing these payloads into permanent Earth orbit. By 1954, however, Van Allen and his colleagues began talking about the possibility of using the larger, more powerful rockets that were then under development. In 1955, President Dwight D. Eisenhower announced that the United States would launch an artificial satellite within two years.

Scientists designated the time period from July 1, 1957, to December 31, 1958, as the International Geophysical Year. During this time period, the Earth and its surrounding area were to be studied intensely by scientists around the world to learn more about the planet. The Soviets announced their intention to launch an artificial satellite as part of this study. On October 4, 1957, they launched Sputnik 1 into Earth orbit.

Beyond the Limits

Van Allen's war experience proved to be invaluable in reducing the weight of experiments launched by the United States' less powerful rockets. Although the payloads were smaller, they were more sophisticated because of the efforts of Van Allen and others. On July 26, 1958, the United States included a Geiger-Müller counter in its launch of the Explorer 4 satellite to detect space radiation. When the counter's radio signal was transmitted to Earth for analysis, it did something strange: It increased to a maximum, decreased to zero, and then increased again to maximum. Van Allen correctly interpreted this not as a result of an actual decrease in radiation but as a result of the instrument's inability to handle high levels of radiation. This is analogous to the distortion one hears when the volume of a radio is turned too high, driving the electronics beyond their design limits.

Further study revealed the nature of the radiation. The Earth's magnetic field temporarily traps electrons and other electrically charged particles emitted by the Sun. These particles constantly flow from the Sun and are known as the solar wind. Some of the particles also may come from Earth's upper atmosphere as its gases interact with the solar particles. The Earth's magnetic field fans out at the magnetic pole in the Southern Hemisphere, arcs over Earth's equator, and converges on the magnetic pole in the


The Van Allen Radiation Belts

Northern Hemisphere. The field is strongest at the poles and weakest halfway between them. Particles such as electrons enter the field and spiral along the field lines. As the field strength increases near the poles, the particles bounce off this area and spiral toward the opposite poles. The particles may perform this spiral bounce motion many times before escaping into outer space.

There are two broad bands, or “belts,” in the Earth’s magnetic field that have high radiation levels. Aligned with the center of Earth, they are both doughnut-shaped, with crescent-shaped cross sections. The inner belt begins at 3,000 kilometers above the Earth’s surface and is at its thickest portion at 5,000 kilometers. The outer belt is 16,000 kilometers from the Earth’s surface and is 6,500 kilometers thick. Although the electrically charged particles consist mostly of electrons, the inner belt does contain some protons and other particles. In honor of Van Allen’s discovery, these belts of high radiation were named the Van Allen radiation belts.

IMPACT

Orbiting satellites provide a very convenient method for communication, navigation, and Earth monitoring. As more satellites are placed in orbit, however, convenient orbital paths are filling up, creating the need to expand space usage farther from Earth. The Van Allen radiation belts complicate this goal because their high levels of radiation require the use of extra shielding for the satellite's instruments, thereby increasing the mass of the payload.

The spiraling and bouncing behavior of the particles in the field may provide an idea for a solution to the energy crisis. Because convenient energy sources are being depleted, other methods must be found for generating the needed energy. One possibility is the fusion of hydrogen nuclei into helium, a process that releases huge amounts of thermonuclear energy. For fusion to occur, however, high temperatures of millions of degrees are needed. No material known is capable of containing such heat. It is, however, possible to produce a magnetic "bottle," in which the high-temperature hydrogen plasma spirals along the field and bounces at the ends of the "bottle," where the field increases in strength. The idea for such a device was taken from analysis of the Van Allen radiation belts. The magnetic bottle is especially useful in a controlled thermonuclear reaction. This is one example of how discoveries in one field of science may influence work in other areas of science, sometimes to the benefit of all of humanity.

See also Geomagnetic Reversals; Solar Wind.

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—*Stephen J. Shulik*

VERY LONG BASELINE INTERFEROMETRY

THE SCIENCE: Very long baseline interferometry made it possible to study distant regions of the universe that had not been studied before.

THE SCIENTISTS:

Sir Martin Ryle (1918-1984), radio astronomer
Karl Jansky (1905-1950), pioneer radio astronomer

LIMITS OF THE RADIO TELESCOPE

Astronomers have always wanted to study stars, planets, quasars, and other objects that are too far from Earth to be seen with conventional optical telescopes. Scientists discovered that they could learn about distant objects by studying the waves of radiation that those objects emit. They constructed radio telescopes—long, dishlike apparatuses that faced up to the sky and that could collect incoming radiation waves. By studying those waves, astronomers could "see" into distant areas of the universe.

Radio astronomy, which uses radio telescopes to study objects and phenomena in the universe, was "discovered" by Karl Jansky in 1929. At that time, he was working at Bell Telephone Laboratories, studying a strange hiss that could be heard on telephone lines. Using the information he collected with a very crude radio telescope, he discovered that the hiss was caused by radio signals that came from the Milky Way.

After World War II ended in 1945, scientists built bigger and bigger radio telescopes. The largest radio telescope, which was built in Arecibo, Puerto Rico, had a 1,000-foot (300-meter) reflector dish to collect radio waves. Radio telescopes must be large because radio waves, which are a kind of radiation, are much longer than the waves of other kinds of radiation, such as visible light. An ordinary optical telescope collects waves of visible light, which are measured in microns (millionths of a meter). Radio waves, however, can be centimeters (hundredths of a meter) or even meters long. Even the largest single-dish radio telescopes are less accurate than the much smaller optical telescopes are, because the waves they collect are so much longer.

An interferometer is an instrument that studies an object by comparing sets of waves, such as radio waves, that are emitted by that object. Two or more separate radio telescopes can be combined by being connected with a cable to "create" a very large and accurate radio telescope. The large radio telescope that is created in this way is an interferometer, because it can compare the sets of waves collected by the separate radio telescopes. This means that scientists can use two radio telescopes to create a telescope to do the same job that it would take a single, huge telescope to do. The distance between the two original telescopes is called the baseline, so the science of creating and using interferometers in this way is called baseline interferometry.

A WORLD-SPANNING RADIO TELESCOPE

Pioneering scientists such as Martin Ryle, whose work in interferometry earned for him the 1974 Nobel Prize in Physics, wanted to make interferometers that would be even larger, and therefore more accurate, than those that could be made by connecting radio telescopes with a cable. Ryle's development of a technique called "aperture synthesis" made it possible to increase dramatically the accuracy of connected radio telescopes. It was not until the atomic clock was perfected, however, that even larger interferometers could be constructed and the techniques of very long baseline interferometry (VLBI) came into existence.

Using the extremely accurate atomic clock, astronomers at observatories very far from each other could monitor the same radio source simultaneously and record the resulting information on tape, along with the signals from the atomic clock. Later, the clock signals could be used to synchronize the information from the two radio telescopes. The result would be the same as if the two telescopes had been connected physically while they were monitoring the radio source. It was no longer necessary for telescopes to be in direct contact while they were monitoring a radio source.

By using the atomic clock, astronomers can make interferometers of two or more radio telescopes that are many kilometers apart. The maximum baseline that can be used for VLBI is the diameter of the Earth: 12,700 kilometers. With a baseline so large, it is possible to obtain extremely accurate results. In fact, the accuracy, or resolution, of VLBI observations is the same as seeing a pinhead at a distance of 200 kilometers.

Although VLBI technology has provided scientists with very precise information, its techniques are difficult and time consuming to use. For example, when radio telescopes that are very far apart are combined, they must collect signals for a long period of time in order to obtain a high-resolution radio signal. Also, two radio telescopes that are separated by the diameter of the Earth form only two tiny parts of the collector that they are trying to create. They cannot form a proper image, although they can determine whether a radio source does contain much detail. More radio telescopes are needed to create a more complete VLBI collector. The results from six radio telescopes, for example, can produce the most detailed astronomical images that can be formed at any wavelength.

IMPACT

VLBI technology has greatly increased the resolution of radio telescopes. Before VLBI existed, radio astronomy had relatively poor resolution. The increased resolution made possible by VLBI gave astronomers an extremely detailed view of the universe.

With VLBI technology, astronomers can explore objects that were previously too far away to be examined. One example of such objects is quasars, which are quasi-stellar objects that are a source of both visible and radio waves. Quasars are almost starlike in appearance, but they are among the most powerful and most distant sources of energy in the universe. High-resolution VLBI observations have revealed that small, jetlike structures shoot outward from the active regions of many quasars. These "small" jets of matter are only a few light-years long (one light-year is about 9.46 billion kilometers); they are aligned with much larger jets of matter that are often millions of light-years long. The existence and position of these jets of matter indicate that there is some connection between the jets and the quasar cores in which they are probably generated.

The development of VLBI technology promises to give astronomers an even more detailed image of the universe. With this technology, scientists are likely to learn more about both quasars and the mysterious "black holes" (extremely dense and invisible stellar objects) that may be the source of their power.

See also Cosmic Microwave Background Radiation; Ionosphere; Isotopes; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Wilkinson Microwave Anisotropy Probe.

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—*David R. Teske*

VIRUSES

THE SCIENCE: The Dutch bacteriologist Martinus Beijerinck demonstrated that cell-free extracts prepared from plants with tobacco mosaic disease could transmit the infection to healthy plants. The preparation contained what Beijerinck called *contagium vivum fluidum*, infectious material that would only replicate in living tissue, and represented the first evidence for the existence of what became known as viruses.

THE SCIENTISTS:

Martinus Beijerinck (1851-1931), Dutch bacteriologist who demonstrated that viruses require living tissue for replication

Adolf Mayer (1843-1942), Dutch biologist who first demonstrated transmission of a viral disease

Dimitri Ivanovski (1864-1920), Russian biologist who first associated a filterable agent with tobacco mosaic disease

Friedrich Löffler (1852-1915), professor of hygiene who codiscovered the foot-and-mouth disease virus

Paul Frosch (1860-1928), codiscoverer, with Löffler, of the foot-and-mouth disease virus

BEYOND THE GERM THEORY

During the last decades of the nineteenth century, Robert Koch and others discovered that bacteria represented the agents behind many human illnesses, which led to the "germ theory of disease," the idea that most illnesses are caused by bacteria. The ability to grow these organisms on laboratory media played a major role in the formation of Koch's postulates, a series of experimental steps linking a disease with a specific organism.

The growing list of diseases found to be associated with bacterial infections gave rise to a belief that most diseases are the result of infection by such microscopic agents. Vaccines had been developed by the 1880's against what are now known to be virally induced diseases, most notably against smallpox and rabies. However, the reluctance to carry out infection in humans by applying extracts from infected tissues meant that the soluble nature of these agents was overlooked; Koch's postulates could not be applied. The difficulty in growing many viral agents in the laboratory, as well as lack of animal models, would remain a problem in applying Koch's postulates to viral diseases well into the twentieth century.

The first experimental transmission of a viral disease could arguably be attributed to Adolf Mayer, director of the agricultural station at Wageningen in The Netherlands. Mayer had been studying tobacco mosaic disease (TMD), a name he coined, which was having a significant economic impact on tobacco growers. Mayer demonstrated that one could transmit the disease to healthy plants by spraying the sap extracted from diseased plants. He attempted to link bacterial agents he had isolated from the diseased plant with TMD by applying Koch's postulates, but once again the inability to culture any specific organism made this impossible. Since it appeared the agent was removed from the preparation following the filtration step, Mayer incorrectly suggested that the agent was probably a bacterium.

The Russian biologist Dimitri Ivanovski repeated and extended Mayer's work in 1892. Mayer had used a double layer of filter paper to remove any bacteria or other cells from his preparation. Instead of using filter paper, however, Ivanovski prepared cell-free filtrates from diseased tobacco plants while using newly developed porcelain Chamberland filter-candles. He was able to transmit the disease to healthy plants even in the absence of bacteria. Ivanovski's conclusion was that a toxin was probably associated with the disease, reflecting the recent discovery by Emil Behring of the relationship between a toxin and human diphtheria. As late as 1903, Ivanovski maintained that the agent behind TMD was probably a bacterium that could not be cultured.

A Contagious Living Fluid

Martinus Beijerinck was probably unaware of Ivanovski's earlier work on the nature of the tobacco mosaic disease agent. In 1898, Beijerinck was collaborating with Mayer in the study of the disease, and he repeated the filtration experiments that, unknown to him, were first conducted six years earlier by Ivanovski. Beijerinck's conclusion was that the sap contained a *contagium vivum fluidum*, a contagious living fluid.

In a more detailed analysis of the agent, Beijerinck first demonstrated it would not grow on the culture media generally used to grow or maintain bacteria. Nor would the agent grow in the sap itself. Beijerinck concluded the agent could not be a bacterium. Further, he found the agent was capable of diffusing through agar, indicating that it was a soluble substance and that it was stable over a period of months even when dried. His work was reported in a publication later that same year.

Beijerinck also carried out studies on the development of tobacco mosaic disease itself. He observed the agent spread through the plant through the phloem, and he noted that it had a preference for young, growing leaves. By passing the sap from plant to plant, Beijerinck demonstrated that it was capable of reproduction—unlike a toxin, which would have lost viability as it became diluted. Beijerinck's conclusion—that the TMD agent was neither bacterial in nature nor a toxin, but that it required living tissue in which to reproduce—set his work apart from that carried out earlier by Ivanovski. Beijerinck correctly has been given priority in the discovery of viruses.

Viruses Need Living Tissue

Shortly after the work by Beijerinck on TMD, the first demonstration of a disease in animals that could be transmitted by cell-free extracts was achieved. Friedrich Löffler, head of a Prussian Research Commission for the study of foot-and-mouth disease, and his collaborator Paul Frosch, a colleague of Robert Koch at Koch's Institute of Infectious Diseases in Berlin, transmitted the disease using extracts from vesicles isolated from infected cattle. Clearly, agents too small to be observed with standard microscopes, and which required living tissue in which to replicate, were associated with diseases.

Tobacco mosaic virus went on to play a major role in the nascent field of virology. It was the first virus to be purified free from host tissue (1935). Also—unlike most organisms, in which DNA was determined by the 1940's to be the genetic material—TMV was the first agent found to contain RNA as a genome.

Impact

Though Beijerinck was not the first to observe the role for a filterable agent as an etiological agent for (plant) disease, he demonstrated that the agent could not be grown in culture media, which likely meant it was not a bacterium. Further, the fact the filterable agent could be shown to multiply eliminated the possibility of its being a toxin. Beijerinck's definition of the *contagium vivum fluidum*, however, could not imply an understanding of a "virus" in the same context as would later be determined. The modern concept of a virus required a leap in understanding that was premature for the science of the day.

Beijerinck's discoveries were particularly significant in that he demonstrated that the agent required living tissue in which to reproduce. Shortly afterward, Löffler and Frosch reported that an analogous agent was associated with foot-and-mouth disease in animals. This led to a twenty-five-year debate over the nature of such "viruses": Were they particles or enzymes? The question was settled only with the independent codiscovery of bacterial viruses by Frederick Twort and Felix d-Herelle, as well as the development of the electron microscope, which allowed viruses to be visualized.

During these same decades, filterable agents were also demonstrated to be etiological agents of human or other animal diseases such as yellow fever, polio, rabies, and possibly even cancer. None of these "organisms" could be grown on laboratory media; they could only be shown to replicate in the animal itself. Scientists gradually came to the conclusion that viruses represented a form of "life" that could not be considered as either animal or plant.

See also AIDS; Human Immunodeficiency Virus; Hybridomas; Immunology; Oncogenes; Polio Vaccine: Sabin; Polio Vaccine: Salk; Smallpox Vaccination; Yellow Fever Vaccine.

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—*Richard Adler*

VITAMIN C

THE SCIENCE: Albert Szent-Györgyi isolated "hexuronic acid," a substance that years later was proven to be vitamin C.

THE SCIENTISTS:

Albert Szent-Györgyi (1893-1986), Hungarian biochemist who won the Nobel Prize in Physiology or Medicine in 1937

Charles Glen King (1896-1988), American biochemist and nutritionist

Joseph L. Svirbely (1906-1995), American chemist

ORANGES AND OXEN

Vitamin C is both a complex chemical substance and the physiological linchpin in the deficiency disease scurvy. Physicians in the Middle Ages had recognized some aspects of this disease, which was characterized by weakness, swollen joints, a tendency to bruise easily, bleeding from the gums, and the loss of teeth. It was not until the eighteenth century, however, that the Scottish physician James Lind recognized that these symptoms constitute a disorder caused by defective nutrition. His experiments on sailors during long ocean voyages showed that the ingestion of certain fruits and vegetables could cure the disease.

The most significant step toward the discovery of vitamin C was made in 1907, when Axel Holst, a bacteriologist, and Theodor Frölich, a pediatrician, published their discovery that, through dietary manipulations, a disease analogous to human scurvy could be generated in guinea pigs. (Like humans and unlike most animals, guinea pigs do not manufacture their own vitamin C.) When Holst and Frölich fed hay and oats (foods deficient in vitamin C) to guinea pigs, the animals developed scurvy, but when they were fed fresh fruits and vegetables, they remained healthy. In this way, Holst and Frölich were able to measure a food's ability to prevent scurvy.

Albert Szent-Györgyi. (The Nobel Foundation)

While other scientists were trying to isolate vitamin C directly, Szent-Györgyi actually found the substance in the course of searching for something else. In the 1920's, his research centered on biological oxidation, that is, on how cells oxidize various foodstuffs. He was particularly entranced by the observation that some plants (apples and potatoes) turn brown after being cut and exposed to air, whereas others (oranges and lemons) experience no color change.

Szent-Györgyi suspected that a certain substance was controlling these color-change reactions, and he looked for it not only in fruits and vegetables but also in the adrenal cortex of mammals. He believed that the color change to a bronzelike skin in patients with Addison's disease (a disorder of the adrenal gland) was associated somehow with the color changes in plants. He hoped to isolate this substance, a powerful reducing agent, from the adrenal glands.

Unfortunately, his research was plagued with problems until he met the English biochemist Frederick Gowland Hopkins at a conference in Sweden in 1926. Hopkins was interested in vitamins and biological oxidation, and he invited Szent-Györgyi to the University of Cambridge to continue his research. Using many glands from oxen, Szent-Györgyi was able to separate a reducing agent from all other substances present. He also was able to obtain the same substance from orange juice and cabbage extracts, a result that his colleagues found most surprising.

"Godnose"

Through chemical analysis, he determined that the substance contained six carbon atoms and eight hydrogen atoms and that it was a carbohydrate related to the sugars. He initially wanted to name the substance "Ignose" (from the Latin *ignosco*, meaning "I don't know," and *ose*, the designating suffix for sugars). The editor of the *Biochemical Journal* thought that the name was too flippant, however, whereupon Szent-Györgyi suggested "Godnose," which was similarly rejected. Because the substance contained six carbon atoms and was acidic, he and his editor agreed on the name "hexuronic acid." News of the discovery of this acid was published in 1928.

At the time, scientists recognized five distinct vitamins. They had failed, however, to isolate any of them successfully. For this reason, it was not clear that Szent-Györgyi's hexuronic acid and vitamin C are the same substance.

In the fall of 1931, Joseph L. Svirbely, a postdoctoral student, arrived at Szeged, Hungary, where Szent-Györgyi had gone to continue his studies of vitamin C. Svirbely had done his doctoral studies on vitamin C under Charles Glen King at the University of Pennsylvania. King was trying, with limited success, to isolate vitamin C from lemon juice. He was testing his results with time-consuming experiments using animals.

Svirbely provided a bridge between King's work and Szent-Györgyi's. Szent-Györgyi had not previously tried to prove that hexuronic acid was identical to vitamin C because he did not enjoy working with animals. Furthermore, he was against vitamin research (he once said that vitamins were problems for the chef, not the scientist).

Nevertheless, when Svirbely mentioned that he could tell if something contained vitamin C or not, Szent-Györgyi gave him some of his hexuronic acid for experimentation. In a fifty-six-day test using guinea pigs, Svirbely established, in the fall of 1931, that the animals without hexuronic acid in their diets died with symptoms of scurvy, while the animals receiving hexuronic acid were healthy and free from scurvy. Further experiments in 1931-1932 proved once and for all that hexuronic acid and vitamin C are identical.

Impact

The isolation of vitamin C generated widespread comment and convinced most scientists that the long-sought vitamin had been found. Vitamin C's impact was deepened and extended by Szent-Györgyi's discovery in 1933 that Hungarian red peppers contained large amounts of the vitamin. Whereas previously biochemists could make only minuscule amounts of the material with great difficulty, Szent-Györgyi now could produce the substance in great quantities. In his lectures about his work, he liked to hold up a bottle containing several kilograms of the vitamin. To scientists accustomed to thinking of vitamins solely in extremely minute amounts, this was a surprising and enlightening experience.

In the 1930's, the League of Nations set up a committee to establish international standards for the vitamin, and the committee recommended that individuals ingest at least 30 milligrams each day to prevent scurvy. The vitamin came to be known as "ascorbic acid" for its property of combating scurvy. In the period during and after World War II (1939-1945), some scientists suggested that dosages larger than the recommended 30 milligrams would help keep humans in the best possible health. Many people, convinced that modern food processing was destroying vitamins, began to supplement their diets with vitamin pills, and some industries began to fortify their products with vitamins.

Beginning in 1965, Nobel-Prize-winning chemist Linus Pauling became interested in the megavitamin theory popularized by industrial chemist Irwin Stone in 1960. Pauling suggested that many maladies, from schizophrenia to cancer to the common cold, could be treated and prevented by large doses of vitamins. Pauling's books and articles created an ongoing controversy, guaranteeing that this fascinating substance, discovered through the efforts of Szent-Györgyi and others, will continue to provide subjects for rewarding scientific research well into the future.

See also Vitamin D.

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—Robert J. Paradowski

VITAMIN D

THE SCIENCE: Elmer McCollum and collaborators established the existence of vitamin D, named it, and contributed to its use in the eradication of rickets.

THE SCIENTISTS:

Elmer Verner McCollum (1879-1967), American biochemist and nutritionist who carried out pioneering research on vitamin D, vitamin A, and the B vitamins

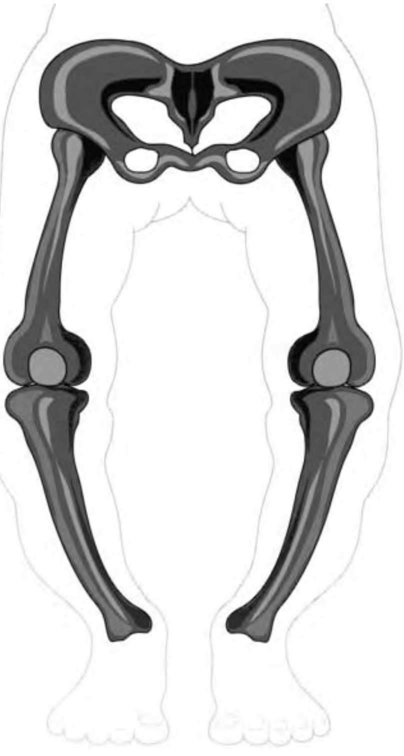
Thomas Burr Osborne (1859-1929), nutritionist under whom McCollum worked at the Connecticut Agricultural Station

John Howland (1873-1926), the physician-in-chief of pediatrics at The Johns Hopkins Hospital who collaborated with McCollum in several studies of rickets

Rickets

Rickets (or rachitis) is a disease that causes abnormal bone formation, particularly in the long bones and the ribs. First described in the second century C.E. by Galen of Pergamum and Soranus of Ephesus, rickets was a widespread health problem until discovery and dissemination of the antirachitic factor, vitamin D. Elmer Verner McCollum and coworkers pioneered this effort in 1922, showing that the antirachitic factor was a distinctive substance. They named this substance vitamin D because it was the fourth vitamin to be discovered. The occurrence of rachitis is now rare—except in underdeveloped countries—as a result of the vitamin D fortification of food (especially milk) in the industrialized nations of the world.

The Effect of Rickets



Rickets, which usually begins before age three, is caused by the improper and incomplete uptake of calcium into the fast-growing bones of children. The resultant insufficient calcification of these bones prevents them from hardening properly. Therefore, the bones of a rachitic child are so soft that they bend and twist into abnormal shapes. Furthermore, they will fracture easily. Fortunately, as afflicted children grow up, their bones harden, but the abnormal shapes are retained. Rickets is rarely fatal, but it produces several cosmetically unappealing conditions including curvature of the spine, bow legs, knock-knee, and chicken breast. Rickets sufferers are also unusually susceptible to the common cold, to bronchitis, and to pneumonia.

Daily Requirements

As may be expected, vitamin D is utilized in preventive chemotherapy, not in the correction of rickets. The two most common forms of the vitamin used in humans are calciferol (vitamin D_2) and cholecalciferol (vitamin D_3). These fatlike substances are derived from the steroids ergosterol and 7-dehydrocholesterol (7-DC), respectively. The human body converts 7-DC to cholecalciferol at the surface of the skin in a process that is energized by ultraviolet light from the Sun. Exposure of adults to normal amounts of sunlight causes enough vitamin D_3 production in the skin to make it unnecessary to add any vitamin D to their diet.

Children, however, require about 0.02 milligram of vitamin D per day in the diet if rickets is to be avoided. One way to administer the vitamin is

Rickets on the Rise?

Rickets became rare in the United States after vitamin D supplementation of milk began in the mid-twentieth century. However, rates of incidence began to climb by the end of the century. Case studies of infants and toddlers with rickets found that all were exclusively breast-fed for at least the first six months of life and that few, if any, had received vitamin D supplementation.

It has been recognized for some time that the vitamin D content of human milk from healthy lactating women is low, approximately 22 International Units per liter. The 1998 edition of the *Pediatric Nutrition Handbook* of the American Academy of Pediatrics (AAP) recommended 400 International Units of vitamin D per day for breast-fed infants but indicated that only breast-fed babies with deeply pigmented skin needed vitamin D supplementation. Studies have shown that lactating women, regardless of skin color, who are deficient in vitamin D themselves produce milk with even lower concentrations of vitamin D.

In October, 2001, a meeting in Atlanta was sponsored by the Centers for Disease Control and Prevention (CDC) to examine the issue. Although many attendees of this meeting believed that universal vitamin D supplementation for all breastfed babies might be a good idea, others took the view that supplementation should be targeted toward specific groups. Some attendees worried that formula manufacturers would use supplement recommendations as a tool to encourage women to abandon breast-feeding. However, it was also made clear that in Canada, where vitamin D supplementation of all breast-fed children is advocated regardless of skin pigmentation, the number of women electing to breast-feed had increased.

By 2003, the American Cancer Society, the CDC, and the AAP had united in a campaign to cut the risk of skin cancer by cutting exposure to direct sunlight. The AAP now maintains that the recommended adequate intake of vitamin D cannot be met with human milk as the sole source of vitamin D for the breast-feeding infant and that some form of supplementation is needed.

as the cholecalciferol in cod-liver oil, a rich natural source of the vitamin. Fortification of milk with vitamin D_2 is more widespread today. It is important to note, however, that excess dietary vitamin D should be avoided. The Food and Nutrition Board of the Institute of Medicine has set the tolerable upper intake level for vitamin D at 25 micrograms (1,000 international units) for those up to 12 months old and 50 micrograms (2,000 international units) for children, adults, and pregnant or lactating women.

Early Vitamin Studies

McCollum, who first identified vitamin D and named it, carried out many of the early important studies on this vitamin. McCollum's interest in biochemistry and vitamins began when he worked at the Connecticut Agricultural Experiment Station under Thomas Burr Osborne. This employment occurred during McCollum's doctoral training in organic chemistry at Yale University, and ended when he was awarded the Ph.D. in 1906. In 1907, McCollum was employed by the Wisconsin College of Agriculture, where he was assigned to investigate the chemical makeup of the food and excrement of dairy cattle. There he developed the first white rat colony in the United States devoted to use in the study of nutrition. Utilization of rats as experimental subjects allowed McCollum and his coworkers the opportunity to circumvent the complicated and tedious methodology that was required to study cattle and other large animals. This revolutionary concept of nutritional research was so successful that other scientists all over the world soon began to emulate McCollum's efforts. In six years, McCollum passed through the academic ranks from instructor to full professor.

Elmer Verner McCollum. (National Library of Medicine)

In 1913, McCollum reported that rats fed "certain fat-deficient" diets exhibited a growth retardation that was reversed by feeding rats with "either extract of egg or of butter." By 1915, McCollum's research group had demonstrated that several trace substances, which McCollum called vitamins A and B, were necessary for normal health and growth in rats. Thus, McCollum helped to initiate the alphabetical names used in vitamin nomenclature. In 1917, McCollum became the chair of the department of chemistry and professor of biochemistry at the School of Hygiene and Public Health of The Johns Hopkins University in Baltimore. He continued his efforts to understand the vitamins and pioneered the study of vitamin D, for which he is best known, again using rats for his experiments.

The Line Test

McCollum's pioneering identification of the existence of vitamin D in 1922 was accompanied by development of the line test for its measurement in foods. The line test begins with removal of bone sections (pieces of bone) from rats fed either normal, vitamin D-deficient, or vitamin D-supplemented diets. These bone sections are soaked in dilute solutions of light-sensitive silver nitrate. This treatment causes a silver compound to become a bone component wherever recent bone calcification has occurred. Exposure to light converts the silver compound to black, metallic silver in a process similar to that seen in photography. With normal bone, a very distinct black line is produced at the bone ends. No such line is seen is severe rickets, and indistinct lines are observed in healing cases of the disease. The test is "expressed with a scale of one to four, using plus and minus signs." It is viewed as both sensitive and accurate.

Impact

In 1922, rickets was a worldwide disorder that affected many children. Today, it has essentially been eradicated in developed nations despite fluctuations in its incidence. The successful treatment of the disease began when McCollum and coworkers produced evidence in 1922 that cod-liver oil contained a specific antirachitic chemical (vitamin D). As McCollum stated in *From Kansas Farm Boy to Scientist* (1964): "The demonstration of the existence of a vitamin which exerts a profound influence in directing the growth of bones proved to be of great public-health value."

McCollum demonstrated that this research stimulated great interest among many investigators. Furthermore, the discovery, coupled with the participation of prominent pediatricians in the effort, such as John Howland, led to rapid general acceptance by physicians of the efficacy of using cod-liver oil to prevent rickets. From that time on, the medical profession passed from haphazard use of the oil—in a skeptical fashion—to its routine use. As a result, rickets soon became rare.

Actualization of the existence of the antirachitic substance quickly led to isolation and characterization of vitamins D_2 and D_3. Subsequently, in the hands of other researchers, study of the pure vitamin began to show promise. First, it became possible to add vitamin D_2 to milk to ensure almost universal dissemination of the vitamin among the population of the industrialized countries. Next, it was shown that vitamin D_2 (or D_3) functioned after conversion as another chemical that was actually a hormone (hormone D).

The form of hormone D made by the body, from vitamin D_3 is called 1,25-dihydroxycholecalciferol. Hormone D acts by stimulating rapid intestinal reabsorption of calcium via a protein. This calcium resorption minimizes calcium loss in the feces and prevents the bone decalcification that results in rickets.

Additional examination of the action of vitamin D has led to better understanding of the processes of bone deposition and resorption as well as to explanation of the interrelationships between hormone D and other calcium-controlling substances (such as calcitonin and parathyroid hormone) made by the body. Such investigations have also led to the realization that bone is not simply a "dead," body-support matrix. Rather, bone is a vital, live tissue that can produce dissolved calcium in the blood to serve many purposes.

This realization has had further ramifications, and it is clear that calcium serves as a biological signal in life processes that include control of the blood pressure, blood clotting, nerve impulse transmission, and muscle contraction. Therefore, the acorn of McCollum's efforts had produced a mighty oak tree of intertwined information about life. This information now promises eventual answers to many elusive but fundamental problems of life science that are clearly associated with calcium.

See also Vitamin C.

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—*Sanford S. Singer*

VOYAGER MISSIONS

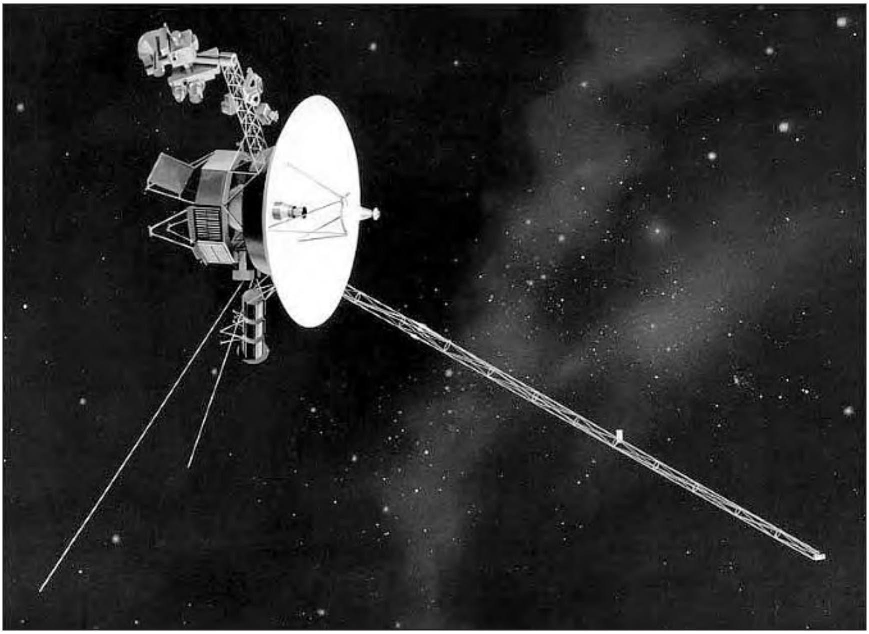
THE SCIENCE: The Voyager probes executed the first Grand Tour in planetary exploration by successively encountering Jupiter, Saturn, Uranus, and Neptune. Such a tour, using the "planetary-gravity-assist" technique to travel from planet to planet, is possible only once every 175 years.

THE SCIENTISTS:

Gary A. Flandro, discoverer of Grand Tour alignments of the outer planets
Charles E. Kohlhase, Principal Mission designer
Donald M. Gray (b. 1929), the navigation team chief of Voyager, NASA, Jet Propulsion Laboratory
Harris M. Schurmeier, Voyager project manager through development phase
John R. Casani (b. 1932), Voyager project manager from launch to Jupiter encounters
Raymond L. Heacock (b. 1928), Voyager project manager for Jupiter and Saturn encounters
Richard P. Laeser, Voyager project manager for Uranus encounter
Norman Ray Haynes (b. 1936), Voyager project manager for Neptune encounter
Edward C. Stone, Jr., Voyager project scientist
Ellis D. Miner (b. 1937), assistant project scientist
Andrei B. Sergeyevsky, principal trajectory designer for the Neptune encounter
Bradford A. Smith, principal investigator, imaging science experiment
G. Leonard Tyler, principal investigator, radio science experiment
Laurence Soderblom (b. 1944), expert on Galilean satellites

THE GRAND TOUR

Often referred to as the "grand tour," the flights of Voyagers 1 and 2 passed the large outer planets of the solar system and returned detailed



Artist's rendition of the Voyager spacecraft. (NASA)

and valuable scientific information. The mission spanned twelve years, from 1977 to 1989.

As the outer planets orbit the Sun, they are, once in a great while, aligned in a pattern that presents an opportunity for a spacecraft launched from Earth to fly past each one of them. Such an alignment occurs only once every 175 years. The fact that the last such favorable planet alignment had occurred during the term of U.S. president Thomas Jefferson was cited by those in favor of the Voyager program. The Voyager missions required a spacecraft designed not only to survive intense radiation but also to be able to detect and react to any problems that might arise. Earth commands would require far too much time for corrective action because of the much greater distance to the outer planets.

VOYAGER 1

Voyager 1 was launched on September 5, 1977. It made its closest approach to Jupiter on March 5, 1979, a year and a half after launch and four months ahead of Voyager 2. (Voyager 2 had been launched on August 20, 1977, sixteen days ahead of Voyager 1.) Passing the planet, it encountered the moons Amalthea, Io, Ganymede, and Callisto and passed to within one million kilometers of Europa, another of Jupiter's moons.

Voyager 1 encountered Saturn and its moons in early November, 1980. The closest approach to the outer moon, Titan, occurred on November 11. It swung beneath Saturn's "ring" system and behind the planet, as viewed from Earth, making its closest approach to the moon Iapetus on November 14, 1980. It then began to travel deeper into space in the direction of the constellation Ophiuchus.

VOYAGER 2

Voyager 2 arrived at Jupiter in July, 1979, with a different trajectory from that of Voyager 1 and at different angles, which permitted photographs of the opposite hemispheres of Callisto and Ganymede, high-resolution images of Europa, and shots of Jupiter's ring. Just as the eighty-hour gravitational tug of Jupiter had propelled the tiny Voyager 2 toward Saturn, so now giant Saturn pulled it into a new direction: directly toward Uranus, a journey of almost four and a half years. As this outward journey from Saturn began, Voyager 2 now became the true trailblazer, going where no spacecraft had ever gone before. It arrived at Uranus on schedule. Then the gravitational pull of that planet bent Voyager's trajectory toward its last assignment, planet Neptune.

Voyager 2 reached Neptune on August 24, 1989, having traveled about seven billion kilometers. That distance was so great that the probe's radio signals required about four hours just to reach Earth. The flyby of Neptune and its moons was a complete success. Approaching the planet, Voyager 2 swung over its north pole and then encountered Triton, Neptune's moon, which has an atmosphere. It then began its one-way trip into deep space, transmitting data as long as its systems remained active.

IMPACT

Both the technological and the scientific successes of the Voyager missions were remarkable and can hardly be overstated. The mechanical and electronic components of the spacecraft functioned exceedingly well over the twelve-year span (1977-1989).

Voyager 1 created an explosion of excitement when it detected a ring around Jupiter. The discovery was unexpected, since no evidence had ever been presented supporting its possible existence. Mission planners had agreed to devote a single photograph to a "one-shot" search for a ring, and luckily that was enough. As for Jupiter's atmosphere, Voyager 1 sent back high-resolution images of the Great Red Spot, which has been observed in Jupiter's upper atmosphere since the early 1800's, showing exquisite detail.

Callisto, the second largest of Jupiter's moons and the most heavily cratered, was determined to have a diameter about one and one-half times that of Earth, although its density is only about one-third as great. This suggested that Callisto is about one-half water and ice. The fact that no deep craters were found supports this model, since water-ice walls are not strong enough to stand very high and tend to flow down into the crater floor.

Though scientists expected to see craters on Io, none were seen. The extremely active volcanoes on Io were the most startling discovery of the mission, and Io is now believed to be the most geologically active object in the solar system. In appearance, Europa exhibits extensive cracks and faults quite unlike any seen before. They are very long, crisscrossing like blood vessels. Triton, orbiting Neptune, showed complex surface features resembling a cantaloupe, signs of past volcanic activity, and a large polar ice cap.

As of 2005, the two Voyager spacecraft were continuing their scientific exploration of interstellar space. Voyager 1 was 13.5 billion kilometers from Earth, nearly three decades after launch, and was traveling away from the solar system at 21 kilometers per second. Voyager 2 was 11 billion kilometers from Earth, traveling at 29 kilometers per second.

See also Cassini-Huygens Mission; Earth Orbit; Galileo Mission; International Space Station; Jupiter's Great Red Spot; Kepler's Laws of Planetary Motion; Mars Exploration Rovers; Moon Landing; Oort Cloud; Planetary Formation; Pluto; Saturn's Rings; Solar Wind; Space Shuttle; Wilkinson Microwave Anisotropy Probe.

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—*Richard C. Jones and William J. Kosmann*

WATER

THE SCIENCE: After discovering "inflammable air" (hydrogen), Henry Cavendish investigated its properties, eventually finding that the product formed when it burned in "dephlogisticated air" (oxygen) was pure water.

THE SCIENTISTS:

Henry Cavendish (1731-1810), English natural philosopher best known for his research on gases and the nature of water

Joseph Priestley (1733-1804), English scientist and Unitarian minister who discovered oxygen and several other new gases

James Watt (1736-1819), English inventor of an improved steam engine who gave an interpretation of water's nature

Antoine-Laurent Lavoisier (1743-1794), French chemist who interpreted water as a compound of hydrogen and oxygen

Sir Charles Blagden (1748-1820), Cavendish's assistant during the years that he studied hydrogen and the nature of water

FROM GAS TO WATER

In the seventeenth and eighteenth centuries, scientists such as Robert Boyle noticed that a flammable gas was generated when acids were added to metals. The Englishman Henry Cavendish was sufficiently intrigued by this gas to study it comprehensively. He prepared it with various metals (iron, zinc, and tin) and acids (what is now known as hydrochloric and sulfuric acids). Using two different methods, he determined the gas's specific gravity, finding it was nearly nine thousand times lighter than water and about one-fourteenth the weight of common air. When he introduced a flame into a mixture of this gas and ordinary air, the gas burned bright blue, and so he called it "inflammable air from the metals," which was later shortened to "inflammable air"; its modern name is hydrogen.

Because Cavendish, like many scientists of his time, believed in the phlogiston theory—which posited that every combustible material contained phlogiston—and because inflammable air burned with no residue, Cavendish interpreted this new gas as phlogiston. In 1766 he published his findings in a tripartite paper in which each part dealt with a specific gas prepared by a certain process: (1) inflammable air from metals and acids, (2) fixed air (carbon dioxide) from alkalis and acids, and (3) "mixed airs" from organic materials by fermentation or putrefaction.

Cavendish's report on inflammable air stimulated Joseph Priestley, who, in 1781, put an electric spark through a mixture of inflammable air and common air in a dry glass container and noticed that the inside of the glass container became coated with moisture. Neither Priestley nor a colleague who helped him understood what they had done, but Cavendish, who repeated their experiment in a systematic and quantitative way, did. During the summer of 1781 he found that all the inflammable air and about one-fifth of the ordinary air had ceased being gases in forming what he discovered was pure water.

Cavendish and Priestley routinely interacted, and so Cavendish was aware of a new gas, "dephlogisticated air" (oxygen), that Priestley had discovered in 1774. He was therefore curious about what would happen when he sparked various mixtures of inflammable air and dephlogisticated air. After several trials he established that a two-to-one ratio of inflammable to dephlogisticated air led to the complete conversion of these gases to water. Although he was the first scientist to establish this experimental fact, his interpretation of his results was confusing. The obvious explanation was to see water as the union of these two gases, but Cavendish was a phlogistonist and still tied, in a way, to the old idea of water as a chemical element on its own (we now know it to be the compound of two hydrogen atoms joined to one atom of oxygen, or H_2O). For Cavendish, inflammable air was either phlogiston or "phlogisticated water" (water united to phlogiston). Dephlogisticated air, on the other hand, was water deprived of its phlogiston. Therefore Cavendish saw water as preexisting in the combining gases, and the spark-induced reaction simply revealed what had previously been hidden.

LAVOISIER'S NEW CHEMISTRY

Even though Cavendish did not publish his experimental results and interpretation until 1784, scientists in England and France learned about them. For example, in 1783 Sir Charles Blagden, Cavendish's assistant, made a trip to Paris during which he met Antoine-Laurent Lavoisier and

LAVOISIER, WATER, AND CHEMICAL ELEMENTS

Until the late eighteenth century, water was considered to be a chemical element rather than a compound. This 1783 report prepared for the Royal Academy relates how Antoine-Laurent Lavoisier advanced Henry Cavendish's experiments to identify water a compound of hydrogen and oxygen:

M. Cavendish . . . observed that if one operates in dry vessels a discernible quantity of moisture is deposited on the inner walls. Since the verification of this fact was of great significance to chemical theory, M. Lavoisier and M. [Pierre-Simon] de la Place proposed to confirm it in a large-scale experiment. . . . The quantity of inflammable air burned in this experiment was about thirty pints [pintes] and that of dephlogisticated air from fifteen to eighteen.

Antoine-Laurent Lavoisier

(Library of Congress)

As soon as the two airs had been lit, the wall of the vessel in which the combustion took place visibly darkened and became covered by a large number of droplets of water. Little by little the drops grew in volume. Many coalesced together and collected in the bottom of the apparatus, where they formed a layer on the surface of the mercury.

After the experiment, nearly all the water was collected by means of a funnel, and its weight was found to be about 5 gros, which corresponded fairly closely to the weight of the two airs combined. This water was as pure as distilled water.

A short time later, M. Monge addressed to the Academy the result of a similar combustion . . . which was perhaps more accurate. He determined with great care the weight of the two airs, and he likewise found that in burning large quantities of inflammable air and dephlogisticated air one obtains very pure water and that its weight very nearly approximates the weight of the two airs used. Finally . . . M. Cavendish recently repeated the same experiment by different means and that when the quantity of the two airs had been well proportioned, he consistently obtained the same result.

It is difficult to refuse to recognize that in this experiment, water is made artificially and from scratch, and consequently that the constituent parts of this fluid are inflammable air and dephlogisticated air, less the portion of fire which is released during the combustion.

Source: "Report of a Memoir Read by M. Lavoisier at the Public Session of the Royal Academy of Sciences of November 12, on the Nature of Water and on Experiments Which Appear to Prove That This Substance Is Not Strictly Speaking an Element but That It Is Susceptible of Decomposition and Recomposition." *Observations sur la Physique* 23 (1783): 452-455. Translated by Carmen Giunta.

informed him about how Cavendish and he had made pure water from two new gases. Lavoisier quickly realized the implications of their results for his new theory of chemistry, which was overturning accepted paradigms of elemental matter: Lavoisier had been conducting investigations into the four "elements"—earth, air, fire, and water—and by 1779 he was disproving the phlogiston theory and in the process identifying a list of more than thirty chemical elements. For this he would become known to posterity as the father of modern chemistry.

In November of 1783, Lavoisier reported to the French Academy of Sciences on experiments that he and Pierre-Simon Laplace had performed demonstrating that water was not an element but a compound of hydrogen and oxygen. Lavoisier failed to mention the stimulus he had received from the research of Cavendish, who did not publish his results until 1784. In this later publication Cavendish was able to complete his earlier studies by showing that the gas that was left behind when dephlogisticated air was removed form common air was a colorless gas in which mice died and a candle would not burn; this gas was what Lavoisier called "azote" and others called "nitrogen."

The Water Controversy

Because the compound nature of water was such a significant discovery and because so many people contributed in one way or another to it, a "water controversy" developed. The debate was basically a priority dispute. Because both Priestley, who could have made a claim but never did, and Cavendish, whose introverted personality ill suited him to controversy, stayed on the sidelines, the contending parties in the first phase of the water controversy were James Watt and Antoine Lavoisier. Watt became involved because Priestley told him about his dew-forming experiments and Watt then circulated his interpretation of Priestley's results to Royal Society members.

When Watt learned of Cavendish's and Lavoisier's reports on water's nature, he accused Cavendish of plagiarizing his ideas and Lavoisier of plagiarizing Cavendish's experiments. For his part, Cavendish was willing to give credit to Lavoisier for interpreting the composition of water in terms of the oxygen theory. Although most historians of science appreciate Lavoisier's contributions, they criticize him for neglecting to give credit to Cavendish. These scholars also find Watt's claims confused and his interpretation derivative. Indeed, they bestow on Cavendish, the least contentious of the claimants, the lion's share of the honor for finding water's true nature.

IMPACT

Some scholars see Cavendish as Britain's preeminent eighteenth century scientist, between Isaac Newton in the seventeenth century and James Clerk Maxwell in the nineteenth. Cavendish's studies of what he called "factitious airs" (those contained in solids) were models of a rigorously quantitative approach to chemistry. Future chemists would use his methods for generating, collecting, transferring, and measuring gases and for determining their unique characteristics. Using these methods he contributed significantly not only to discovering the composition of water but also to clarifying the nature of such compounds as nitric acid. His quantitative studies of the specific combining volumes of the gases necessary to form water constituted an important step toward the law enunciated by Joseph Louis Gay-Lussac in 1809 that the ratios of the volumes of reacting gases are always small whole numbers.

Cavendish's experimental contributions were much more important than his theoretical contributions, and his adherence to the phlogiston theory hampered his understanding of his experimental results almost to the end of his life, when he finally began to see some value in the new chemistry of Lavoisier.

The water controversy was significant because of what it revealed about the changing nature of science. Before the eighteenth century scientists tended to work alone, and their discoveries were often seen as a consequence of their individual genius. In the eighteenth century scientific discoveries increasingly involved many talented individuals working in concert with or in cognizance of many others. Inevitably more than one scientist would sometimes arrive at the same conclusion or discovery at about the same time. Some scholars attribute the water controversy to the casual way in which scientific data were then gathered, dated, and reported. Other scholars point to nationalism as a factor in the water controversy, especially as it continued in the nineteenth century after the deaths of the original contenders. French and British scholars, using newly available primary sources, argued about the credit that should be given to Watt and Cavendish.

One significant by-product of the study of Cavendish's papers was the role that some his data played in the discovery of a new element in 1894. When Cavendish in the eighteenth century had removed oxygen and nitrogen from ordinary air, he found a small bubble of gas still remaining. In the late nineteenth century this bubble of gas was shown to be argon, a new noble gas, a belated testimony to the meticulousness of Cavendish's experimental prowess.

See also Atomic Theory of Matter; Carbon Dioxide; Definite Proportions Law; Oxygen; Photosynthesis.

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—*Robert J. Paradowski*

WAVE-PARTICLE DUALITY OF LIGHT

THE SCIENCE: Louis de Broglie provided a mechanical explanation for the wave-particle duality of light.

THE SCIENTISTS:

Louis de Broglie (1892-1987), French prince, historian, and physicist who won the 1929 Nobel Prize in Physics

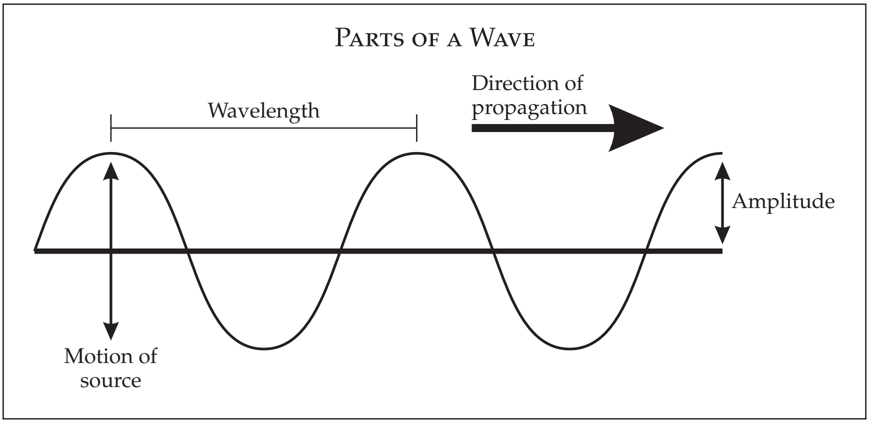
Niels Bohr (1885-1962), Danish physicist who won the 1922 Nobel Prize in Physics

Erwin Schrödinger (1887-1961), Austrian physicist who won the 1933 Nobel Prize in Physics

BOTH A WAVE AND A PARTICLE

In the early 1900's, scientists were having difficulty describing the nature of light. For a long time, light had been regarded as acting like a particle. In the late nineteenth century, the wavelike nature of light had been demonstrated. Early in the twentieth century, however, this belief was shifted again by experiments that confirmed the particle nature of light. The wave-particle duality of light was an experimental phenomenon in search of a theory.

At the beginning of the twentieth century, German physicist Max Planck had used the concept of the wave nature of light to explain blackbody radiation (radiation from a theoretical celestial body capable of completely absorbing all radiation falling on it). As a wave, light has a wavelength (the dis-



tance between crests) and a corresponding frequency (the number of crests passing a point in a given amount of time). Planck had shown that light of a particular frequency had a definite amount of energy; that is, energy is quantized. This seemed to favor the belief that light was wavelike in nature.

Nevertheless, five years later, in 1905, American physicist Albert Einstein reasoned that light behaved like particles. Einstein used Planck's theory of quantized light to explain why light striking the surface of certain metals resulted in the ejection of electrons from that metal (the photoelectric effect), but only when this involved certain frequencies of light. He pictured the light striking the metal surface as particles of light, or photons, with sufficient energy to knock off electrons.

The wave-particle nature of light was constantly debated and seemed dependent upon the experiment being performed. For example, the dispersion of white light into its component colors by a prism is a result of the wave nature of light. By contrast, the ability of a stream of photons to eject electrons from a metal surface points to the particle nature of light. Einstein had shown by his relativity theory that light could behave like both waves and particles and that the physical properties of each nature were related. He showed that the momentum of the photon (a particle property) was related to the wavelength of the light (a wave property). Einstein's results demonstrated that light has wave and particle duality.

A SNAKE SWALLOWING ITS OWN TAIL

Louis de Broglie had been studying Planck's theories of quantized light and Einstein's wave-particle concept of light. He wrote several papers calling attention to the dual behavior of light. De Broglie wished to provide a mechanical explanation for the wave-particle duality. Thus, he needed to find a mechanical reason for a particle—the photon—to have an energy that was determined by a wave, or rather by the frequency of that wave. While he was thinking about light, the idea occurred to de Broglie that matter (a particle) might have a wave nature also.

At about this time, Niels Bohr had revealed a theory for the electronic structure of atoms. Bohr's theory was that the electrons in an atom were restricted to particular energy levels and positions called "orbitals." Only by exact additions of unit amounts of energy could the energy and orbital of an electron be changed.

De Broglie was struck by the analogy of Bohr's orbital energies to standing waves. As a result, de Broglie discovered an example of wave-particle duality in matter.

De Broglie used his explanations of the wave-particle duality of matter in writing his doctoral dissertation in physics. He presented his dissertation before the Faculty of Sciences at the University of Paris in 1923. His theory demonstrated that matter, like light, had a wavelike nature.

De Broglie noticed that the momentum of the electron orbitals proposed by Bohr were whole number units of a fundamental quantity, Planck's constant. He knew that standing waves had unit changes in their momenta also. A standing wave can be thought of as a string, fixed at both ends, that is plucked. The string will oscillate back and forth, yet some points will remain at rest. The number of rest points will increase as the frequency of the vibration increases. De Broglie reasoned that Bohr's orbitals could therefore be seen as a circular string, a snake swallowing its own tail.

Moreover, de Broglie discovered that the matter waves he had proposed fit Bohr's electron orbits exactly. He also found that the momenta and wavelengths of his matter waves were related, like those of light. He had succeeded in explaining Bohr's orbits: Each orbit was a steady wave pattern, and these orbits had determined and fixed sizes so that these distinct "quantized" wave patterns could exist.

When de Broglie somewhat reluctantly submitted his dissertation, the faculty at the University of Paris was unsure of the use of strings to explain Bohr's orbits and asked Einstein to judge the acceptability of the dissertation. Einstein confirmed that it was sound. The thesis was accepted, and later de Broglie was awarded the Nobel Prize.

Impact

De Broglie's waves had offered a picture of what was occurring inside an atom. A way to visualize the shifting patterns of the wave was needed when the atom changed energy and produced light.

Erwin Schrödinger, an Austrian physicist, found a mathematical equation that explained the changing wave patterns inside an atom. Schrödinger's equation provides a continuous mathematical description of the wave-particle duality of matter. He viewed the atom as analogous to de Broglie's vibrating string. The movement of the electron from one orbit to another was a simple change in the frequency of the standing waves of the string. In a musical string, this occurs as the harmony of two wave patterns, the result being the differences in the frequency of the two waves.

The understanding of the wave-particle duality of matter, as modeled by Schrödinger's equation, was instrumental in the founding of quantum physics. Quantum physics has been responsible for many of the technological advances in the twentieth century. These advances are traceable to de Broglie's pronouncement of the wave-particle duality of matter.

See also Alpha Decay; Atomic Structure; Compton Effect; Diffraction; Electrons; Exclusion Principle; Grand Unified Theory; Heisenberg's Uncertainty Principle; Lasers; Optics; Photoelectric Effect; Quantized Hall Effect; Quantum Chromodynamics; Quantum Mechanics; Schrödinger's Wave Equation; Superconductivity; X-Ray Fluorescence.

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—*Scott A. Davis*

WEATHER FRONTS

The Science: Vilhelm Bjerknes's model of the atmosphere emphasized the idea of "fronts," those boundaries along which masses of warm and cold air clash and converge to produce the weather.

THE SCIENTISTS:

Vilhelm Bjerknes (1862-1951), Norwegian meteorologist
Jacob Bjerknes (1897-1975), Norwegian meteorologist
Carl-Gustav Arvid Rossby (1898-1957), Swedish American meteorologist
Tor Bergeron (1891-1977), Swedish meteorologist

GATHERING INFORMATION

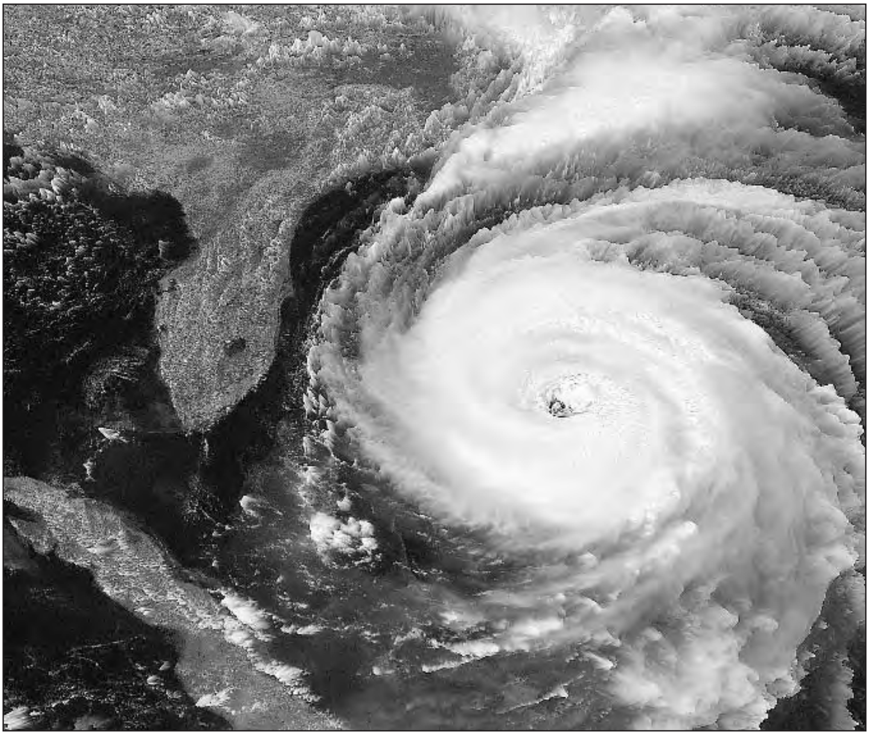
Vilhelm Bjerknes, a Norwegian geophysicist and meteorologist, knew in the early 1900's that accurate forecasting of weather required much information. He also knew that local weather was tied to the global circulation of the atmosphere. While teaching at Stockholm University from 1895 to 1907, he proposed that movements in the atmosphere are stimulated by heat from the Sun. At the same time, these movements radiate heat as air masses rub up against one another, causing friction.

Bjerknes was motivated by the need for improved weather prediction for commercial fishing and agriculture. In part, the urgent need for better domestic food production arose from restrictions of imports and communications as a result of World War I (1914-1918). He persuaded the Norwegian government to help set up strategically located observing stations. In addition to the stations, he founded a school at Bergen that attracted meteorologists from all over the world, including his son Jacob Bjerknes; Carl-Gustav Arvid Rossby, a Swedish American meteorologist; and Tor Bergeron, a Swedish meteorologist.

Weather types and changes, along with moving masses of air and their interaction, have been studied and noted for centuries. In the nineteenth century, Luke Howard, an English physicist, had written of northerly and southerly winds blowing alongside each other, with the colder wedging in under the warmer and the warmer gliding up over the colder and causing extensive and continued rains. In 1852, evidence had been found of a polar wind advancing under a warm, nearly saturated tropical wind and pushing it upward producing cumulus clouds.

EXPLAINING THE WEATHER

Vilhelm Bjerknes was a pioneer in the development of a mathematical theory of fronts and their effects. In addition, along with his son, he was the first to study extratropical cyclones and use them to forecast the weather. Extratropical cyclones are cyclones that may cross an ocean in ten days, lose most of their intensity, and then develop again into large and vigorous



One of the most terrifying weather fronts is that of a hurricane—here, Hurricane Fran in 1996. (NASA/GSFC)

storms. In the years following World War I, Norwegian meteorologists had a fairly good understanding of the action in the big storms sweeping across the Atlantic. From this knowledge, Vilhelm Bjerknes theorized that the main idea in storm development is a clashing of two air masses, one warm, the other cold, along a well-defined boundary, or front.

Aside from the idea of storm fronts, his view of cyclone development produced another important idea. At the beginning of the life cycle of a storm, there is an undisturbed state in which cold and warm air masses flow side by side, separated by a front. Each air mass flows along its side of the front until some of the warmer air begins to invade the cooler air, leading to a wave disturbance. This disturbance spreads and grows, creating low-pressure areas at the tip of the wave. Air motions try to spiral into these areas, and both fronts begin to advance. The cold air generally moves faster, catching up with and moving under the lighter warm air. As the storm grows deeper, the cold front becomes more pronounced. The whole process—from the time the polar air meets the northward-flowing warm air to the point at which the area of low pressure is filled completely—is known as the "life cycle of a frontal system." This description is based on the wave theory, which was originally developed by Vilhelm Bjerknes in 1921.

In 1919, when this work began, upper atmosphere studies were limited by the lack of knowledge of such things as radar images, lasers, computers, and satellites. Vilhelm Bjerknes showed that the atmosphere is composed of distinct masses of air meeting at various places to produce different meteorological effects. He published the study *On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motion* in 1921.

IMPACT

The weather forecasting stations established by Vilhelm Bjerknes in the 1920's were a monumental accomplishment, considering the limited amount of information and the lack of high-speed, worldwide communications. All the computations were done without the assistance of a computer or modern weather satellites to analyze and model the data. Today, these and other tools have made it possible to compile data into real-time images of the current weather patterns around the globe. It was pioneers such as Vilhelm Bjerknes who paved the way.

See also Atmospheric Circulation; Atmospheric Pressure; Chaotic Systems; Fractals; Ionosphere; Stratosphere and Troposphere.

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—*Earl G. Hoover*

WILKINSON MICROWAVE ANISOTROPY PROBE

THE SCIENCE: The Wilkinson Microwave Anisotropy Probe (WMAP), a space-based astronomical observatory designed to measure the "echo" or "afterglow" of the big bang known as cosmic microwave background, provided the first accurate measure of the age of the universe, changed the way astronomers think about the earliest star formation, and supported some of the leading cosmological theories.

THE SCIENTISTS:

David T. Wilkinson (1935-2002), project scientist, Princeton University

Robert H. Dicke (1916-1997), experimental physicist at Princeton University

AFTER THE BIG BANG

Astronomer George Gamow speculated in 1948 on the existence of an "echo" of the early events in the history of the universe. After the big bang, or moment of creation, light and matter were bound together in such a way that the universe was opaque to light. When the temperatures from the hot big bang cooled to approximately 300 Kelvins (degrees above absolute zero), matter and light separated in what is called "last scattering." The light from that moment is still reaching Earth today but has been redshifted to 2.73 Kelvins given the large distance. This cosmic microwave background radiation (CMB) was accidentally discovered in 1965 by astronomers and Bell Telephone Laboratory scientists Arno A. Penzias and Robert W. Wilson. They discovered this seemingly isotropic radiation while studying emissions from the Milky Way. This discovery earned them the Nobel Prize in Physics in 1978.

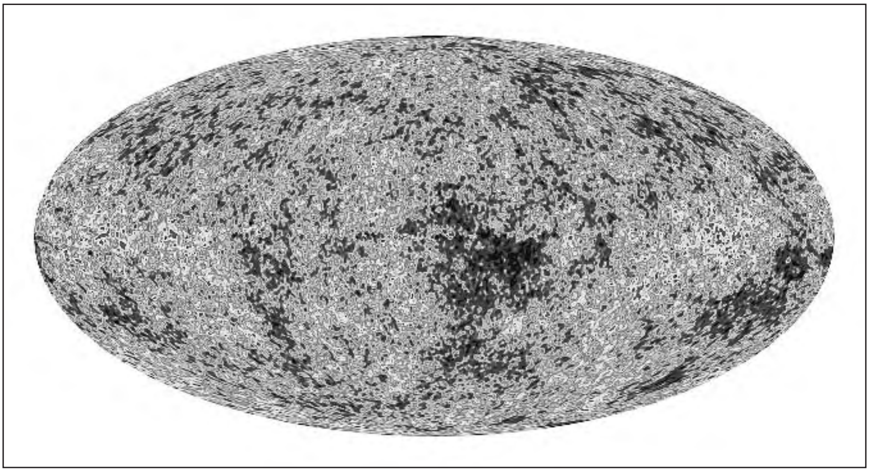
Astronomers continued to study the CMB for decades. However, it puzzled them in that the measured temperature was perfectly smooth in all directions. After all, if the universe was perfectly smooth, then clumps of matter like galaxies, stars, and planets could not have formed. Hence, although the existence of the CMB supported the big bang theory, its uniformity did not fit in with observations of the modern universe. Finally, in 1992, the Cosmic Background Explorer satellite (COBE, which had been launched on November 9, 1989) measured anisotropies, or irregularities, in the CMB temperature on small scales. Although this fuzzy picture did not provide much scientific detail, the seeds of the early galaxies had finally been detected.

Mapping the Universe

At Princeton University, David Wilkinson had been working with Robert Dicke on a receiver to detect the CMB. Originally named the Microwave Anisotropy Probe (MAP) and later the Wilkinson Microwave Anisotropy Probe (WMAP), it was proposed to NASA in 1995 to follow up on the COBE discoveries and was authorized in 1997. It became a space-based observatory and the most successful observational cosmology project to date. Launched on June 30, 2001, this unique orbiting radio telescope began a journey that would answer many fundamental questions about the evolution of the universe.

WMAP featured two radio telescopes 140° apart in order to map the temperature of the sky in all directions. This design allowed for differential mapping—or subtracting the temperature in one area of the sky from the temperature at another point—which allows for subtraction of false signals. In other words, the relative temperatures of different regions are measured. In this way, WMAP can achieve a sensitivity of 0.000020 Kelvin. This is necessary in order to determine the tiny density variations in a radiation field that is only 2.73 Kelvins. The temperature of an object or energy field is related to the peak wavelength of the emission. Since the CMB temperature is so low, it has a low energy and therefore peaks at long wavelengths, specifically in the microwave region of the electromagnetic spectrum.

The cosmic background radiation is easily washed out by "foreground"



The Wilkinson Microwave Anisotropy Probe provided data that made possible this spectacular map of the early universe, including the very first anisotropies, which grew into the stars and galaxies that exist today. (NASA) objects, mainly galaxies, gas clouds, or human-made signals. Therefore, WMAP operates at five frequencies: 22, 30, 40, 60, and 90 gigahertz. Because many ground-based telescopes operate at these frequencies, astronomers know much about objects in the radio sky and can subtract that radiation from the CMB radiation in the WMAP data with great precision.

The result was a spectacular map of the early universe and the very first anisotropies that grew into the stars and galaxies that exist today. The map of the universe that was produced from the first-year results has become a mainstay of science media. The map is color-coded to show tiny temperature variations. The warmer temperature spots indicate density clumps, and the cooler spots indicate empty space. These clumps vary in temperature by 0.0002 Kelvin. From these data, many conclusions could be made about the nature, history, and future of the universe.

How Old Is the Universe?

The data gleaned from the WMAP mission helped astronomers pin down the most important cosmological parameters. Using sophisticated modeling techniques, astronomers are now able to start with a clear early picture of the universe and test different evolutionary models until the result resembles the current universe. For the first time, the age of the universe has been pinpointed with incredible accuracy at 13.7 billion years, because the Hubble constant, or a measure of the expansion rate of the universe, has been determined to be 71 (km/sec)/Mpc. (A megaparsec, or Mpc, is approximately 3.26 million light-years; kilometers per second is denoted as km/sec.)

Also, the first stars seem to have turned on, or have begun nuclear fusion, 200 million years after the big bang—long before anyone had originally thought.

WMAP also confirmed that the geometry of the universe is flat. That is, the Euclidean geometry that is learned in high school applies over large scales. Other theories had surmised that the universe could be curved. In these strange geometries, parallel lines could eventually intersect or diverge over long distances.

Dark Matter, Dark Energy

Our universe has its own strange qualities, nevertheless. This flat geometry, along with other cosmological data to date, suggest that only 4 percent of the matter in the universe is the matter that makes up stars, planets, and humans, or baryonic matter, while 23 percent of the matter in the universe is known as dark matter—that which has not yet been detected but exerts gravitational forces on nearby objects.

An even stranger thing, known only as dark energy, forms 73 percent of the universe. Theorists do not yet know of what this “energy” may consist. However, they propose that it exerts a long-distance repulsive force. This dark energy is also known as Albert Einstein’s cosmological constant," or a constant used by Einstein to complete his theory of gravitation. Einstein had originally called it his “greatest blunder,” but this constant was resurrected in 1998 when astronomers discovered the recent acceleration of the expansion of the universe. If this is the case, the universe will continue to expand forever, long after all the stars have grown dark and cold.

IMPACT

WMAP data support the inflationary model of the universe and have provided the first accurate measure of the age of the universe. Not only did the data identify Hubble’s constant to an extremely precise degree, but with the concomitantly precise calculation of the age of the universe many astronomers have come to accept the leading cosmological model: that the first few seconds after the big bang involved a very rapid, energetic expansion of space.

In order to confirm this model further, however, even more sensitive maps of the CMB are needed. Inflation should have created gravitational waves that would be imprinted on the CMB, and until these can be detected, other theories of early universe formation cannot be entirely ruled out.

See also Big Bang; Black Holes; Cosmic Microwave Background Radiation; Expanding Universe; Galaxies; Inflationary Model of the Universe; Quarks; String Theory.

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—*Nicole E. Gugliucci*

X Radiation

The Science: X rays, first observed by Wilhelm Röntgen, have remarkable penetrating power that has been widely used for medical and industrial applications.

The Scientists:

Wilhelm Röntgen (1845-1923), experimental physicist who discovered X rays

William Crookes (1832-1919), inventor of the vacuum tube that bears his name

Heinrich Hertz (1857-1894), discoverer of radio waves

Philipp Lenard (1862-1947), experimental physicist who studied cathode rays

Ludwig Zehnder (1854-1935), Röntgen's laboratory assistant, colleague, and co-author of several research papers

Cathode Rays

X rays were discovered in 1895 by Wilhelm Röntgen, a professor of physics at the University of Würzburg, Germany. He was investigating the radiation produced in a partially evacuated glass bulb when a high voltage was applied.

William Crookes in 1869 had published a research report in which he described the bright glow that occurred inside such a bulb. Another physicist, Philipp Lenard, then showed that the electrical discharge inside the glass bulb could penetrate a thin aluminum window, producing an external beam that traveled through several centimeters of open air. This beam was called a "cathode ray" because it originated at the negative voltage terminal, which is the cathode. Lenard was able to trace the path of cathode rays by using fluorescent paint on a small screen that glowed in the dark when radiation struck it. He showed that cathode rays could be deflected by a magnet.

A Mysterious Glow

Röntgen was an experienced experimentalist with twenty-five years of laboratory research and more than forty technical publications. Using the same type of apparatus as Crookes and Lenard, he first confirmed their observations for himself. In order to see the external beam more clearly, he surrounded the glass bulb with opaque, black paper, so that the light produced inside the bulb would be blocked out and the external beam would show up more clearly. On November 9, 1895, according to his laboratory notebook, he noticed something quite unusual. A piece of cardboard coated with fluorescent paint, lying on the table more than a meter away, started to glow whenever the electric discharge was turned on. This was a startling observation because cathode rays could not travel that far. Was there a new type of radiation coming through the black paper?

Image Not Available

Working by himself, Röntgen began a systematic investigation of the mysterious rays. He observed fluorescence at a distance as much as two meters from the discharge tube. The radiation had penetrated opaque black paper, so he decided to test various other materials for their transparency. Even behind a book of one thousand pages, he found that the fluorescent screen lit up brightly. Blocks of wood and sheets of aluminum transmitted the radiation fairly well, but two millimeters of lead proved to be opaque. When holding his hand between the discharge apparatus and the fluorescent screen, he was able to see the shadow of the bones inside the faint outline of his fingers.

Photographs of the Invisible

Further experiments showed that photographic plates were sensitive to the radiation. This enabled Röntgen to make a permanent record of the observations that he had seen by eye previously. He had to be careful not to store unused photographic plates near the apparatus or they would become fogged by stray radiation. In his publications, Röntgen referred to the new type of radiation as X rays because they were a mystery. He used a glass prism to see if X rays could be refracted like ordinary light, but the result was negative. He also found that X rays were not reflected by a mirror and could not be focused by a lens. Diffraction gratings, which had been used to measure the wavelengths of visible light with high precision, had no effect on X rays, and a magnet caused no deflection.

On December 22, 1895, Röntgen asked his wife to help him in the laboratory. He placed the X-ray tube just underneath a table while she held her hand on the table surface with the photographic plate above her hand. The exposure time was about five minutes. When he developed the photograph, it showed the bones in her hand with her wedding ring on one finger. A photography assistant made multiple prints from this and several other negatives. On January 1, 1896, Röntgen sent a ten-page article with photographs to the Physical-Medical Society of Würzburg, as well as to colleagues at other universities. The pictures created a sensation. Nothing like them had ever been seen before.

Radiology Centennial, Inc.

Within a few days, newspapers all over Europe had published stories and photographs about this new scientific development. A flood of messages came to Röntgen with invitations to give lectures and demonstrations. He turned them all down, except he could not refuse one that came from the emperor of Germany, Kaiser Wilhelm I. On January 13, he traveled to Berlin with his X-ray apparatus and showed to the assembled court how metal objects inside a closed box could be photographed. On January 23, he gave a lecture to the faculty and students at his own university. He told the audience about his experiments, giving credit to earlier contributions made by Hertz and Lenard. Toward the close of the lecture, he made an X-ray photograph of the hand of a faculty colleague, which was quickly developed and passed around the room. Prolonged applause came as the lecture ended.

Over the next several weeks, Röntgen received letters from many scientists who were experimenting with X rays. One person sent a photograph of a fish showing its detailed bone structure. His friend Ludwig Zehnder, whom he had known since graduate school in Zürich, took several photographs of the human body, which he pasted together to obtain a complete skeleton from head to foot. There were some crackpot letters, such as the one asking for a sum of money to solve the secrets of weather forecasting with X rays. The greatest honor for Röntgen was to be awarded the 1901 Nobel Prize, the first year in which the award was given.

IMPACT

Röntgen felt that the benefits of X rays should be available to humankind without restrictions. He did not take out a patent on his discovery even although it could have made him wealthy. His apparatus was not expensive or difficult to duplicate. The most difficult part would have been to get a glass blower to make a glass bulb with two metal electrodes inside, connected by wires going through the glass to two terminals on the outside. Many hospitals and research laboratories were able to set up their own X-ray machines. Within one year of Röntgen's initial publication, nearly one thousand articles on X rays appeared in various technical journals.

The medical profession enthusiastically welcomed X rays as a new diagnostic tool. Doctors were able to determine the severity of broken bones and to locate swallowed objects or an embedded bullet in the body. Annual chest X rays for schoolchildren became a routine procedure to diagnose early signs of tuberculosis. Irradiation of cancerous tumors was found to be a beneficial therapy as long as the dose was carefully regulated. In the 1970's, a major improvement in X-ray technology, called the CT-scan, was developed. A narrow beam of X rays was swept across a portion of the body from many different angles, and then the information was correlated by a computer to produce a picture on a screen.

X-ray apparatus came into common use at airports to inspect baggage before boarding. X rays have been used to search for hidden microphones in the wall of a room before a diplomatic conference. In the pipeline industry, after individual sections of pipe have been welded together, portable X-ray machines have been used to detect possible hairline cracks at the welds that might later allow fluid to leak. X-ray analysis has been widely used by chemists to determine the structure of complex molecules, such as the DNA helix. Röntgen's discovery of X rays, therefore, provides a fine example of how pure research can lead to a multitude of unanticipated practical applications.

See also Compton Effect; Electromagnetism; Electrons; Isotopes; Radioactivity; X Radiation; X-Ray Astronomy; X-Ray Crystallography; X-Ray Fluorescence.

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—*Hans G. Graetzer*

X-RAY ASTRONOMY

THE SCIENCE: Riccardo Giacconi and his colleagues launched a rocket-borne X-ray telescope that detected X rays from the constellation Scorpius.

THE SCIENTISTS:

Riccardo Giacconi (b. 1931), Italian American physicist and astronomer
Herbert Friedman (1916-2000), American cosmic-ray physicist
Norman Harmon (b. 1929), senior scientist at American Science and Engineering, Inc.
Frank Bethune McDonald (b. 1925), American astrophysicist

X RAYS FROM SCORPIUS

All stars in the universe emit electromagnetic radiation as a result of the enormous thermonuclear reactions and complex chemical reactions that take place within them. Such radiation comes in many forms that have their own frequencies and wavelengths. The electromagnetic spectrum ranges from low-frequency, long-wavelength radiations, such as radio, television, microwaves, and visible light, to higher-frequency, shorter-wavelength radiations such as ultraviolet rays, X rays, gamma rays, and cosmic rays. High-frequency radiations are mostly blocked by Earth’s ozone layer, a chemical shield that reacts with these radiations as they bombard the Earth’s atmosphere. Consequently, physicists and astronomers who wish to study extraterrestrial high-energy (high-frequency) radiations must place measuring instruments into orbit above the Earth’s atmosphere.

During the late 1950’s, a group of physicists at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, established a company whose primary focus was high-energy physics and space research. The company, American Science and Engineering, Inc., joined forces with Riccardo Giacconi of Princeton University in 1959 to establish a space science research division.

In collaboration with the National Aeronautics and Space Administration (NASA), American Science and Engineering decided to test the emission of X rays from stars. This work had been started in the late 1940's by Herbert Friedman of the Naval Research Laboratory. Friedman launched X-ray detectors above the Earth's atmosphere aboard captured German V-2 rockets and demonstrated that the Sun emits X rays.

During 1960 and 1961, a research team that included Giacconi and Norman Harmon devised a small, highly sensitive X-ray telescope that could detect faint X-ray emissions from specific regions of space and that could ride aboard rockets that could fly as high as 160 kilometers. They attempted several launches of X-ray telescopes from White Sands Missile Range in New Mexico beginning in the fall of 1961. At midnight on June 18-19, 1962, with a six-minute suborbital flight, the X-ray telescope received and recorded stellar X-ray emissions on film.

Careful analysis of the X-ray film showed a higher emission of X rays emanating from the southern constellation Scorpius. They named this X-ray source Scorpius X-1, the first-discovered X-ray source outside the solar system. Friedman's research group quickly confirmed Giacconi's discovery. Other high-energy astrophysicists entered the field and discovered additional X-ray sources, including Cygnus X-1 and the Crab nebula in Taurus. The ultimate goal for Giacconi and his colleagues was to place a series of orbiting X-ray telescopes around Earth for precise measurements of hundreds of stellar X-ray sources. They planned the development of these satellites in coordination with Frank Bethune McDonald of the NASA Goddard Space Flight Center in Greenbelt, Maryland.

Launching Uhuru

During the late 1960's, Giacconi and his colleagues continued their work on a proposed orbiting X-ray telescope. Friedman's group at the Naval Research Laboratory and McDonald's group at the Goddard Space Flight Center were working toward the same goal. On December 12, 1970, the Cosmic X-Ray Explorer satellite was launched from an oil rig located off the coast of Kenya. Kenya was chosen because from there the satellite could easily enter an orbit that would carry the satellite around the Earth's equator, enabling the X-ray telescope to detect X-ray sources from practically every direction around Earth. X-ray data were relayed to a ground-based control station. The X-Ray Explorer, the Small Astronomy Satellite 1, was nicknamed Uhuru, the Kenyan word for "freedom," because it was launched on Kenya's Independence Day.

Many X-ray sources were identified by Uhuru as sunlike stars and galactic nuclei. Still other sources were determined to be superdense collapsed stars called neutron stars. Other scientists speculate that some X-ray sources (Cygnus X-1) may be black holes, gravitational singularities that are collapsed stars so dense that matter and light cannot escape.

Later X-Ray Observatories

Additional Small Astronomy Satellites were launched during the early 1970's, each satellite carrying a variety of high-energy detection equipment designed by Giacconi, Friedman, McDonald, and other physicists. A more advanced satellite series, the High-Energy Astronomy Observatory, consisted of three satellites. It was created in 1978 and was operational through 1981. It contained a powerful X-ray telescope that detected X-ray emissions from "quasars" (quasi-stellar radio sources), the most distant and oldest objects yet discovered in the universe. Other satellites followed: the Einstein Observatory, in 1979, the first satellite with focusing X-ray mirrors enabling it to see fainter sources; the Röntgen X-Ray Satellite (ROSAT) in 1990—a joint project of Germany, the United Kingdom, and the United States—the first satellite to make an all-sky survey with an imaging telescope; and the Japanese satellite ASCA, launched in 1993 by Japan and the United States, the first to use the new-generation charge-coupled devices (CCD) x-ray detectors.

One of the most ambitious projects in X-ray astronomy was launched on July 23, 1999, when the Chandra X-Ray Observatory (CXO) was lofted into orbit aboard space shuttle *Columbia*. This observatory is designed to image and measure the temperatures of extremely hot objects such as supernova remnants, neutron star accretion disks, and cosmic gas clouds. It is far more sensitive than previous x-ray telescopes and capable of revealing much finer detail.

The XMM-Newton was successfully launched December 10, 1999. It can detect fainter sources than Chandra, but Chandra has better resolution, enabling it to record finer details.

Data from Chandra

Chandra's results often confirm what previously was only suspected, but occasionally it has made completely unanticipated discoveries as well. The facts that the Milky Way's black hole candidate emits fewer X rays than expected and that the environment of Andromeda's black hole candidate is cooler than expected strongly suggest that the processes involved are more complex and less well understood than previously supposed.

To see what faint sources might be present, scientists pointed Chandra at a small patch of sky in the direction of the constellation Canis Venatici and collected data for 27.7 hours. Since the early 1960's scientists have known that space is filled with a faint X-ray glow, but they did not know if that glow came from very hot diffuse gas spread throughout the universe or if it came from a large number of discrete sources. ROSAT had previously shown that much of the lower-energy X-ray background comes from distant objects such as quasars or active galactic nuclei (AGNs). AGNs are thought to be supermassive (billion-solar-mass) black hole candidates that are rapidly accreting more mass. Mass spiraling inward forms an accretion disk about the black hole candidate, and the gravitational energy released heats the disk so that it emits gamma rays, X rays, and visible light.

With better resolution and sensitivity, Chandra confirmed the ROSAT result and extended it to higher-energy X rays. Most of the X-ray background does come from discrete sources. Chandra found that about one-third of the sources are AGNs with brightly shining cores, but that another third of the X-ray sources are galactic nuclei that emit little or no visible light from their cores. Perhaps dust or gas surrounding their cores blocks visible light. If so, there may be tens of millions of similar objects over the whole sky, and the optical surveys of AGNs are very incomplete. Chandra found that the final third of the X-ray sources are in ultrafaint galaxies, galaxies that are barely detectable, if at all, in visible light. If they are so faint because they are far away, they would be among the most distant objects ever discovered.

Impact

Giacconi's discovery of the first extrasolar X-ray source was a tremendous astronomical achievement that changed scientists' view of the universe and led to a greater understanding of stellar astrophysics. The knowledge that many objects, including stars, planets, galaxies, and quasars, emit X rays has enabled scientists to comprehend the nature of these objects and the processes that occur within them. Giacconi's discovery created the field of X-ray astronomy, which continually yields new information about the universe.

The first X-ray telescopes, launched aboard sounding rockets by Giacconi and Friedman, pioneered later missions that revealed many cosmic X-ray emitters. With succeeding X-ray telescope missions, X-ray sources were discovered in every section of the universe. Soon, astronomers were able to draw up a comprehensive map of stellar X-ray emission.

In a larger context, X-ray astronomy is part of a larger movement, starting in the 1930's with radio astronomy, to use the nonvisible portions of the electromagnetic spectrum—from radio waves and microwaves to ultraviolet ranges—to gather data on the universe and its objects. What is "visible" in these ranges has provided more insight into the universe and its dynamics than the preceding four hundred years of visible telescopy.

See also Big Bang; Black Holes; Cepheid Variables; Chandrasekhar Limit; Cosmic Microwave Background Radiation; Cosmic Rays; Electromagnetism; Expanding Universe; Extrasolar Planets; Galactic Superclusters; Galaxies; Gamma-Ray Bursts; Hubble Space Telescope; Inflationary Model of the Universe; Neutron Stars; Ozone Hole; Pulsars; Quasars; Radio Astronomy; Radio Galaxies; Radio Maps of the Universe; Solar Wind; Space Shuttle; Spectroscopy; Stellar Evolution; Very Long Baseline Interferometry; Wilkinson Microwave Anisotropy Probe; X Radiation.

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—*David Wason Hollar, Jr., and David G. Fisher*

X-RAY CRYSTALLOGRAPHY

THE SCIENCE: The invention of X-ray crystallography provided an important technique for using X rays to determine the crystal structures of many substances.

THE SCIENTISTS:

Sir William Henry Bragg (1862-1942), English mathematician and physicist and cowinner of the 1915 Nobel Prize in Physics

Sir Lawrence Bragg (1890-1971), the son of Sir William Henry Bragg and cowinner of the 1915 Nobel Prize in Physics

Max von Laue (1879-1960), German physicist who won the 1914 Nobel Prize in Physics
Wilhelm Conrad Röntgen (1845-1923), German physicist who won the 1901 Nobel Prize in Physics
René-Just Haüy (1743-1822), French mathematician and mineralogist
Auguste Bravais (1811-1863), French physicist

CRYSTALS

A crystal is a body that is formed once a chemical substance has solidified. It is uniformly shaped, with angles and flat surfaces that form a network based on the internal structure of the crystal's atoms. Determining what these internal crystal structures look like is the goal of the science of X-ray crystallography. To do this, it studies the precise arrangements into which the atoms are assembled.

Central to this study is the principle of X-ray diffraction. This technique involves the deliberate scattering of X rays as they are shot through a crystal, an act that interferes with their normal path of movement. The way in which the atoms are spaced and arranged in the crystal determines how these X rays are reflected off them while passing through the material. The light waves thus reflected form a telltale interference pattern. By studying this pattern, scientists can discover variations in the crystal structure.

The development of X-ray crystallography in the early twentieth century helped to answer two major scientific questions: What are X rays? and What are crystals? It gave birth to a new technology for the identification and classification of crystalline substances.

From studies of large, natural crystals, chemists and geologists had established the elements of symmetry through which one could classify, describe, and distinguish various crystal shapes. René-Just Haüy, about a century before, had demonstrated that diverse shapes of crystals could be produced by the repetitive stacking of tiny solid cubes.

Auguste Bravais later showed, through mathematics, that all crystal forms could be built from a repetitive stacking of three-dimensional arrangements of points (lattice points) into "space lattices," but no one had ever been able to prove that matter really was arranged in space lattices. Scientists did not know if the tiny building blocks modeled by space lattices actually were solid matter throughout, like Haüy's cubes, or if they were mostly empty space, with solid matter located only at the lattice points described by Bravais.

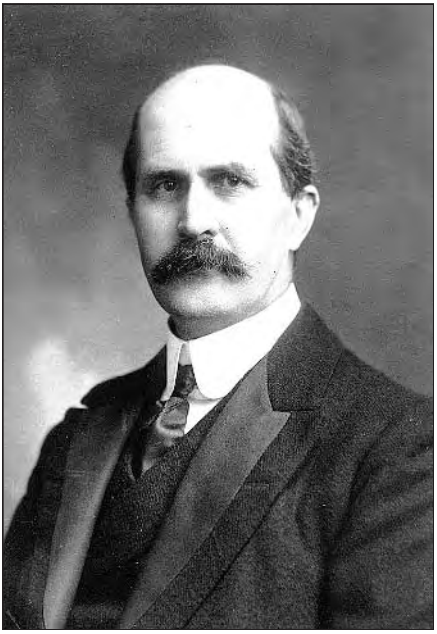
With the disclosure of the atomic model of Danish physicist Niels Bohr in 1913, determining the nature of the building blocks of crystals took on a special importance. If crystal structure could be shown to consist of atoms at lattice points, then the Bohr model would be supported, and science then could abandon the theory that matter was totally solid.

X RAYS EXPLAIN CRYSTAL STRUCTURE

In 1912, Max von Laue first used X rays to study crystalline matter. Laue had the idea that irradiating a crystal with X rays might cause diffraction. He tested this idea and found that X rays were scattered by the crystals in various directions, revealing on a photographic plate a pattern of spots that depended on the orientation and the symmetry of the crystal.

The experiment confirmed in one stroke that crystals were not solid and that their matter consisted of atoms occupying lattice sites with substantial space in between. Further, the atomic arrangements of crystals could serve to diffract light rays. Laue received the 1914 Nobel Prize in Physics for his discovery of the diffraction of X rays in crystals.

Still, the diffraction of X rays was not yet a proved scientific fact. Sir William Henry Bragg contributed the final proof by passing one of the diffracted beams through a gas and achieving ionization of the gas, the same effect that true X rays would have caused. He also used the spectrometer he built for this purpose to detect and measure specific wavelengths of X rays and to note which orientations of crystals produced the strongest reflections. He noted that X rays, like visible light, occupy a definite part of the electromagnetic spectrum. Yet most of Bragg's work focused on actually using X rays to deduce crystal structures.



William Henry Bragg. (The Nobel Foundation)

Bragg's son, Sir Lawrence Bragg, was also deeply interested in this new phenomenon. In 1912, he had the idea that the pattern of spots was an indication that the X rays were being reflected from the planes of atoms in the crystal. If that were true, Laue pictures could be used to obtain information about the structures of crystals. Bragg developed an equation that described the angles at which X rays would be most effectively diffracted by a crystal. This was the start of the X-ray analysis of crystals.

William Henry Bragg had at first used his spectrometer to try to determine whether X rays had a particulate nature. It soon became evident, however, that the device was a far more powerful way of analyzing crystals than the Laue photograph method had been. Not long afterward, father and son joined forces and founded the new science of X-ray crystallography. By experimenting with this technique, Lawrence Bragg came to believe that if the lattice models of Bravais applied to actual crystals, a crystal structure could be viewed as being composed of atoms arranged in a pattern consisting of a few sets of flat, regularly spaced, parallel planes.

Diffraction became the means by which the Braggs deduced the detailed structures of many crystals. Based on these findings, they built three-dimensional scale models out of wire and spheres that made it possible for the nature of crystal structures to be visualized clearly even by nonscientists. Their results were published in the book *X-Rays and Crystal Structure* (1915).

Impact

The Braggs founded an entirely new discipline, X-ray crystallography, which continues to grow in scope and application. Of particular importance was the early discovery that atoms, rather than molecules, determine the nature of crystals. X-ray spectrometers of the type developed by the Braggs were used by other scientists to gain insights into the nature of the atom, particularly the innermost electron shells. The tool made possible the timely validation of some of Bohr's major concepts about the atom.

X-ray diffraction became a cornerstone of the science of mineralogy. The Braggs, chemists such as Linus Pauling, and a number of mineralogists used the tool to do pioneering work in deducing the structures of all major mineral groups. X-ray diffraction became the definitive method of identifying crystalline materials.

Metallurgy progressed from a technology to a science as metallurgists became able, for the first time, to deduce the structural order of various alloys at the atomic level.

Diffracted X rays were also applied in the field of biology, particularly at the Cavendish Laboratory under the direction of Lawrence Bragg. X-ray crystallography proved to be essential for deducing the structures of hemoglobin, proteins, viruses, and eventually the double-helix structure of deoxyribonucleic acid (DNA).

See also X-Ray Fluorescence.

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—*Edward B. Nuhfer*

X-RAY FLUORESCENCE

THE SCIENCE: By studying the interaction between X rays and matter, Charles Glover Barkla succeeded in determining important physical characteristics of X rays and the atomic structure of matter.

THE SCIENTISTS:

Charles Glover Barkla (1877-1944), English physicist who was awarded the 1917 Nobel Prize in Physics for his work on X-ray scattering and his discovery of the characteristic Röntgen radiations of the elements

Wilhelm Conrad Röntgen (1845-1923), German physicist who discovered X rays in 1895 and was a recipient of the first Nobel Prize in Physics in 1901

George Gabriel Stokes (1819-1903), eminent British mathematician and physicist who theorized about the cause and nature of X rays

Sir Joseph John Thomson (1856-1940), British physicist and teacher who startled scientists by announcing his experimental confirmation that cathode rays consisted of charged particles more than one thousand times lighter than the smallest atom and was awarded the 1906 Nobel Prize in Physics

MATTER IN A NEW STATE

For several decades in the nineteenth century, physicists studied the cathode rays. For an even longer time, scientists had known of the existence of atoms. Nevertheless, during the last decade of the nineteenth century, scientists still had great difficulty in comprehending the physical nature of either cathode rays or atoms. Apparently, atoms of some chemical elements were heavier, and others were lighter. It was not known why. The reason could have been that atoms consisted of different materials, or that the heavier ones had more of the same materials. Chemical facts gave clues about the existence of atoms. Cathode rays appeared to be "tentacles" originating from the atom.

In December, 1895, a sequence of clues, and tentacles, emerged. First, Wilhelm Conrad Röntgen reported from the University of Würzburg that he had discovered X rays. In 1896, Antoine-Henri Becquerel announced to the French Academy of Sciences that uranium spontaneously emitted invisible radiations, which would blacken a photographic plate yet which seemed different from X rays. In 1898, Pierre Curie and Marie Curie detected two new elements that apparently also emitted the same types of radiation. At the same time, in England, Sir Joseph John Thomson made remarkable progress in the study of the cathode rays. He would conclude from experimental evidence that these rays consisted of charged particles. He declared that these charged particles were "matter in a new state" and that the chemical elements were made up of matter.

X-Ray Scattering

By the beginning of the twentieth century, scientists were confronted with a number of intriguing questions about the nature of X rays, how to account for radioactivity, and how to reconcile the apparent endlessness of radioactive emanations with the principle of the first law of thermodynamics, the conservation of energy. It was in this atmosphere of challenging scientific inquiry that Charles Glover Barkla began his scientific career. From 1899 to 1902, he conducted research with Thomson. In 1902, he attended University College in Liverpool and began his lifelong study of X rays.

The veteran mathematical physicist George Gabriel Stokes proposed the "ether pulse" theory about the nature of X rays. He hypothesized that X rays were irregular electromagnetic pulses created by the irregular accelerations of the cathode rays when they were stopped by the atoms in the target of the X-ray tube. With this theory, Thomson derived a mathematical formula expressing the scattering of X rays by electrons. Barkla's first research project was to test experimentally Stokes's and Thomson's theories.

Five years previously, Georges Sagnac had experimented in France on the absorption of X rays by solids—a phenomenon that was directly related to scattering. Sagnac found that the secondary scattered radiation was of distinctly greater absorbability. Barkla showed that the secondary radiation from light gaseous elements was of the same absorbability as that of the primary beam. He worked on air first, then extended the investigation to hydrogen, carbon dioxide, sulfur dioxide, and hydrogen sulfide. The presence of the secondary radiation was tested by an electroscope, with the assumption that the amount of ionization should be proportional to the intensity of the radiation passing through the instrument.

To check the absorbability of the rays—primary and secondary—Barkla used a thin aluminum plate. He published the results in 1903. At the time, the fact that scattering did not modify the absorbability of the radiation appeared to be strong support for the ether pulse theory. From the same set of experiments, Barkla demonstrated that "this scattering is proportional to the mass of the atom." This was a highly satisfying result because it supported the theory that the atoms of different substances are different systems of similar corpuscles, where, in the atom, the number is proportional to its atomic weight. These similar corpuscles, according to most contemporary physicists, was Thomson's "matter in a new state."

Polarized X Rays

In 1904, Barkla began a new series of experiments that would disclose additional physical characteristics of X rays. Because ordinary light, as the propagation of electromagnetic oscillations, is a transverse wave, it can be polarized relatively easily: When it is scattered in the direction at right angles to the incident (primary) beam, the transverse vibrations constituting the light are confined to a plane perpendicular to the primary beam. Barkla was researching the question of whether X rays could be polarized in the same way so that they could be confirmed as electromagnetic waves. This proved to be a serious challenge. It took Barkla two years to perform the difficult experiment and arrive at a clear conclusion that the scattered beam was highly polarized; consequently, X rays were most probably transverse waves, like ordinary light.

X-Ray Scattering

While investigating the intensity in different directions of the secondary radiation, Barkla found that light elements—such as carbon, aluminum, and sulfur—showed marked variation in intensity with direction; calcium showed much less. With iron and even heavier elements, there was practically no difference in intensity in different directions. This phenomenon led Barkla to a closer investigation of the relation between atomic weight and absorbability. The result of his experiments showed that for light elements, the scattered radiation closely resembled the primary radiation, but for elements heavier than calcium, the scattered radiation was quite different from the primary. When Barkla examined the scattered (secondary) radiation more closely, he found that the secondary radiation from metals contained not only scattered radiation of the same character as the primary but also homogeneous radiation that was characteristic of the metallic element itself.

Atomic Weight and Characteristic Radiation

Meanwhile, Barkla also discovered an X-ray phenomenon that was analogous to a discovery made by Stokes: Fluorescent substances fluoresced only when exposed to light of shorter wavelength than that of the fluorescent light emitted by the substance. This phenomenon is known as Stokes's law. Barkla found that the emission of the homogeneous (secondary) radiation occurred only when the incident X-ray beam was harder than the characteristic radiation itself. Moreover, Barkla found some revealing facts about the homogeneous characteristic radiations. Beginning with calcium, and moving toward the heavier elements, the characteristic X-ray radiations form one or two series. From calcium (atomic weight 40) to rhodium (atomic weight 103), there appeared a K series; from silver (atomic weight 108) to cerium (atomic weight 140), there appeared a K series and an L series; from tungsten (atomic weight 184) to bismuth (atomic weight 208), there appeared an L series only. K radiations were softer, L radiations harder. The heavier the atom was, the harder its characteristic radiations. Such phenomena, correlating atomic weight to characteristic X rays closely, showed that the latter must have originated from the atom. In fact, Barkla's discoveries anticipated the assignment to each chemical element an atomic number, which, in general, was recognized as about one-half the atomic weight.

Impact

Following these discoveries in 1906, Barkla and other physicists researched interactions between X rays and matter and achieved historic results. These achievements, accomplished between 1909 and 1923, were categorized in three stages.

First, X rays interact with crystal lattices. In 1909, Max von Laue attended the University of Munich and was influenced by Röntgen and mineralogists who informed him of theories on the structure of crystal solids. Von Laue proceeded to combine the study of X rays with that of solid structures. He developed a mathematical theory based on the assumption that crystal lattices could serve as "diffraction gratings" (a type of instrument in optical experiments that demonstrates the wave character of light) for X rays. This idea was experimentally confirmed, and the confirmation has been highly praised. It opened vast potentials for studying the nature of X rays and the structure of crystal solids. Shortly after von Laue's publication of his work in 1912, William Henry Bragg and his eldest son, Lawrence Bragg, founded the science of crystallography. In particular, William Henry Bragg created the "ionization spectrometer" for measuring the exact wavelengths of X rays; Lawrence Bragg derived the influential equation now named after him. The Bragg equation tells at what angles X rays will be most efficiently diffracted by a crystal layer.

The second stage was the recognition that X rays interact with atoms, especially heavy atoms. Henry Moseley used the Bragg spectrometer soon after its introduction to study the characteristic X rays from the atom. With a new, powerful instrument, Moseley turned to Barkla's line of investigation. Moseley could now measure Barkla's K series and L series with exactness. Significantly extending such measurements, he made wonderful discoveries that have since been called Moseley's law: the mathematical formula that relates the X-ray spectrum of an element to its atomic number. Moseley also made a series of verifiable predictions about the periodic table of elements. Tragically, Moseley was killed in World War I at the Dardanelles. Later, studies in X-ray spectroscopy and its interpretation were accomplished by Karl Manne Georg Siegbahn, winner of the 1924 Nobel Prize in Physics.

The third stage was the recognition that X rays interact with light atoms (free electrons). When Barkla delivered his Nobel Prize speech in 1920 (for Physics in 1917), he declared that in the phenomena of scattering, there is strong positive evidence against any quantum theory. Three years later, in 1923, Arthur Holly Compton was to prove the folly of Barkla's statement. He followed Barkla in experimenting on the comparison of secondary X rays with primary X rays, especially when the former were scattered from light atoms. Compton experimented with the spectrometer and theoretically with the concept of photons and was awarded the Nobel Prize in 1927.

See also X-Ray Crystallography.

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—*Wen-yuan Qian*

YELLOW FEVER VACCINE

THE SCIENCE: The first safe vaccine against the virulent yellow fever virus mitigated some of the deadliest epidemics of the nineteenth and early twentieth centuries.

THE SCIENTISTS:

Max Theiler (1899-1972), South African microbiologist
Wilbur Augustus Sawyer (1879-1951), American physician
Hugh Smith (1902-1995), American physician

A YELLOW FLAG

Yellow fever, caused by a virus and transmitted by mosquitoes, infects humans and monkeys. After the bite of the infecting mosquito, it takes several days before symptoms appear. The onset of symptoms is abrupt, with headache, nausea, and vomiting. Because the virus destroys liver cells, yellowing of the skin and eyes is common. Approximately 10 to 15 percent of patients die after exhibiting the terrifying signs and symptoms. Death occurs usually from liver necrosis (decay) and liver shutdown. Those that survive, however, recover completely and are immunized.

At the beginning of the twentieth century, there was no cure for yellow fever. The best that medical authorities could do was to quarantine the afflicted. Those quarantines usually waved the warning yellow flag, which gave the disease its colloquial name, "yellow jack."

After the *Aëdes aegypti* mosquito was clearly identified as the carrier of the disease in 1900, efforts were made to combat the disease by wiping out the mosquito. Most famous in these efforts were the American army surgeon Walter Reed and the Cuban physician Carlos J. Finlay. This strategy was successful in Panama and Cuba and made possible the construction of the Panama Canal. Still, the yellow fever virus persisted in the tropics, and the opening of the Panama Canal increased the danger of its spreading aboard the ships using this new route.

Moreover, the disease, which was thought to be limited to the jungles of South and Central America, had begun to spread arounds the world to wherever the mosquito *Aëdes aegypti* could carry the virus. Mosquito larvae traveled well in casks of water aboard trading vessels and spread the disease to North America and Europe.

Immunization by Mutation

Max Theiler received his medical education in London. Following that, he completed a four-month course at the London School of Hygiene and Tropical Medicine, after which he was invited to come to the United States to work in the department of tropical medicine at Harvard University.

Max Theiler. (The Nobel Foundation)

While there, Theiler started working to identify the yellow fever organism. The first problem he faced was finding a suitable laboratory animal that could be infected with yellow fever. Until that time, the only animal successfully infected with yellow fever was the rhesus monkey, which was expensive and difficult to care for under laboratory conditions. Theiler succeeded in infecting laboratory mice with the disease by injecting the virus directly into their brains.

Laboratory work for investigators and assistants coming in contact with the yellow fever virus was extremely dangerous. At least six of the scientists at the Yellow Fever Laboratory at the Rockefeller Institute died of the disease, and many other workers were infected. In 1929, Theiler was infected with yellow fever; fortunately, the attack was so mild that he recovered quickly and resumed his work.

During one set of experiments, Theiler produced successive generations of the virus. First, he took virus from a monkey that had died of yellow fever and used it to infect a mouse. Next, he extracted the virus from that mouse and injected it into a second mouse, repeating the same procedure using a third mouse. All of them died of encephalitis (inflammation of the brain). The virus from the third mouse was then used to infect a monkey. Although the monkey showed signs of yellow fever, it recovered completely. When Theiler passed the virus through more mice and then into the abdomen of another monkey, the monkey showed no symptoms of the disease. The results of these experiments were published by Theiler in the journal *Science*.

This article caught the attention of Wilbur Augustus Sawyer, director of the Yellow Fever Laboratory at the Rockefeller Foundation International Health Division in New York. Sawyer, who was working on a yellow fever vaccine, offered Theiler a job at the Rockefeller Foundation, which Theiler accepted. Theiler's mouse-adapted, "attenuated" virus was given to the laboratory workers, along with human immune serum, to protect them against the yellow fever virus. This type of vaccination, however, carried the risk of transferring other diseases, such as hepatitis, in the human serum.

In 1930, Theiler worked with Eugen Haagen, a German bacteriologist, at the Rockefeller Foundation. The strategy of the Rockefeller laboratory was a cautious, slow, and steady effort to culture a strain of the virus so mild as to be harmless to a human but strong enough to confer a long-lasting immunity. (To "culture" something—tissue cells, microorganisms, or other living matter—is to grow it in a specially prepared medium under laboratory conditions.) They started with a new strain of yellow fever harvested from a twenty-eight-year-old West African named Asibi; it was later known as the "Asibi strain." It was a highly virulent strain that in four to seven days killed almost all the monkeys that were infected with it. From time to time, Theiler or his assistant would test the culture on a monkey and note the speed with which it died.

It was not until April, 1936, that Hugh Smith, Theiler's assistant, called to his attention an odd development as noted in the laboratory records of strain 17D. In its 176th culture, 17D had failed to kill the test mice. Some had been paralyzed, but even these eventually recovered. Two monkeys who had received a dose of 17D in their brains survived a mild attack of encephalitis, but those who had taken the infection in the abdomen showed no ill effects whatever. Oddly, subsequent subcultures of the strain killed monkeys and mice at the usual rate. The only explanation possible was that a mutation had occurred unnoticed.

The batch of strain 17D was tried over and over again on monkeys with no harmful effects. Instead, the animals were immunized effectively. Then it was tried on the laboratory staff, including Theiler and his wife, Lillian. The batch injected into humans had the same immunizing effect. Neither Theiler nor anyone else could explain how the mutation of the virus had resulted. Attempts to duplicate the experiment, using the same Asibi virus, failed. Still, this was the first safe vaccine for yellow fever. In June, 1937, Theiler reported this crucial finding in the *Journal of Experimental Medicine*.

IMPACT

Following the discovery of the vaccine, Theiler's laboratory became a production plant for the 17D virus. Before World War II (1939-1945), more than one million vaccination doses were sent to Brazil and other South American countries. After the United States entered the war, eight million soldiers were given the vaccine before being shipped to tropical war zones. In all, approximately fifty million people were vaccinated in the war years.

Yet although the vaccine, combined with effective mosquito control, eradicated the disease from urban centers, yellow fever is still present in large regions of South and Central America and of Africa. The most severe outbreak of yellow fever ever known occurred from 1960 to 1962 in Ethiopia; out of one hundred thousand people infected, thirty thousand died.

The 17D yellow fever vaccine prepared by Theiler in 1937 continues to be the only vaccine used by the World Health Organization, more than fifty years after its discovery. There is a continuous effort by that organization to prevent infection by immunizing the people living in tropical zones.

See also AIDS; Human Immunodeficiency Virus; Hybridomas; Immunology; Oncogenes; Polio Vaccine: Sabin; Polio Vaccine: Salk; Smallpox Vaccination; Stem Cells; Streptomycin; Viruses.

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—*Gershon B. Grunfeld*

Zinjanthropus

THE SCIENCE: At Olduvai Gorge, Tanzania, Louis and Mary Leakey discovered *Zinjanthropus boisei* (later reclassified as *Australopethicus boisei*), one of the oldest hominid fossils.

THE SCIENTISTS:

Louis S. B. Leakey (1903-1972), English anthropologist
Mary Leakey (1913-1996), English archaeologist and anthropologist

OLDUVAI FOSSIL BEDS

The Olduvai Gorge in northern Tanzania owes its origins to massive geological faulting approximately 100,000 years ago. As a result of the changing geology, the Great Rift Valley was formed, which stretches over 6,400 kilometers of East Africa, from Jordan in the north through Kenya and Tanzania to Mozambique in the south. A newly formed river rapidly cut through the previously laid down strata. The strata were formed from a series of Ngorongoro and Lemagrut volcanic eruptions, combined with lake and river deposits laid down millions of years ago.

The gorge has four distinct layers, or beds, numbered I (at the bottom of the gorge) through IV (nearest the top). Bed I is the oldest and has been dated to be more than 2 million years old. While Olduvai is more than 40 kilometers in length and approximately 92 meters deep, it is a small portion of the Great Rift system.

A stone-tool technology was encountered at Olduvai, along with the discovery of several extinct vertebrates, including a 26-million-year-old primate, a member of the genus *Proconsul*. The Oldowan tool tradition, named for Olduvai, was dated to the Lower Pleistocene epoch, which, at that time, was believed to have begun about a million years ago. (More recent dating techniques have pushed this age back another million years.)

THE NUTCRACKER MAN

Louis and Mary Leakey, both anthropologists, had been introduced to the Oldowan tradition and were conducting research in the area, Louis beginning in 1931 and Mary in 1935. On the morning of July 17, 1959, Mary discovered the remains for which she and her husband had long been searching: the animal believed to be responsible for the previously discovered Oldowan tools. She had happened upon the upper dentition and a few fragments of a never-before-documented hominid fossil. The fossil was found very near the bottom of the gorge.

During the next nineteen days, the Leakeys recovered more than four hundred pieces from an almost complete skull. Similar hominid fossils (later reclassified as members of the genus *Australopithecus*) had been found previously in South Africa by anthropologist Raymond Arthur Dart in 1924 and paleontologist Robert Broom in 1936. Yet firm dates could not be established for the South African finds; evidence of associated tool use was not as accurately documented as that encountered at Olduvai.

The hominid discovered by the Leakeys is thought to have lived approximately 1.75 million years ago. They recognized the remains as those of a young adult male, basing their conclusion on the degree of dental

Louis and Mary Leakey

Louis S. B. Leakey, born to English missionary parents in Kenya and initiated into the Kikuyu tribe as a young boy, had varied interests but was ultimately trained as an anthropologist at the University of Cambridge. In 1931, he was accompanied on his first paleontological expedition to Olduvai by Hans Reck, a German geologist. Reck, who had worked at Olduvai prior to 1914, discouraged Leakey from his hope of finding evidence of prehistoric human activity at the gorge; however, within the first day of their arrival, a hand ax was discovered. Leakey recognized this site as an important one, and it was to become famous twenty-eight years later with the discovery by Mary Leakey, his second wife, of the hominid fossil *Zinjanthropus boisei*.

Mary Douglas Nicol was born in England in 1913. She was educated in England as an archaeologist. When she met Leakey in 1933, she was becoming well known for her illustrations of lithic tools. Indeed, it was soon after they met that Leakey asked her to undertake the drawings for the first edition of his book *Adam's Ancestors* (1934). They were married on Christmas Eve, 1936, in England, only days before their departure for Kenya. In 1959, Mary found the *Zinjanthropus* (*Australopithecus boisei*) fossil, which was to propel the Leakey family to worldwide fame. Louis Leakey became something of an instant celebrity with this discovery (if Mary did not), with his picture on newspaper and magazine covers along with the "Nutcracker man."

Mary and Louis grew apart after the *boisei* discovery. By consensus the better scientist of the two, Mary remained at Olduvai working alone for the most part. Louis pursued other projects, as well as some of the benefits of fame. In 1974, Mary began working at Laetoli to the south, where in 1978 she and her colleagues found the amazingly complete footprints of two bipedal hominids cast in volcanic ash. She continued working with paleoanthropologist Tim White, who had also worked with Donald Johanson of Lucy fame. She and White discovered hominid bones and more footprints—narrow and arched, much like those of modern humans—that dated between 3.7 and 3.5 million years ago, about twice the age of *boisei*.

In 1983, Mary retired to Nairobi after more than two decades in the field. She died thirteen years later, at age eighty-three. Despite her lack of formal education, she is considered one of the top anthropologists of the twentieth century.

eruption and development and the evidence of extreme robustness. Furthermore, the dental, facial, and cranial morphology (shape and structure) of the Leakey discovery was distinct from the hominids previously known from South Africa. As a result, the Leakeys classified their discovery into a new genus, *Zinjanthropus*, and species, *boisei*. *Zinj* is Arabic for "East Africa," *anthropus* is Greek for "humankind," and *boisei* is a latinization of "Boise," the family name of Leakey's benefactor, Charles Boise. Because of the specimen's cranial robustness and massive teeth, the fossil's popular name became Nutcracker man.

Impact

The discovery of *Zinjanthropus* affected human paleontology in many ways. The age of the first hominids was pushed back dramatically. Although Dart, Broom, and others had previously given the world cause to accept the notion proposed by the English naturalist Charles Darwin in 1871 that Africa was the cradle of humankind, the various hominid fossils recovered from South Africa did not lend themselves to accurate dating. The discovery of *Zinjanthropus boisei* and the Oldowan tools from the volcanic contexts of Olduvai Gorge, however, allowed accurate radiometric dates

The Leakeys (from left): Son Richard, Mary, and Louis. (Win Parks, National Geographic Society) to be applied. Thus, the age of this early hominid pushed back the age of the earliest hominids well beyond that which previously had been suggested.

It was later determined that the Leakeys' hominid did not represent an entirely new genus but was simply a very robust species of *Australopithecus*, and it was accordingly reclassified as *Australopithecus boisei*, and it is believed to have lived roughtly between 2 million and 1.2 million years ago.

Perhaps the most important impact of the Leakey team was the attention they drew to hominid research. While the Leakeys had become well known among their scientific peers in archaeology, prehistory, and paleontology, the public became equally familiar with their work after their discovery of *Zinjanthropus*. The discussion of this discovery—complete with color photographs and Louis Leakey's personal account in the September, 1960, issue of *National Geographic* magazine—played an important role in obtaining public support in the quest to document the human paleontological record. The support offered by the National Geographic Society led to the doubling of the excavation work being conducted at Olduvai. The increase in the recognition and support of paleontology had a dramatic impact on the scientific search for human fossil ancestors.

See also *Australopithecus*; Cro-Magnon Man; Gran Dolina Boy; Human Evolution; Langebaan Footprints; Lascaux Cave Paintings; Lucy; Neanderthals; Peking Man; Qafzeh Hominids.

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—*Turhon A. Murad, updated by Christina J. Moose*

Nobel Prize Science Laureates

Chemistry

1901	Jacobus H. van't Hoff
1902	Emil Fischer
1903	Svante Arrhenius
1904	Sir William Ramsay
1905	Adolf von Baeyer
1906	Henri Moissan
1907	Eduard Buchner
1908	Ernest Rutherford
1909	Wilhelm Ostwald
1910	Otto Wallach
1911	Marie Curie
1912	Victor Grignard, Paul Sabatier
1913	Alfred Werner
1914	Theodore W. Richards
1915	Richard Willstätter
1916	[Prize held in special fund]
1917	[Prize held in special fund]
1918	Fritz Haber
1919	[Prize held in special fund]
1920	Walther Nernst
1921	Frederick Soddy
1922	Francis W. Aston
1923	Fritz Pregl
1924	[Prize held in special fund]
1925	Richard Zsigmondy
1926	Theodor Svedberg
1927	Heinrich Wieland
1928	Adolf Windaus
1929	Arthur Harden, Hans von Euler-Chelpin
1930	Hans Fischer
1931	Carl Bosch, Friedrich Bergius
1932	Irving Langmuir
1933	[One-third to main fund, two-thirds to special fund]
1934	Harold C. Urey
1935	Frédéric Joliot, Irène Joliot-Curie
1936	Peter Debye

1937	Norman Haworth, Paul Karrer
1938	Richard Kuhn
1939	Adolf Butenandt, Leopold Ruzicka
1940	[One-third to main fund, two-thirds to special fund]
1941	[One-third to main fund, two-thirds to special fund]
1942	[One-third to main fund, two-thirds to special fund]
1943	George de Hevesy
1944	Otto Hahn
1945	Artturi Virtanen
1946	James B. Sumner, John H. Northrop, Wendell M. Stanley
1947	Sir Robert Robinson
1948	Arne Tiselius
1949	William F. Giauque
1950	Otto Diels, Kurt Alder
1951	Edwin M. McMillan, Glenn T. Seaborg
1952	Archer J. P. Martin, Richard L. M. Synge
1953	Hermann Staudinger
1954	Linus Pauling
1955	Vincent du Vigneaud
1956	Sir Cyril Hinshelwood, Nikolay Semenov
1957	Lord Todd
1958	Frederick Sanger
1959	Jaroslav Heyrovsky
1960	Willard F. Libby
1961	Melvin Calvin
1962	Max F. Perutz, John C. Kendrew
1963	Karl Ziegler, Giulio Natta
1964	Dorothy Crowfoot Hodgkin
1965	Robert B. Woodward
1966	Robert S. Mulliken
1967	Manfred Eigen, Ronald G. W. Norrish, George Porter
1968	Lars Onsager
1969	Derek Barton, Odd Hassel
1970	Luis Leloir
1971	Gerhard Herzberg
1972	Christian Anfinsen, Stanford Moore, William H. Stein
1973	Ernst Otto Fischer, Geoffrey Wilkinson
1974	Paul J. Flory
1975	John Cornforth, Vladimir Prelog
1976	William Lipscomb
1977	Ilya Prigogine

1978	Peter Mitchell
1979	Herbert C. Brown, Georg Wittig
1980	Paul Berg, Walter Gilbert, Frederick Sanger
1981	Kenichi Fukui, Roald Hoffmann
1982	Aaron Klug
1983	Henry Taube
1984	Bruce Merrifield
1985	Herbert A. Hauptman, Jerome Karle
1986	Dudley R. Herschbach, Yuan T. Lee, John C. Polanyi
1987	Donald J. Cram, Jean-Marie Lehn, Charles J. Pedersen
1988	Johann Deisenhofer, Robert Huber, Hartmut Michel
1989	Sidney Altman, Thomas R. Cech
1990	Elias James Corey
1991	Richard R. Ernst
1992	Rudolph A. Marcus
1993	Kary B. Mullis, Michael Smith
1994	George A. Olah
1995	Paul J. Crutzen, Mario J. Molina, F. Sherwood Rowland
1996	Robert F. Curl, Jr., Sir Harold Kroto, Richard E. Smalley
1997	Paul D. Boyer, John E. Walker, Jens C. Skou
1998	Walter Kohn, John Pople
1999	Ahmed Zewail
2000	Alan Heeger, Alan G. MacDiarmid, Hideki Shirakawa
2001	William S. Knowles, Ryoji Noyori, K. Barry Sharpless
2002	John B. Fenn, Koichi Tanaka, Kurt Wüthrich
2003	Peter Agre, Roderick MacKinnon
2004	Aaron Ciechanover, Avram Hershko, Irwin Rose
2005	Yves Chauvin, Robert H. Grubbs, Richard R. Schrock

Physics

1901	Wilhelm Conrad Röntgen
1902	Hendrik A. Lorentz, Pieter Zeeman
1903	Henri Becquerel, Pierre Curie, Marie Curie
1904	Lord Rayleigh
1905	Philipp Lenard
1906	J. J. Thomson
1907	Albert A. Michelson
1908	Gabriel Lippmann
1909	Guglielmo Marconi, Ferdinand Braun
1910	Johannes Diderik van der Waals

1911	Wilhelm Wien
1912	Gustaf Dalén
1913	Heike Kamerlingh Onnes
1914	Max von Laue
1915	William Bragg, Lawrence Bragg
1916	[Prize held in special fund]
1917	Charles Glover Barkla
1918	Max Planck
1919	Johannes Stark
1920	Charles Edouard Guillaume
1921	Albert Einstein
1922	Niels Bohr
1923	Robert A. Millikan
1924	Manne Siegbahn
1925	James Franck, Gustav Hertz
1926	Jean Baptiste Perrin
1927	Arthur H. Compton, C. T. R. Wilson
1928	Owen Willans Richardson
1929	Louis de Broglie
1930	Venkata Raman
1931	[Prize held in special fund]
1932	Werner Heisenberg
1933	Erwin Schrödinger, Paul A. M. Dirac
1934	[One-third to main fund, two-thirds to special fund]
1935	James Chadwick
1936	Victor F. Hess, Carl D. Anderson
1937	Clinton Davisson, George Paget Thomson
1938	Enrico Fermi
1939	Ernest Lawrence
1940	[One-third to main fund, two-thirds to special fund]
1941	[One-third to main fund, two-thirds to special fund]
1942	[One-third to main fund, two-thirds to special fund]
1943	Otto Stern
1944	Isidor Isaac Rabi
1945	Wolfgang Pauli
1946	Percy W. Bridgman
1947	Edward V. Appleton
1948	Patrick M. S. Blackett
1949	Hideki Yukawa
1950	Cecil Powell
1951	John Cockcroft, Ernest T. S. Walton

1952	Felix Bloch, E. M. Purcell
1953	Frits Zernike
1954	Max Born, Walther Bothe
1955	Willis E. Lamb, Polykarp Kusch
1956	William B. Shockley, John Bardeen, Walter H. Brattain
1957	Chen Ning Yang, Tsung-Dao Lee
1958	Pavel A. Cherenkov, Il’ja M. Frank, Igor Y. Tamm
1959	Emilio Segrè, Owen Chamberlain
1960	Donald A. Glaser
1961	Robert Hofstadter, Rudolf Mössbauer
1962	Lev Landau
1963	Eugene Wigner, Maria Goeppert-Mayer, J. Hans D. Jensen
1964	Charles H. Townes, Nicolay G. Basov, Aleksandr M. Prokhorov
1965	Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman
1966	Alfred Kastler
1967	Hans Bethe
1968	Luis Alvarez
1969	Murray Gell-Mann
1970	Hannes Alfvén, Louis Néel
1971	Dennis Gabor
1972	John Bardeen, Leon N. Cooper, Robert Schrieffer
1973	Leo Esaki, Ivar Giaever, Brian D. Josephson
1974	Martin Ryle, Antony Hewish
1975	Aage N. Bohr, Ben R. Mottelson, James Rainwater
1976	Burton Richter, Samuel C. C. Ting
1977	Philip W. Anderson, Sir Nevill F. Mott, John H. van Vleck
1978	Pyotr Kapitsa, Arno Penzias, Robert Woodrow Wilson
1979	Sheldon Glashow, Abdus Salam, Steven Weinberg
1980	James Cronin, Val Fitch
1981	Nicolaas Bloembergen, Arthur L. Schawlow, Kai M. Siegbahn
1982	Kenneth G. Wilson
1983	Subramanyan Chandrasekhar, William A. Fowler
1984	Carlo Rubbia, Simon van der Meer
1985	Klaus von Klitzing
1986	Ernst Ruska, Gerd Binnig, Heinrich Rohrer
1987	J. Georg Bednorz, K. Alex Müller
1988	Leon M. Lederman, Melvin Schwartz, Jack Steinberger
1989	Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul
1990	Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor
1991	Pierre-Gilles de Gennes
1992	Georges Charpak

1993	Russell A. Hulse, Joseph H. Taylor, Jr.
1994	Bertram N. Brockhouse, Clifford G. Shull
1995	Martin L. Perl, Frederick Reines
1996	David M. Lee, Douglas D. Osheroff, Robert C. Richardson
1997	Steven Chu, Claude Cohen-Tannoudji, William D. Phillips
1998	Robert B. Laughlin, Horst L. Störmer, Daniel C. Tsui
1999	Gerardus ‘t Hooft, Martinus J. G. Veltman
2000	Zhores I. Alferov, Herbert Kroemer, Jack S. Kilby
2001	Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman
2002	Raymond Davis, Jr., Masatoshi Koshiba, Riccardo Giacconi
2003	Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett
2004	David J. Gross, H. David Politzer, Frank Wilczek
2005	Roy J. Glauber, John L. Hall, Theodor W. Hänsch

Physiology or Medicine

1901	Emil von Behring
1902	Ronald Ross
1903	Niels Ryberg Finsen
1904	Ivan Pavlov
1905	Robert Koch
1906	Camillo Golgi, Santiago Ramón y Cajal
1907	Alphonse Laveran
1908	Ilya Mechnikov, Paul Ehrlich
1909	Theodor Kocher
1910	Albrecht Kossel
1911	Allvar Gullstrand
1912	Alexis Carrel
1913	Charles Richet
1914	Robert Bárány
1915	[Prize held in special fund]
1916	[Prize held in special fund]
1917	[Prize held in special fund]
1918	[Prize held in special fund]
1919	Jules Bordet
1920	August Krogh
1921	[Prize held in special fund]
1922	Archibald V. Hill, Otto Meyerhof
1923	Frederick G. Banting, John Macleod
1924	Willem Einthoven
1925	[Prize held in special fund]

1926	Johannes Fibiger
1927	Julius Wagner-Jauregg
1928	Charles Nicolle
1929	Christiaan Eijkman, Sir Frederick Hopkins
1930	Karl Landsteiner
1931	Otto Warburg
1932	Sir Charles Sherrington, Edgar Adrian
1933	Thomas H. Morgan
1934	George H. Whipple, George R. Minot, William P. Murphy
1935	Hans Spemann
1936	Sir Henry Dale, Otto Loewi
1937	Albert Szent-Györgyi
1938	Corneille Heymans
1939	Gerhard Domagk
1940	[One-third to main fund, two-thirds to special fund]
1941	[One-third to main fund, two-thirds to special fund]
1942	[One-third to main fund, two-thirds to special fund]
1943	Henrik Dam, Edward A. Doisy
1944	Joseph Erlanger, Herbert S. Gasser
1945	Sir Alexander Fleming, Ernst B. Chain, Sir Howard Florey
1946	Hermann J. Muller
1947	Carl Cori, Gerty Cori, Bernardo Houssay
1948	Paul Müller
1949	Walter Hess, Egas Moniz
1950	Edward C. Kendall, Tadeus Reichstein, Philip S. Hench
1951	Max Theiler
1952	Selman A. Waksman
1953	Hans Krebs, Fritz Lipmann
1954	John F. Enders, Thomas H. Weller, Frederick C. Robbins
1955	Hugo Theorell
1956	André F. Cournand, Werner Forssmann, Dickinson W. Richards
1957	Daniel Bovet
1958	George Beadle, Edward Tatum, Joshua Lederberg
1959	Severo Ochoa, Arthur Kornberg
1960	Sir Frank Macfarlane Burnet, Peter Medawar
1961	Georg von Békésy
1962	Francis Crick, James Watson, Maurice Wilkins
1963	Sir John Eccles, Alan L. Hodgkin, Andrew F. Huxley
1964	Konrad Bloch, Feodor Lynen
1965	François Jacob, André Lwoff, Jacques Monod
1966	Peyton Rous, Charles B. Huggins

1967	Ragnar Granit, Haldan K. Hartline, George Wald
1968	Robert W. Holley, H. Gobind Khorana, Marshall W. Nirenberg
1969	Max Delbrück, Alfred D. Hershey, Salvador E. Luria
1970	Sir Bernard Katz, Ulf von Euler, Julius Axelrod
1971	Earl W. Sutherland, Jr.
1972	Gerald M. Edelman, Rodney R. Porter
1973	Karl von Frisch, Konrad Lorenz, Nikolaas Tinbergen
1974	Albert Claude, Christian de Duve, George E. Palade
1975	David Baltimore, Renato Dulbecco, Howard M. Temin
1976	Baruch S. Blumberg, D. Carleton Gajdusek
1977	Roger Guillemin, Andrew V. Schally, Rosalyn Yalow
1978	Werner Arber, Daniel Nathans, Hamilton O. Smith
1979	Allan M. Cormack, Godfrey N. Hounsfield
1980	Baruj Benacerraf, Jean Dausset, George D. Snell
1981	Roger W. Sperry, David H. Hubel, Torsten N. Wiesel
1982	Sune K. Bergström, Bengt I. Samuelsson, John R. Vane
1983	Barbara McClintock
1984	Niels K. Jerne, Georges J. F. Köhler, César Milstein
1985	Michael S. Brown, Joseph L. Goldstein
1986	Stanley Cohen, Rita Levi-Montalcini
1987	Susumu Tonegawa
1988	Sir James W. Black, Gertrude B. Elion, George H. Hitchings
1989	J. Michael Bishop, Harold E. Varmus
1990	Joseph E. Murray, E. Donnall Thomas
1991	Erwin Neher, Bert Sakmann
1992	Edmond H. Fischer, Edwin G. Krebs
1993	Richard J. Roberts, Phillip A. Sharp
1994	Alfred G. Gilman, Martin Rodbell
1995	Edward B. Lewis, Christiane Nüsslein-Volhard, Eric F. Wieschaus
1996	Peter C. Doherty, Rolf M. Zinkernagel
1997	Stanley B. Prusiner
1998	Robert F. Furchgott, Louis J. Ignarro, Ferid Murad
1999	Günter Blobel
2000	Arvid Carlsson, Paul Greengard, Eric R. Kandel
2001	Leland H. Hartwell, Tim Hunt, Sir Paul Nurse
2002	Sydney Brenner, H. Robert Horvitz, John E. Sulston
2003	Paul C. Lauterbur, Sir Peter Mansfield
2004	Richard Axel, Linda B. Buck
2005	Barry J. Marshall, J. Robin Warren

Time Line

The more than 750 events below represent milestones in the major sciences, theoretical and applied, from ancient times to 2005.

585 B.C.E.	Thales of Miletus, a Greek philosopher, predicts a solar eclipse. About the same time he theorizes that water is the fundamental element for all substances.
c. 550 B.C.E.	Construction of trireme changes naval warfare.
c. 550 B.C.E.	Greek philosopher and astronomer Anaximander proposes a theory of biological evolution.
c. 530 B.C.E.	Greek mathematician and philosopher Pythagoras invents the Pythagorean theorem. He also argues that the Earth is a sphere and that the Sun, stars, and planets revolve around it.
c. 500 B.C.E.	Chinese physicians begin the practice of acupuncture.
500 B.C.E.	Some Greek city-states take care of sick people in hospitals called *aesculapia* (named after Aesclepius, the god of medicine).
c. 500 B.C.E.	The Greek physician and scientist Alcmaeon of Croton makes the first known dissections of dead human bodies.
5th cent. B.C.E.	Greek philosopher Anaxagoras writes *On Nature*, arguing that mind exists and that matter is composed of an infinite number of atomic elements.
c. 430 B.C.E.	Death of Greek philosopher Empedocles, who held that all matter is made of four elements: water, fire, air, and earth.
c. 400 B.C.E.	Greek philosopher Philolaus is the first known person to argue that Earth orbits around the Sun.
c. 370 B.C.E.	Death of Greek physician Hippocrates, author of many books with detailed case histories and proposed physical explanations for diseases. The Hippocratic Oath, which appears later, represents his principles.
c. 325 B.C.E.	Greek physician Praxagoras of Cos discovers the value of measuring the pulse when diagnosing diseases.
c. 323 B.C.E.	Aristotle theorizes about the nature of species, reproduction, and hybrids.

c. 320 B.C.E.	Theophrastus initiates the study of botany.
312 B.C.E.	First Roman aqueduct is built.
300 B.C.E.	Babylonian mathematicians develop a symbol for zero.
c. 300 B.C.E.	Greek mathematician Euclid of Egypt writes *Elements*, which includes a summary of plane and solid geometry.
c. 300 B.C.E.	*The Yellow Emperor's Classic of Internal Medicine*, a compilation attributed to Chinese emperor Huangdi, contains references to the function of the heart and the circulation of the blood.
Early 3d cent. B.C.E.	Greek astronomer Aristarchus of Samos writes *On the Size and Distance of the Sun and the Moon*, arguing that the Earth revolves around the Sun.
c. 250 B.C.E.	Greek scientist Archimedes discovers the law of specific gravity, later known as Archimedes' principle.
From 240 B.C.E.	Romans learn to use the arch in building.
240 B.C.E.	Chinese astronomers make the first known observation of Halley's comet.
240 B.C.E.	Eratosthenes of Cyrene, librarian of Alexandria, Egypt, correctly calculates the circumference of the Earth at about 25,000 miles.
221 B.C.E.-220 C.E.	Advances are made in Chinese agricultural technology.
200 B.C.E.	The Greeks invent the astrolabe to determine the positions of the stars.
165 B.C.E.	The Chinese make the first known observations of sunspots.
150 B.C.E.	Greek astronomer Hipparchus of Nicaea calculates that the Moon is about 240,000 miles from the Earth.
100 B.C.E.	The Romans begin to use water power to mill flour.
c. 100 B.C.E.	Greek philosopher Poseidonius shows correlation between tides and the lunar cycle.
46 B.C.E.	Establishment of the Julian calendar.
7 B.C.E.	Greek philosopher Strabo summarizes geographical knowledge in his *Geography*.
c. 62 C.E.	Hero of Alexander invents a simple steam engine, which is never found to have a practical use.

77 C.E.	Roman natural philosopher Pliny the Elder publishes *Natural History*, which will serve as a standard scientific handbook until the Renaissance.
2d cent. C.E.	The Daoist religious leader Zhang Daoling composes a guide of charms and incantations that presumably cure diseases.
c. 105 C.E.	Chinese inventor Cai Lun makes paper out of wood, rags, or other materials containing cellulose.
c. 150 C.E.	Alexandrian scientist Ptolemy argues that all heavenly bodies revolve around a fixed Earth in the *Almagest*.
c. 157-201 C.E.	Greek physician and anatomist Galen proves that the arteries carry blood but incorrectly explains how the blood passes through the heart.
c. 250 C.E.	The Maya in Mexico and Central America are beginning scientific and technological advances that will continue for about six hundred years.
c. 350 C.E.	The Chinese invent an early form of printing.
369 C.E.	Saint Basil erects a hospital at Caesarea.
c. 400 C.E.	The Chinese invent the wheelbarrow.
563	Silk worms are smuggled to the Byzantine Empire.
595-665	Invention of decimals and negative numbers.
7th-early 8th cent.	Maya build astronomical observatory at Palenque.
7th-8th cent.	Papermaking spreads to Korea, Japan, and Central Asia.
c. 700	The bow and arrow spread into North America.
c. 700-1000	The heavy plow increases agricultural yields.
Mid-9th cent.	Invention of firearms using gunpowder.
c. 1045	In China, Bi Sheng develops movable earthenware type.
c. 1200	Development of scientific cattle-breeding techniques.
1275	Invention of the first mechanical clock.
1328	Thomas Bradwardine's *Treatise on Proportions* begins a period of intense investigation at Merton College, Oxford, into what would later be called the laws of physics.
c. 1450-1456	Gutenberg pioneers the printing press, culminating in the publication of Gutenberg's Mazarin Bible.

1462	Regiomontanus (Johann Müller) completes the *Epitome* of Ptolemy's *Almagest*. His work forms the basis of trigonometry in Western Europe as handed down from the Arab world, and his astronomical observations and charts will be used by Christopher Columbus.
1474	Great Wall of China is built.
c. 1478-1519	Leonardo da Vinci compiles his notebooks.
1490's	Aldus Manutius founds the Aldine Press.
Beginning 1490	Development of the camera obscura.
1490-1492	Martin Behaim builds the first world globe.
16th cent.	Evolution of the galleon.
16th cent.	Proliferation of firearms.
c. 1510	Invention of the watch.
1517	Fracastoro develops his theory of fossils.
1530's-1540's	Paracelsus presents his theory of disease.
1543	Copernicus publishes *De revolutionibus*, articulating his heliocentric view of the universe.
1543	Vesalius publishes *On the Fabric of the Human Body*, which will be used for human anatomical studies for generations.
1546	Fracastoro discovers that contagion spreads disease.
1550's	Tartaglia publishes *The New Science*.
1553	Michael Servetus describes the circulatory system.
c. 1560's	Invention of the "lead" (graphite) pencil.
1569	Mercator publishes his world map.
1572-1574	Tycho Brahe observes a supernova and conducts astronomical observations and measurements on which Johannes Kepler will base much of his work.
1580's-1590's	Galileo conducts his early experiments in motion and falling bodies.
1582	Gregory XIII reforms the Western calendar.
1600	William Gilbert publishes *De Magnete*, pioneering the study of magnetism and Earth's magnetic field.
17th cent.	England undergoes an agricultural revolution.

17th cent.	Rise of the “gunpowder empires” with a new type of warfare and geopolitical relations based on advances in firearms and gunpowder-based weaponry.
1601-1672	Rise of European scientific societies, which join great mathematical and scientific minds with official approval and institutionalized support.
Sept., 1608	Hans Lippershey invents a simple telescope, credited as the first.
1609-1619	Johannes Kepler develops his laws of planetary motion.
1610	Galileo confirms the heliocentric model of the solar system.
1612	Sanctorius (Santorio) invents the clinical thermometer.
1615-1696	Sir Isaac Newton and Gottfried Wilhelm Leibniz independently invent the calculus.
1620	Sir Francis Bacon publishes *Novum Organum*, in which he advocates an inductive, empirical scientific method.
1623-1674	Appearance of the earliest calculators.
1629	In Persia (Iran), the Ṣafavid Dynasty flourishes under ʿAbbās the Great.
1632	Galileo publishes *Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*.
1637	René Descartes publishes *Discourse on Method*, articulating the Cartesian scientific method.
1638	The printing press arrives in North America.
1643	Evangelista Torricelli measures atmospheric pressure.
1651	William Harvey suggests that all living things must originate in an egg.
1655-1663	Francesco Grimaldi discovers the principle of light diffraction.
Feb., 1656	Christiaan Huygens identifies the rings of Saturn.
1660’s-1700	Antoni van Leeuwenhoek and others conduct the first observations using microscopes.

1660-1692	The "father of modern chemistry," Robert Boyle, discovers the inverse relationship between the pressure and volume of a gas and uses a corpuscular (atomic) theory of matter to explain his experimental results.
1664	Thomas Willis identifies the basal ganglia.
1665	Gian Domenico Cassini discovers Jupiter's Great Red Spot.
1669	Nicholas Steno, the "father of stratigraphy," presents his theories of fossils and dynamic geology.
c. 1670	First widespread smallpox inoculations using a method imported from the Ottoman Empire, variolation.
Late Dec., 1671	Sir Isaac Newton builds the first reflecting telescope.
1673	Christiaan Huygens explains the pendulum.
1676	Thomas Sydenham advocates clinical observation.
Dec. 7, 1676	Ole Rømer calculates the speed of light.
1677	Antoni van Leeuwenhoek describes sperm and eggs and collects evidence that helps disprove the theory of spontaneous generation.
1686	Edmond Halley develops the first weather map.
Summer, 1687	Sir Isaac Newton publishes his *Principia*, the most important scientific treatise of the century, in which he presents his theory of universal gravitation.
1691-1694	German botanist Rudolph Jacob Camerarius establishes the existence of sex in plants.
July 25, 1698	Thomas Savery patents the first successful steam engine.
1701	Jethro Tull invents the seed drill.
1704	Sir Isaac Newton publishes *Opticks*.
1705	Edmond Halley predicts the return of his comet.
1705-1712	Thomas Newcomen develops the steam engine.
1709	Darby invents coke-smelting of iron ore.
1714	Mill patents the typewriter.
1714	Daniel Fahrenheit develops the mercury thermometer.
1714-1735	The quest for a means of determining longitude at sea leads John Harrison to develop his chronometer.

1718	Publication of Daniel Bernoulli's *Calculus of Variations*.
1718	Geoffroy issues the *Table of Affinites*.
1722	René-Antoine Réaumur discovers carbon's role in hardening steel.
1722-1733	Abraham de Moivre describes the bell-shaped curve.
1723	Stahl postulates phlogiston as the basis for combustion.
1724	The St. Petersburg Academy of Sciences is established in Russia.
1725	John Flamsteed, Britain's first astronomer royal, issues the first comprehensive star catalog, *Historia Coelistis Britannica*.
1729	Stephen Gray discovers the principles of electric conduction.
1733	Charles Du Fay describes positive and negative electric charge.
1733	John Kay invents the flying shuttle.
1735	George Hadley describes atmospheric circulation.
1735	Carl Linnaeus creates the binomial system of classification of plants and animals.
1735-1743	Charles La Condamine measures a meridional arc at the equator and explores the Amazon River basin.
1738	Daniel Bernoulli proposes the kinetic theory of gases.
1742	Anders Celsius proposes an international fixed temperature scale.
1743-1744	Jean le Rond d'Alembert develops his axioms of motion.
1745	Invention of the Leyden jar.
1745	Mikhail Lomonosov issues the first catalog of minerals.
1746	John Roebuck develops the lead-chamber process.
1747	Andreas Marggraf extracts sugar from beets.
1748	James Bradley discovers the nutation of Earth's axis.
1748	Jean-Antoine Nollet discovers osmosis.

1748	Maria Agnesi publishes *Analytical Institutions*, a two-volume textbook on the calculus that offers a complete synthesis of the mathematical methods developed in the scientific revolution.
1748	Leonhard Euler develops integral calculus.
1749-1789	Georges Leclerc (comte de Buffon) publishes his *Natural History*, the first comprehensive examination of the natural world.
1751	Pierre Louis de Maupertuis postulates “hereditary particles” as the basis for inherited traits.
1752	Benjamin Franklin demonstrates the electrical nature of lightning.
1752	Johann Tobias Mayer’s lunar tables enable mariners to determine longitude at sea.
1753	James Lind identifies citrus fruit as a preventive for scurvy.
1755	Joseph Black identifies carbon dioxide.
1757	Alexander Monro distinguishes between lymphatic and blood systems.
1759	Franz Aepinus publishes *Theory of Electricity and Magnetism*.
1760’s	Robert Bakewell begins selective livestock breeding.
1764	James Hargreaves invents the spinning jenny, which dramatically increases the output of the textile industry.
1764	The Reverend Thomas Bayes issues his “Essay Towards Solving a Problem in the Doctrine of Chances,” on inverse probability.
1765-1769	James Watt develops his steam engine.
1766	Albrecht von Haller publishes *Elements of Human Physiology*.
1767-1768	Lazzaro Spallanzani refutes the theory of spontaneous generation.
1768-1771	Richard Arkwright develops the water frame.
1769-1770	Nicolas Cugnot builds a steam-powered road carriage.
1771	Discovery of picric acid and its explosive properties.
1772-1789	Antoine-Laurent Lavoisier devises the modern system of chemical nomenclature.

c. 1773	Sir William Herschel builds his reflecting telescope.
1774	Joseph Priestley discovers oxygen.
1776	First test of a submarine in warfare.
1777	Jan Ingenhousz discovers photosynthesis.
1779	Compton invents the spinning mule.
1783	Henry Cort improves iron processing.
1783	Nicolas Leblanc develops a process for producing soda from common salt.
1784	Adrien-Marie Legendre introduces polynomials.
1784-1785	Henry Cavendish discovers the composition of water.
1784-1788	Andrew Meikle invents the drum thresher.
1785	Edmund Cartwright invents the steam-powered loom.
1785-1788	James Hutton proposes the uniformitarian theory of the history of Earth and geologic change.
1789	Invention of the guillotine.
1790	Samuel Slater invents a cotton-spinning mill and will become known as the father of the American cotton industry.
1793	Eli Whitney invents the cotton gin.
1795	Invention of the flax spinner.
1796	Pierre-Simon Laplace articulates his nebular hypothesis.
1796-1798	Edward Jenner develops smallpox vaccination.
1798	Thomas Robert Malthus publishes *An Essay on the Principle of Population*.
1799	Discovery of the earliest anesthetics.
1799	Joseph Louis Proust establishes law of definite proportions, thus effectively distinguishing between chemical elements and chemical compounds.
1800	Alessandro Volta invents the battery.
1801	Astronomers make the first discovery of an asteroid, Ceres.
1803-1807	John Dalton formulates the atomic theory of matter.
1804	Nicolas de Saussure publishes *Chemical Research in Vegetation*.
1804	First successful steam locomotive runs in Wales.

c. 1805	William H. Wollaston develops principles of modern metallurgy and later discovers the dark lines in the solar spectrum.
1809	Sir Humphry Davy invents the arc lamp.
1809	Jean-Baptiste Lamarck publishes *Zoological Philosophy*, in which he sets forth his law of acquired characteristics.
1814	Joseph Fraunhofer invents the spectroscope.
1816	René Laennec invents the stethoscope.
1818-1843	Triangulation Survey of India.
1820’s	André Ampère reveals magnetism’s relationship to electricity.
1823	William Buckland conducts early studies of dinosaurs.
1829	Louis Braille invents printing for the blind.
1830	Sir Charles Lyell publishes *Principles of Geology*.
1831	Michael Faraday converts magnetic force into electricity.
1831	Cyrus Hall McCormick invents the reaper.
1835	Charles Babbage invents a mechanical calculator.
1836	Samuel Colt patents the revolver.
1838	G. J. Mulder precipitates a fibrous material from cells, which he calls “protein.”
1838-1839	Matthias Schleiden and Theodor Schwann’s cell theory becomes the foundation of modern biology.
1839	Louis Daguerre and Joseph Niepce invent daguerreotype photography.
1840	Justus von Liebig invents artificial fertilizers.
1844	Charles Goodyear patents vulcanized rubber.
1846	Elias Howe patents his sewing machine.
1846	First demonstration of surgical anesthesia by ether inhalation.
1847	Ignaz Philipp Semmelweis recognizes that puerperal fever is spreading by transmission from doctors, nurses, and medical students within his hospital and advances antiseptic practices by insisting on hand washing.

1847	George Boole publishes *Mathematical Analysis of Logic*, establishing the field of mathematical logic.
1850	Rudolf Clausius formulates second law of thermodynamics.
1850	The giant moa becomes extinct.
1850	Theodore Schwann, Matthias Schleiden, and Rudolf Virchow recognize that tissues are made up of cells.
1855	Florence Nightingale reforms nursing in the Crimea.
1855	Alfred Russel Wallace publishes *On the Law Which Has Regulated the Introduction of New Species*, in which he develops the theory of natural selection around the same time as Charles Darwin.
1855-1859	Sir Henry Bessemer develops new methods for processing steel.
1856	A Neanderthal skull is found near Düsseldorf.
1856	Louis Pasteur begins research into fermentation, later developing his "pasteurization" process.
1858	Étienne Lenoir invents the internal combustion engine.
1859	Charles Darwin publishes *On the Origin of Species by Means of Natural Selection*, in which he sets forth his theory of natural selection, the mechanism of evolution.
1861	The oldest bird fossil, *Archaeopteryx*, is discovered at Solnhofen.
1864-1867	Joseph Lister promotes antiseptic surgery.
1866	Alfred Nobel invents dynamite.
1866	Ernst Haeckel develops the hypothesis that hereditary information is transmitted by the cell nucleus.
1866	Gregor Mendel, an Austrian monk, publishes a paper introducing his ideas of the mechanisms of heredity, including dominant and recessive traits.
1868	The bones of a Cro-Magnon skeleton, thought to be the earliest modern human being, are discovered in France.
1868	Christopher Latham Sholes patents a practical typewriter.
1869	George Westinghouse patents air brakes.

1869	Friedrich Miescher isolates “nuclein” from the nuclei of white blood cells, which is later found to be the nucleic acids DNA and RNA.
1869	Dmitry Mendeleyev develops the periodic table of elements.
1871	Darwin Publishes *The Descent of Man and Selection in Relation to Sex*.
1873	Jean-Martin Charcot publishes *Leçons sur les maladies du systeme nerveux*.
1875	Oskar Hertwig demonstrates the fertilization of an ovum in a sea urchin, establishing the principle of sexual reproduction: the union of egg and sperm cells.
1876	Alexander Graham Bell demonstrates the telephone.
1876	Nikolaus Otto invents a practical internal combustion engine.
1877	Thomas Alva Edison patents the cylinder phonograph.
1878	Eadweard Muybridge uses photography to study animal movement.
1879	Thomas Alva Edison demonstrates the incandescent lamp, an early form of the lightbulb.
1880	Walter Fleming first describes mitosis.
1882	The first birth control clinic is established in Amsterdam.
1882-1884	Robert Koch isolates microorganisms that cause tuberculosis and cholera.
1883	Wilhelm Roux theorizes that mitosis must result in equal sharing of all chromosomal particles.
1883	Francis Galton founds the field of eugenics.
1884	Hiram Stevens Maxim improves the machine gun.
1885	Carl Benz develops the first practical automobile.
1887	Hannibal Williston Goodwin develops celluloid film.
1887-1890	Theodor Boveri notes that chromosomes are preserved through cell division and that sperm and egg contribute equal numbers of chromosomes.
1888	John Boyd Dunlop patents the pneumatic tire.

1888-1906	Santiago Ramón y Cajal establishes the neuron as the functional unit of the nervous system.
1890-1901	Emil von Behring discovers the diphtheria antitoxin.
1893	Rudolf Diesel patents the diesel engine.
1895	Wilhelm Röntgen discovers X rays.
1896	Guglielmo Marconi patents the telegraph.
1897	Felix Hoffman invents aspirin.
1897	Sir Ronald Ross discovers the malaria bacillus.
1897-1901	John Jacob Abel and Jokichi Takamine independently isolate adrenaline.
July, 1897-July, 1904	Vilhelm Bjerknes publishes the first weather forecasting computational hydrodynamics.
1898	Martinus Beijerinck discovers viruses.
1898-1902	Teisserenc de Bort discovers the stratosphere and the troposphere.
Sept., 1898-July, 1900	David Hilbert develops a model for Euclidean geometry in arithmetic.
1899-1902	Henri-Léon Lebesgue develops new integration theory.
Early 1900's	Willem Einthoven develops the forerunner of the electrocardiogram.
1900	Sir Frederick Hopkins discovers tryptophan, an essential amino acid.
1900	Emil Wiechert invents the inverted pendulum seismography.
Mar.-June, 1900	Hugo de Vries and associates discover Gregor Johann Mendel's ignored studies of inheritance.
Mar. 23, 1900	Arthur Evans discovers the Minoan civilization on Crete.
1900-1901	Karl Landsteiner discovers human blood groups.
June, 1900-Feb., 1901	Walter Reed establishes that yellow fever is transmitted by mosquitoes.
July 2, 1900	Ferdinand von Zeppelin constructs the first dirigible that flies.
Dec. 14, 1900	Max Planck announces his quantum theory.
1901	Peter Cooper Hewitt invents the mercury vapor lamp.

1901	Julius Elster and Hans Friedrich Geitel demonstrate radioactivity in rocks, springs, and air.
1901	The first synthetic vat dye, indanthrene blue, is synthesized.
1901	Gerrit Grijns proposes that beriberi is caused by a nutritional deficiency.
1901	Ilya Ivanov develops artificial insemination.
Dec. 12, 1901	Guglielmo Marconi receives the first transatlantic telegraphic radio transmission.
1901-1904	Frederic Stanley Kipping discovers silicones.
1902	Eldridge R. Johnson perfects the process to mass-produce disc recordings.
1902	Beppo Levi recognizes the axiom of choice in set theory.
1902	Clarence McClung plays a role in the discovery of the sex chromosome.
1902	Walter S. Sutton states that chromosomes are paired and could be carriers of hereditary traits.
1902	Alexis Carrel develops a technique for rejoining severed blood vessels.
1902	Richard Zsigmondy invents the ultramicroscope.
1902	Arthur Edwin Kennelly and Oliver Heaviside propose the existence of the ionosphere.
1902-1903	Ivan Pavlov develops the concept of reinforcement.
Jan., 1902	The French expedition at Susa discovers the Hammurabi code.
Apr.-June, 1902	William Maddock Bayliss and Ernest Henry Starling discover secretin and establish the role of hormones.
June 16, 1902	Bertrand Russell discovers the “Great Paradox” concerning the set of all sets.
1903	Konstantin Tsiolkovsky proposes that liquid oxygen be used for space travel.
1903-1904	George Ellery Hale establishes Mount Wilson Observatory.
Sept. 10, 1903	Antoine-Henri Becquerel wins the Nobel Prize for the discovery of natural radioactivity.
Dec. 17, 1903	The Wright brothers launch the first successful airplane.

1904-1905	William Crawford gorgas develops effective methods for controlling mosquitoes.
1904-1907	L. E. J. Brouwer develops intuitionist foundations of mathematics.
1904-1908	Ernst Zermelo undertakes the first comprehensive axiomatization of set theory.
1904-1912	Jacques Edwin Brandenberger invents cellophane.
1904	Julius Elster and Hans Friedrich Geitel devise the first practical photoelectric cell.
1904	Johannes Franz Hartmann discovers the first evidence of interstellar matter.
1904	Jacobus Cornelis Kapteyn discovers two star streams in the galaxy.
Apr.-May, 1904	Sir Charles Scott Sherrington delivers *The Integrative Action of the Nervous System*.
Summer, 1904	Construction begins on the Panama Canal.
Nov. 16, 1904	Sir John Ambrose Fleming files a patent for the first vacuum tube.
1905	George Washington Crile performs the first direct blood transfusion.
1905	Albert Einstein develops his theory of the photoelectric effect.
1905-1907	Leo Hendrik Baekeland invents Bakelite.
1905-1907	Bertram Boltwood uses radioactivity to obtain the age of rocks.
1905	Ejnar Hertzsprung notes the relationship between color and luminosity of stars.
1905	Punnett's *Mendelism* presents his diagrams for showing how hereditary traits are passed from one generation to the next.
Aug., 1905	Percival Lowell predicts the existence of Pluto.
1906	Frederick Gardner Cottrell invents the electronstat precipitation process.
1906	Sir Frederick Hopkins suggests that food contains vitamins essential to life.
1906	Hermann Anschütz-Kaempfe installs a gyrocompass onto a German battleship.
1906	Charles Glover Barkla discovers the characteristic X rays of the elements.

1906	Maurice Fréchet introduces the concept of abstract space.
1906	Andrey Markov discovers the theory of linked probabilities.
1906-1910	Richard D. Oldham and Andrija Mohorovičić determine the structure of the Earth's interior.
1906-1913	Richard Willstätter discovers the composition of chlorophyll.
Aug. 4, 1906	The first German U-boat submarine is launched.
Dec., 1906	J. J. Thomson wins the Nobel Prize for the discovery of the electron.
Dec. 24, 1906	Reginald Aubrey Fessenden perfects radio by transmitting music and voice.
1907	Louis and Auguste Lumière develop color photography.
1907	John Scott Haldane develops stage decompression for deep-sea divers.
1907	Ejnar Hertzsprung describes giant and dwarf stellar divisions.
Spring, 1907	Ross Granville Harrison observes the development of nerve fibers in the laboratory.
1908	Fritz Haber develops a process for extracting nitrogen from the air.
1908	Hardy and Weinberg present a model of population genetics.
1908	Howard Hughes, Sr., revolutionizes oil-well drilling.
1908	Charles Proteus Steinmetz warns of pollution in *The Future of Electricity*.
1908-1915	Thomas Hunt Morgan develops the gene-chromosome theory.
Feb. 11, 1908	Hans Geiger and Ernest Rutherford develop the Geiger counter.
June 26, 1908	George Ellery Hale discovers strong magnetic fields in sunspots.
Nov.-Dec., 1908	Paul Ehrlich and Élie Metchnikoff conduct pioneering research in immunology.
Dec., 1908	Marcellin Boule reconstructs the first Neanderthal skeleton.

1909	Wilhelm Johannsen coins the terms “gene,” “genotype,” and “phenotype.”
1909	The study of mathematical fields by Ernst Steinitz inaugurates modern abstract algebra.
Jan.-Aug., 1909	Robert Andrews Millikan conducts his oil-drop experiment.
July 25, 1909	Louis Blériot makes the first airplane flight across the English channel.
1910	The electric washing machine is introduced.
1910	Peyton Rous discovers that some cancers are caused by viruses.
1910	Bertrand Russell and Alfred North Whitehead’s *Principia Mathematica* develops the logistic movement in mathematics.
1910	J. J. Thomson confirms the possibility of isotopes.
Apr., 1910	Paul Ehrlich introduces Salvarsan as a cure for syphilis.
1911	Franz Boas publishes *The Mind of Primitive Man*.
July 24, 1911	Hiram Bingham discovers an Inca city in the Peruvian jungle.
Fall, 1911	Alfred H. Sturtevant produces the first chromosome map.
1912	Henrietta Swan Leavitt’s study of variable stars unlocks galactic distances.
1912	Vesto Slipher obtains the spectrum of a distant galaxy.
1912-1913	Niels Bohr writes a trilogy on atomic and molecular structure.
1912-1914	John Jacob Abel develops the first artificial kidney.
1912-1915	X-ray crystallography is developed by William Henry and Lawrence Bragg.
Jan., 1912	Alfred Lothar Wegener proposes the theory of continental drift.
Mar. 7, 1912	Ernest Rutherford presents his theory of the atom.
Aug. 7 and 12, 1912	Victor Franz Hess discovers cosmic rays through high-altitude ionizations.
1913	Thomas Alva Edison introduces the kinetophone to show the first talking pictures.

1913	Henry Ford produces automobiles on a moving assembly line.
1913	Ejnar Hertzsprung uses cepheid variables to calculate the distances to stars.
1913	Geothermal power is produced for the first time.
1913	Beno Gutenberg discovers the Earth's mantle-outer core boundary.
1913	Albert Salomon develops mammography.
1913	Béla Schick introduces the Schick test for diphtheria.
Jan., 1913	William Merriam Burton introduces thermal cracking for refining petroleum.
Jan. 17, 1913	Charles Fabry quantifies ozone in the upper atmosphere.
Dec., 1913	Henry Norris Russell announces his theory of stellar evolution.
1914	Ernest Rutherford discovers the proton.
Apr., 1915	The first transcontinental telephone call is made.
May, 1915	The Fokker aircraft are the first airplanes equipped with machine guns.
May 20, 1915	Corning Glass Works trademarks pyrex and offers pyrex cookware for commercial sale.
Sept., 1915-Feb., 1916	Jay McLean discovers the natural anticoagulant heparin.
Oct., 1915	Transatlantic radiotelephony is first demonstrated.
Oct., 1915-Mar., 1917	Paul Langevin develops active sonar for submarine detection and fathometry.
Nov. 25, 1915	Albert Einstein completes his theory of general relativity.
1916	Karl Schwarzschild develops a solution to the equations of general relativity.
1917	Clarence Birdseye develops freezing as a way of preserving foods.
1917	Insecticide use intensifies when arsenic proves effective against the boll weevil.
Nov., 1917	George Ellery Hale oversees the installation of the Hooker Telescope on Mount Wilson.
Jan. 8, 1918	Harlow Shapley proves the Sun is distant from the center of our galaxy.

1919	Francis William Aston builds the first mass spectrograph and discovers isotopes.
1919	Richard von Mises develops the frequency theory of probability.
1919	The principles of shortwave radio communication are discovered.
1919-1921	Vilhelm Bjerknes discovers fronts in atmospheric circulation.
Spring, 1919	Karl von Frisch discovers that bees communicate through body movements.
Nov. 6, 1919	Albert Einstein's theory of gravitation is confirmed.
Early 1920's	Vesto Slipher presents evidence of redshifts in galactic spectra.
1920-1930	Robert Andrews Millikan names cosmic rays and investigates their absorption.
Dec. 13, 1920	Albert A. Michelson measures the diameter of a star.
1921	John A. Larson constructs the first modern polygraph.
1921	Albert Calmette and Camille Guérin develop the tuberculosis vaccine BCG.
1921	Emmy Noether publishes the theory of ideals in rings.
1921-1923	William Grant Banting and J. J. R. Macleod win the Nobel Prize for the discovery of insulin.
1922	Elmer McCollum names vitamin D and pioneers its use against rickets.
Nov. 4, 1922	Howard Carter discovers the tomb of Tutankhamen.
1923	Arthur Holly Compton discovers the wavelength change of scattered X rays.
1923	Roy Chapman Andrews discovers the first fossilized dinosaur eggs.
1923	Vladimir Zworykin develops an early type of television.
1923	Louis de Broglie introduces the theory of wave-particle duality.
1923-1951	Reuben Leon Kahn develops a modified syphilis test and the universal serologic test.
Summer, 1923	Otto Zdansky discovers Peking man.

1924	Harry Steenbock discovers that sunlight increases vitamin D in food.
1924	Theodor Svedberg develops the ultracentrifuge.
Mar., 1924	Arthur Stanley Eddington formulates the mass-luminosity law for stars.
Summer, 1924	Raymond Arthur Dart discovers the first recognized australopithecine fossil.
Dec., 1924	Edwin Powell Hubble determines the distance to the Andromeda nebula and demonstrates that other galaxies are independent systems.
1925	Fred Whipple finds iron to be an important constituent of red blood cells.
Spring, 1925	Wolfgang Pauli formulates the exclusion principle.
Apr., 1925-May, 1927	The German *Meteor* expedition discovers the Mid-Atlantic Ridge.
Mar. 16, 1926	Robert Goddard launches the first liquid fuel propelled rocket.
July, 1926	Arthur Stanley Eddington publishes *The Internal Constitution of the Stars*.
Aug., 1926-Sept., 1928	Warner Bros. introduces talking motion pictures.
1927	Georges Lemaître proposes the big bang theory.
1927	Jan Hendrik Oort proves the spiral structure of the Milky Way.
Feb.-Mar., 1927	Werner Heisenberg articulates the uncertainty principle.
May 20-21, 1927	Charles Lindbergh makes the first nonstop solo flight across the Atlantic Ocean.
1928	Vannevar Bush builds the first differential analyzer.
1928	George Gamow explains radioactive alpha-decay with quantum tunneling.
1928-1932	Albert Szent-Györgyi discovers vitamin C.
Jan., 1928	George N. Papanicolaou develops the Pap test for diagnosing uterine cancer.
Aug., 1928	Margaret Mead publishes *Coming of Age in Samoa*.
Sept., 1928	Alexander Fleming discovers penicillin in molds.
1929	Edwin Powell Hubble confirms the expanding universe.

Apr. 22, 1929	Hans Berger develops the electroencephalogram (EEG).
July, 1929	Philip Drinker and Louis Shaw develop an iron lung mechanical respirator.
July, 1929-July, 1931	Kurt Gödel proves incompleteness-inconsistency for formal systems, including arithmetic.
Winter, 1929-1930	Bernhard Voldemar Schmidt invents the corrector for the Schmidt camera and telescope.
1930	Construction begins on the Empire State Building.
1930	Thomas Midgley introduces dichlorodifluoromethane as a refrigerant gas.
1930	Hans Zinsser develops an immunization against typhus.
1930	Bernard Lyot builds the coronagraph for telescopically observing the Sun’s outer atmosphere.
1930-1931	Linus Pauling develops his theory of the chemical bond.
1930-1932	Karl G. Jansky’s experiments lead to the founding of radio astronomy.
1930-1935	Edwin H. Armstrong perfects FM radio.
Feb. 18, 1930	Clyde Tombaugh discovers Pluto.
Jan. 2, 1931	Ernest Orlando Lawrence develops the cyclotron.
Apr., 1931	Ernst Ruska creates the first electron microscope.
May 27, 1931	Auguste Piccard travels to the stratosphere by balloon.
1931-1935	Subramanyan Chandrasekhar calculates the upper limit of a white dwarf star’s mass.
Feb., 1932	James Chadwick discovers the neutron.
Apr., 1932	John Douglas Cockcroft and Ernest Walton split the atom with a particle accelerator.
Sept., 1932	Carl David Anderson discovers the positron.
1932-1935	Gerhard Domagk discovers that a sulfonamide can save lives.
Nov., 1933	Enrico Fermi proposes the neutrino theory of beta decay.
1933-1934	Frédéric Joliot and Irène Joliot-Curie develop the first artificial radioactive element.
1934	Ruth Benedict publishes *Patterns of Culture*.

1934	Pavel Cherenkov discovers the Cherenkov effect.
1934	Fritz Zwicky and Walter Baade propose their theory of neutron stars.
1934-1938	Chester F. Carlson invents xerography.
Aug. 11-15, 1934	William Beebe and Otis Barton set a diving record in a bathysphere.
Fall, 1934	John H. Gibbon develops the heart-lung machine.
Nov., 1934-Feb., 1935	Hideki Yukawa proposes the existence of mesons.
1935	Robert Alexander Watson-Watt and associates develop the first radar.
1935	Sydney Chapman determines the lunar atmospheric tide at moderate latitudes.
1935-1936	Alan M. Turing invents the Universal Turing Machine.
Jan., 1935	Charles F. Richter develops a scale for measuring earthquake strength.
Feb., 1935-Oct., 1938	Wallace Carothers patents nylon.
Nov.-Dec., 1935	Antonio Egas Moniz develops prefrontal lobotomy.
1936	Inge Lehmann discovers the Earth’s inner core.
1936	Erwin Wilhelm Müller invents the field emission microscope.
Mar. 1, 1936	The completion of Boulder Dam creates Lake Mead, the world’s largest reservoir.
Nov. 23, 1936	Fluorescent lighting is introduced.
1937	Max Theiler introduces a vaccine against yellow fever.
1937	Ugo Cerletti and Lucino Bini develop electroconvulsive therapy for treating schizophrenia.
Jan.-Sept., 1937	Emilio Segrè identifies the first artificial element, technetium.
Mar., 1937	Hans Adolf Krebs describes the citric acid cycle.
June-Sept., 1937	Grote Reber builds the first radio telescope.
Fall, 1937-Winter, 1938	Franz Weidenreich reconstructs the face of Peking man.
1938	George S. Callendar connects industry with increased atmospheric carbon dioxide.
1938	Albert Hofmann synthesizes the potent psychedelic drug LSD-25.

1938	Peter Kapitsa explains superfluidity.
Dec., 1938	Otto Hahn splits an atom of uranium.
1939	The Bourbaki group publishes *Éléments de mathématique*.
1939	Paul Hermann Müller discovers that DDT is a potent insecticide.
Feb. 15, 1939	J. Robert Oppenheimer calculates the nature of black holes.
Early 1940's	A secret English team develops Colossus.
Late 1940's	Willard F. Libby introduces the carbon-14 method of dating ancient objects.
1940	The first color television broadcast takes place.
May, 1940	Baron Florey and Ernst Boris Chain develop penicillin as an antibiotic.
Sept. 12, 1940	Seventeen-thousand-year-old paintings are discovered in Lascaux cave.
Feb. 23, 1941	Glenn Seaborg and Edwin McMillan make element 94, plutonium.
May 15, 1941	The first jet plane using Frank Whittle's engine is flown.
1942-1947	Grote Reber makes the first radio maps of the universe.
Dec. 2, 1942	Enrico Fermi creates the first controlled nuclear fission chain reaction.
1943-1944	Oswald Avery, Colin Macleod, and Maclyn McCarty determine that DNA carries hereditary information.
1943-1944	Carl Friedrich von Weizsäcker finalizes his quantitative theory of planetary formation.
1943-1946	John Presper Eckert and John William Mauchly develop the ENIAC computer.
Spring, 1943	Jacques Cousteau and Émile Gagnan develop the Aqua-Lung.
Sept., 1943-Mar., 1944	Selman Abraham Waksman discovers the antibiotic streptomycin.
Nov. 4, 1943	The world's first nuclear reactor is activated.
1944	The Germans use the V-1 flying bomb and the V-2 goes into production.
Jan., 1944	Gerard Peter Kuiper discovers that Titan has an atmosphere.

Nov., 1944	Alfred Blalock and Helen Taussig perform the first "blue baby" operation.
1944-1949	Dorothy Crowfoot Hodgkin solves the structure of penicillin.
1944-1952	Sir Martin Ryle's radio telescope locates the first known radio galaxy.
1945	Benjamin Minge Duggar discovers aureomycin, the first of the tetracyclines.
Jan., 1945	Artificial fluoridation of municipal water supplies to prevent dental decay is introduced.
July 16, 1945	The first atomic bomb is successfully detonated.
July 12, 1946	Vincent Joseph Schaefer performs cloud seeding by using dry ice.
Nov., 1946	University of California physicists develop the first synchrocyclotron.
1947	Dennis Gabor develops the basic concept of holography.
1947	Willis Eugene Lamb, Jr., and Robert C. Retherford discover the lambshift.
Spring, 1947	Archaeologists unearth ancient Dead Sea scrolls.
Nov.-Dec., 1947	William Shockley, John Bardeen, and Walter Brattain discover the transistor.
1948	George Gamow and associates develop the big bang theory.
1948	The steady-state theory of the universe is advanced by Hermann Bondi, Thomas Gold, and Fred Hoyle.
1948	Eric Jacobsen introduces a drug for the treatment of alcoholism.
June 3, 1948	George Ellery Hale constructs the largest telescope of the time.
Nov. 26, 1948	Edwin Herbert Land invents a camera/film system that develops instant pictures.
1949	X rays from a synchrotron are first used in medical diagnosis and treatment.
Feb. 24, 1949	The first rocket with more than one stage is created.
Aug., 1949	BINAC, the first electronic stored-program computer, is completed.
1950's	Robert Wallace Wilkins discovers Reserpine, the first tranquilizer.

1950's	Choh Hao Li isolates the human growth hormone.
1950	The artificial sweetener cyclamate is introduced.
1950	William Clouser Boyd defines human races by blood groups.
Mid-1950's	Severo Ochoa creates synthetic RNA.
1951	Robert Hofstadter discovers that protons and neutrons each have a structure.
1951	Fritz Albert Lipmann discovers acetyl coenzyme a.
1951	UNIVAC I becomes the first commercial electronic computer and the first to use magnetic tape.
1951-1952	Edward Teller and Stanislaw Ulam develop the first hydrogen bomb.
1951-1953	James Watson and Francis Crick develop the double-helix model for DNA.
May, 1951-May, 1954	Jan Hendrik Oort postulates the existence of the Oort Cloud.
Dec. 20, 1951	The world's first breeder reactor produces electricity while generating new fuel.
1952	Eugene Aserinsky discovers rapid eye movement (REM) in sleep and dreams.
Feb. 23, 1952	Douglas Bevis describes amniocentesis as a method for disclosing fetal genetic traits.
July 2, 1952	Jonas Salk develops a polio vaccine.
Aug., 1952	Walter Baade corrects an error in the cepheid luminosity scale.
1952-1956	Erwin Wilhelm Müller develops the field ion microscope.
1953	Vincent du Vigneaud synthesizes oxytocin, the first peptide hormone.
1953	Stanley Miller reports the synthesis of amino acids.
1953	Gérard de Vaucouleurs identifies the local supercluster of galaxies.
1953-1959	The liquid bubble chamber is developed.
1954-1957	John Backus's IBM team develops the FORTRAN computer language.
Apr. 30, 1954	Elso Barghoorn and Stanley Tyler discover 2-billion-year-old microfossils.

May, 1954	Bell Telephone scientists develop the photovoltaic cell.
1955	Kenneth Franklin and Bernard Burke discover radio emissions from Jupiter.
1955	Sir Martin Ryle constructs the first radio interferometer.
1956	The first transatlantic telephone cable is put into operation.
1956	Bruce Heezen and Maurice Ewing discover the midoceanic ridge.
Apr.-Dec., 1956	Birth control pills are tested in Puerto Rico.
1957	Albert Bruce Sabin develops an oral polio vaccine.
1957	Alick Isaacs and Jean Lindenmann discover interferons.
1957	Sony develops the pocket-sized transistor radio.
Feb. 7, 1957	John Bardeen, Leon N. Cooper, and John Robert Schrieffer explain superconductivity.
Aug., 1957	The Jodrell Bank radio telescope is completed.
Oct. 4, 1957	The Soviet Union launches the first artificial satellite, Sputnik 1.
Oct. 11, 1957	Leo Esaki demonstrates electron tunneling in semiconductors.
Dec. 2, 1957	The United States opens the first commercial nuclear power plant.
1958	Frederick Sanger wins the Nobel Prize for the discovery of the structure of insulin.
1958	James Van Allen discovers the Earth's radiation belts.
1958	Ian Donald is the first to use ultrasound to examine unborn children.
Jan. 2, 1958	Eugene N. Parker predicts the existence of the solar wind.
Jan. 31, 1958	The United States launches its first orbiting satellite, Explorer 1.
1959	Grace Hopper invents the computer language COBOL.
1959	A corroded mechanism is recognized as an ancient astronomical computer.

1959	A radio astronomy team sends and receives radar signals to and from the Sun.
June 26, 1959	The St. Lawrence Seaway is opened.
July 17, 1959	Louis and Mary Leakey find a 1.75-million-year-old fossil hominid.
Sept. 13, 1959	Luna 2 becomes the first human-made object to impact on the Moon.
Early 1960's	The plastic IUD is introduced for birth control.
Early 1960's	Anthropologists claim that Ecuadorian pottery shows transpacific contact in 3000 B.C.E.
Early 1960's	Roger Sperry discovers that each side of the brain can function independently.
1960	The Mössbauer effect is used in the detection of gravitational redshifting.
1960	Scientists develop a technique to date ancient obsidian.
1960-1962	Harry Hammond Hess concludes the debate on continental drift.
1960-1969	A vaccine is developed for German measles.
Spring, 1960	Juan Oró detects the formation of adenine from cyanide solution.
Apr. 1-June 14, 1960	Tiros 1 becomes the first experimental weather reconnaissance satellite.
July, 1960	The first laser is developed in the United States.
Aug. 12, 1960	Echo, the first passive communications satellite, is launched.
1961	Frank L. Horsfall announces that cancer results from alterations in the DNA of cells.
1961	Marshall Nirenberg invents an experimental technique that cracks the genetic code.
Apr. 12, 1961	Yuri Gagarin becomes the first human to orbit Earth.
May 5, 1961	Alan Shepard is the first United States astronaut in space.
Dec., 1961	Melvin Calvin identifies the chemical pathway of photosynthesis.
1962	Lasers are used in eye surgery for the first time.
1962	John Glenn is the first American to orbit Earth.

1962	Riccardo Giacconi and associates discover the first known X-ray source outside the solar system.
July 10, 1962	Telstar, the first commercial communications satellite, relays live transatlantic television pictures.
Aug., 1962-Jan., 1963	Mariner 2 becomes the first spacecraft to study Venus.
Sept. 27, 1962	Rachel Carson publishes *Silent Spring*.
1962-1967	Colin Renfrew, J. E. Dixon, and J. R. Cann reconstruct ancient Near Eastern trade routes.
1963	The cassette for recording and playing back sound is introduced.
1963	Maarten Schmidt makes what constitutes the first recognition of a quasar.
1963	Paul J. Cohen shows that Georg Cantor's continuum hypothesis is independent of the axioms of set theory.
1963-1965	Arno Penzias and Robert Wilson discover cosmic microwave background radiation.
1964	Quarks are postulated by Murray Gell-Mann and George Zweig.
1964-1965	John G. Kemeny and Thomas E. Kurtz develop the BASIC computer language.
1964-1965	Richard Rayman Doell and Brent Dalrymple discover the magnetic reversals of Earth's poles.
Nov. 21, 1964	The Verrazano Bridge opens.
1965	The Sealab 2 expedition concludes.
Mar. 18, 1965	The first spacewalk is conducted from Voskhod 2.
Nov. 16, 1965-Mar. 1, 1966	Venera 3 is the first spacecraft to impact on another planet.
Dec., 1965	The orbital rendezvous of Gemini 6 and 7 succeeds.
1966	Robert Ardrey's *The Territorial Imperative* argues that humans are naturally territorial.
Jan., 1966	Elwyn L. Simons identifies a 30-million-year-old primate skull.
Jan. 31-Feb. 8, 1966	The Soviet Luna 9 makes the first successful lunar soft landing.
Aug. 10-Oct. 29, 1966	The Lunar Orbiter 1 sends photographs of the Moon's surface.

1967	Rene Favaloro develops the coronary artery bypass operation.
1967	Syurkuro Manabe and Richard Wetherald warn of the greenhouse effect and global warming.
1967	Raymond Davis constructs a solar neutrino detector.
1967	Benoît Mandelbrot develops non-Euclidean fractal measures.
1967-1968	Elso Barghoorn and coworkers find amino acids in 3-billion-year-old rocks.
Aug.-Sept., 1967	Arthur Kornberg and coworkers synthesize biologically active DNA.
Nov., 1967-Feb., 1968	Jocelyn Bell discovers pulsars, the key to neutron stars.
Dec., 1967	Christiaan Barnard performs the first human heart transplant.
1968	Jerome I. Friedman, Henry W. Kendell, and Richard E. Taylor discover quarks.
1968	The *Glomar Challenger* obtains thousands of ocean floor samples.
1968	John Archibald Wheeler names the phenomenon “black holes.”
1969	Bubble memory devices are created for use in computers.
1969	The Soyuz 4 and 5 spacecraft dock in orbit.
1969-1970	The first jumbo jet service is introduced.
1969-1974	Very long baseline interferometry is developed for high-resolution astronomy and geodesy.
July 20, 1969	Neil Armstrong and Edwin “Buzz” Aldrin land on the Moon.
Dec. 10, 1969	Derek H. R. Barton and Odd Hassel share the Nobel Prize for determining the three-dimensional shapes of organic compounds.
1970	The floppy disk is introduced for storing data used by computers.
Nov. 10, 1970-Oct. 1, 1971	Lunokhod 1 lands on the Moon.
1971	Direct transoceanic dialing begins.
1971	The microprocessor “computer on a chip” is introduced.

1971-1972	Mariner 9 is the first known spacecraft to orbit another planet.
May 19, 1971-Mar., 1972	Mars 2 is the first spacecraft to impact on Mars.
Mar., 1972	Pioneer 10 is launched.
Apr., 1972	Godfrey Hounsfield introduces a cat scanner that can see clearly into the body.
Sept., 1972	Murray Gell-Mann formulates the theory of quantum chromodynamics (qcd).
Sept., 1972	Texas Instruments introduces the first commercial pocket calculator.
Sept. 23, 1972	David Janowsky publishes a cholinergic-adrenergic hypothesis of mania and depression.
Dec. 31, 1972	The United States government bans DDT use to protect the environment.
1973	Stanley Cohen and Herbert Boyer develop recombinant DNA technology.
Feb., 1973-Mar., 1974	Organic molecules are discovered in Comet Kohoutek.
May 14, 1973-Feb. 8, 1974	Skylab inaugurates a new era of space research.
Nov. 3, 1973-Mar. 24, 1975	Mariner 10 is the first mission to use gravitational pull of one planet to help it reach another.
Dec., 1973-June, 1974	F. Sherwood Rowland and Mario J. Molina theorize that ozone depletion is caused by Freon.
Feb., 1974	Howard Georgi and Sheldon Glashow develop the first grand unified theory.
Apr., 1974	Optical pulses shorter than one trillionth of a second are produced.
June, 1974	Tunable, continuous wave visible lasers are developed.
Aug.-Sept., 1974	The J/psi subatomic particle is discovered.
Nov., 1974	Donald Johansen and Tim White discover "Lucy," an early hominid skeleton.
Oct. 22, 1975	Soviet Venera spacecraft transmit the first pictures from the surface of Venus.
1976	Thomas Kibble proposes the theory of cosmic strings.
July 20-Sept. 3, 1976	Viking spacecraft send photographs to Earth from the surface of Mars.

1977	Alan J. Heeger and Alan G. MacDiarmid discover that iodine-doped polyacetylene conducts electricity.
1977	Deep-sea hydrothermal vents and new life-forms are discovered.
Mar. 10-11, 1977	Astronomers discover the rings of the planet Uranus.
Apr., 1977	Apple II becomes the first successful preassembled personal computer.
May, 1977	The first commercial test of fiber-optic telecommunications is conducted.
Sept. 16, 1977	Andreas Gruentzig uses percutaneous transluminal angioplasty, via a balloon catheter, to unclog diseased arteries.
Sept., 1977-Sept., 1989	Voyager 1 and 2 explore the planets.
July 25, 1978	Louise Brown gives birth to the first “test-tube” baby.
1978-1981	Heinrich Rohrer and Gerd Binnig invent the scanning tunneling microscope.
Mar. 4-7, 1979	The first ring around Jupiter is discovered.
Aug., 1979	An ancient sanctuary is discovered in El Juyo Cave, Spain.
1980	Paul Berg, Walter Gilbert, and Frederick Sanger develop techniques for genetic engineering.
1980	Evidence is found of a worldwide catastrophe at the end of the Cretaceous period.
1980	The inflationary theory solves long-standing problems with the big bang.
Jan. 14, 1980	Robert Louis Griess constructs “The Monster,” the last sporadic group.
Feb. 5, 1980	Klaus von Klitzing discovers the quantized Hall effect.
May, 1980	Pluto is found to possess a thin atmosphere.
June, 1980	Radar observations show that Mayan agricultural centers are surrounded by canals.
1981	The U.S. Centers for Disease Control recognizes AIDS for the first time.
1981-1982	A human growth hormone gene transferred to a mouse creates giant mice.

May-June, 1981	Bell Laboratories scientists announce a liquid-junction solar cell of 11.5 percent efficiency.
June, 1981	Joseph Patrick Cassinelli and associates discover R136a, the most massive star known at the time.
Aug. 12, 1981	The IBM personal computer, using DOS, is introduced.
Sept., 1981	William H. Clewell corrects hydrocephalus by surgery on a fetus.
Nov. 12-14, 1981	*Columbia*'s second flight proves the practicality of the space shuttle.
1982	Thomas Cech and Sidney Altman demonstrate that RNA can act as an enzyme.
1982	William Castle Devries implants the first Jarvik-7 artificial heart.
1982	Étienne-Émile Baulieu develops RU-486, a pill that induces abortion.
1982-1983	Compact disc players are introduced.
1982-1983	Fernand Daffos uses blood taken through the umbilical cord to diagnose fetal disease.
1982-1989	Astronomers discover an unusual ring system of the planet Neptune.
Apr., 1982	Solar One, the prototype power tower, begins operation.
May 14, 1982	The first commercial genetic engineering product, Humulin, is marketed by Eli Lilly.
1983	The artificial sweetener aspartame is approved for use in carbonated beverages.
1983	Carlo Rubbia and Simon van der Meer isolate the intermediate vector bosons.
Jan.-Oct., 1983	The first successful human embryo transfer is performed.
Mar. 8, 1983	IBM introduces a personal computer with a standard hard disk drive.
Apr. 4, 1983	The first tracking and data-relay satellite system opens a new era in space communications.
Sept., 1983	Andrew Murray and Jack Szostak create the first artificial chromosome.
Nov. 28, 1983	*Spacelab* 1 is launched aboard the space shuttle.

1984	Optical disks for the storage of computer data are introduced.
1984	Charles Gald Sibley and Jon Ahlquist discover a close human and chimpanzee genetic relationship.
1984	Steen M. Willadsen clones sheep using a simple technique.
1985	The British Antarctic Survey confirms the first known hole in the ozone layer.
1985	Construction of the world's largest land-based telescope, the Keck, begins in Hawaii.
Mar. 6, 1985	Alec Jeffreys discovers the technique of genetic fingerprinting.
Oct., 1985	The Tevatron particle accelerator begins operation at Fermilab.
1986-1987	R. Brent Tully discovers the Pisces-Cetus supercluster complex.
Jan., 1986	J. Georg Bednorz and Karl Alexander Müller discover a high-temperature superconductor.
Feb. 20, 1986	The first permanently manned space station is launched.
Apr. 26, 1986	The Chernobyl nuclear reactor explodes.
July, 1986	A genetically engineered vaccine for hepatitis B is approved for use.
Oct., 1986	A gene that can suppress the cancer retinoblastoma is discovered.
Dec. 14-23, 1986	Burt Rutan and Chuck Yeager pilot the *Voyager* around the world without refueling.
Feb. 23, 1987	Supernova 1987a corroborates the theories of star formation.
Sept., 1987	Wade Miller discovers a dinosaur egg containing the oldest known embryo.
1987-1988	Scientists date a *Homo sapiens* fossil at ninety-two thousand years.
1988	Henry Erlich develops DNA fingerprinting from a single hair.
Apr. 24, 1990	NASA launches the Hubble Space Telescope.

1990's-2002	Particle physicists demonstrate that neutrinos—atomic particles long thought to be without mass—do indeed have mass and that they can change "flavor."
1992	China revives the Cold War threat of international nuclear war with the explosion of one of the most powerful nuclear devices ever tested.
1992	More than ten thousand scientists and AIDS (acquired immune deficiency syndrome) activists meeting in Amsterdam reveal the possibility of a new AIDS-like virus.
1993	Andrew Wiles presents his proof of the "Last Theorem" of Pierre de Fermat, which had defied solution by mathematicians for more than three and a half centuries.
1993	In the most dramatic report of ozone depletion since the phenomenon was first reported, the World Meteorological Organization announces a rapid decline in ozone levels in the Northern Hemisphere.
1994	Astronomers use the Hubble Space Telescope to find evidence for the existence of a black hole in the center of galaxy M87.
1994	The Hubble Space Telescope provides astronomers with clear images of distant objects in the universe.
1994	Colombia, a major exporter of cocaine to the United States, legalizes the possession and private use of small amounts of cocaine, marijuana, and some other drugs for its citizens, provoking anger among U.S. drug enforcement officials.
1994	An international conference sponsored by the United Nations emphasizes links among population control, economic development, and the advancement of women.
1995	National and international health organizations react quickly to contain an outbreak of the deadly Ebola virus in Kikwit, Zaire.
1995	After sixty years' absence, wolves are restored to Yellowstone National Park in the western United States under a provision of the Endangered Species Act.

1995 The Kobe, Japan, earthquake of January 17, 1995, kills 5,500 people, injures 37,000, and does damage exceeding $50 billion, one of the most costly natural disasters on record.

1995 Two teams of physicists announce the discovery of the top quark, the last of six such subatomic particles predicted by scientific theory.

1995 U.S. astronauts aboard the shuttle *Atlantis* dock with the space station Mir on a mission that sets the stage for future rendezvous and construction of an international space station.

1995 At 12:01 A.M. on August 24, 1995, the first copy of Microsoft Windows 95 is sold. Windows 95, which makes using an Intel personal computer easy and intuitive, becomes the operating system of choice for personal computers and one of the most successful software products ever developed.

1995 The second assessment report of the Intergovernmental Panel on Climate Change (IPCC) projects a rise in global mean surface temperatures. The rise would constitute the fastest rate of change since the end of the last Ice Age.

1995 Six years after its deployment from the space shuttle *Atlantis* I, the Galileo spacecraft reaches its destination, the planet Jupiter.

1996 Dolly the sheep, is born. She is the first vertebrate cloned from the cell of an adult vertebrate.

1996 Scientists at the National Aeronautics and Space Administration (NASA) find traces of life processes and possible microscopic fossils in a meteorite believed to have come from Mars.

1997 Physicists at the Massachusetts Institute of Technology announce the success of an elementary version of a laser that produces a beam of atoms rather than a beam of light.

1997 After a six-year journey through interplanetary space, the Galileo spacecraft passes within 370 miles of Jupiter’s moon Europa, revealing an ice-enshrouded world whose surface characteristics suggest an underlying planetary ocean that may harbor extraterrestrial life.

1997 Anthropologists discover the fossil skull of a boy who lived in Spain nearly 800,000 years ago. His skull combines features of both modern humans and earlier human species.

1997 A spacecraft that was launched from the Kennedy Space Center in Florida on December 4, 1996, lands safely on Mars after a flight lasting seven months.

1997 The discovery of ancient Roman shipwrecks in the Mediterranean Sea confirms the theory that ancient sailors did not simply hug the coast as they were engaging in trade across the Mediterranean.

1997 Scientists discover ancient fossil footprints left by a woman who walked on the shores of Langebaan Lagoon, South Africa, 117,000 years ago.

1998 Scientists announce that preliminary findings from the Lunar Prospector mission suggest the presence of water ice in the shadowed craters near the Moon's poles.

1998 The Monahans meteorite is the first extraterrestrial object to provide a sample of liquid water from an asteroid. The water, trapped in salt crystals, demonstrates that liquid water existed early in the history of the solar system, and the association of water with salt crystals suggests that brine evaporated on or near the surface of the asteroid.

1998 Developed by a team of scientists of the Pfizer Company, Viagra is the first anti-impotence drug to be approved by the U.S. Food and Drug Administration.

1998 Despite condemnation from the proponents of nuclear nonproliferation, India and Pakistan test nuclear weapons and join those countries possessing nuclear weapons.

1998 The annual ozone hole extends a record 10.5 million square miles (27.3 million square kilometers).

1998 The first digital high-definition television signals are broadcast.

1999 A team of surgeons perform a successful hand transplant operation in Louisville, Kentucky, enabling the recipient to perform twisting and gripping functions and to feel sensation in the hand.

1999	Scientists trace HIV, the virus that causes AIDS, to chimpanzees.
1999	In an effort to produce alternative sources of clean energy, researchers generate nuclear energy on a tabletop by both fusion and fission.
1999	A Danish physicist and her collaborators reduce light's speed from 186,000 miles (299,274 kilometers) per second to 38 miles (61 kilometers) per hour.
1999	Careful analysis of light from Upsilon Andromedae reveals the first known multiple-planet system orbiting a normal star.
1999	A team of scientists at the Lawrence Berkeley Laboratory Nuclear Science Division detect the formation of two new elements, with atomic numbers 116 and 118, as the result of bombarding lead targets with krypton ions in the 88-inch (2.2-meter) cyclotron.
1999	Continuous occupation of the Russian Mir Space Station ends in August, 1999, and Mir falls out of Earth orbit in 2001.
1999	Physicists produce nickel-48, the most proton-rich nucleus, an international breakthrough in nuclear physics.
1999	The Mars Climate Orbiter, a $125 million robotic spacecraft designed to investigate weather on Mars, disappears as it is about to enter orbit around Mars. The error is later traced to human miscalculation.
1999	Researchers announce the identification of an enzyme that plays a key role in the development of Alzheimer's disease.
1999	A team of scientists at Brown University present topographical measurements that indicate that an ocean once existed on Mars.
Oct. 12, 1999	According to United Nations data, the world's six billionth person is born.
Dec., 1999	Seven astronauts aboard the space shuttle *Discovery* successfully restore the Hubble Space Telescope to operation.

2000 Intel introduces its Pentium 4 microprocessor, with processing speeds of 1.5 gigahertz, a vast improvement over its first microprocessor, the Intel 8088, introduced in 1979 for the IBM personal computer.

2000 Imaging radar aboard the space shuttle *Endeavour* captures data to assemble the most comprehensive topographic map of Earth, covering 80 percent of its land surface.

2000 The Framingham study, which has followed thousands of women throughout their lives, reveals that hormone-replacement therapy (HRT) might not prevent coronary disease in postmenopausal women, as previously thought; most physicians immediately order their patients on HRT to diminish or cease their dosages.

2000 Scholars from two research institutions announce the discovery of at least nine planets around stars other than the Sun, bringing the total number of known extrasolar planets to at least fifty; by 2005, the number of known extrasolar planets has exceeded one hundred.

2000 The Food and Drug Administration approves medical abortions using mifepristone (RU-486) as an alternative to surgical abortion.

2000 The first construction begins on the International Space Station, a structure for scientific and biological research to be erected in Earth orbit.

2000 The gas-electric "hybrid" automobile is brought to market.

2000 With the aid of computers, geneticists are rapidly sequencing the genomes of many organisms, culminating in the year's sequencing of the complete genome *Drosophila melanogaster*, the fruit fly.

Feb. 14, 2000 The Near Earth Asteroid Rendezvous (NEAR) spacecraft begins a yearlong orbit of the asteroid Eros, gathering data on its chemical composition, mineralogy, shape, and structure.

2001 Scientists advance a new area of applied science, nanoelectronics, by assembling molecules into basic circuits.

Feb. 10, 2001	The human genome is completely sequenced, opening a new era of medical promise; the event marks the most important breakthrough in genetics since the discovery of the double-helical structure of DNA in 1953.
2002	A variety of small RNA molecules are discovered to be capable of altering gene expression and even the genome itself.
2002-2003	Researchers announce genetic predispositions toward depression and bipolar disorder.
2003	Biophysicists experiment with "quantum dots," tiny semiconductor nanocrystals that glow in the presence of laser light, to enhance biological imaging techniques.
2003	Biologists discover that mouse stem cells can develop into both sperm and egg cells in vitro, raising the question of whether the same is possible with human stem cells.
2003	Physicists confirm the existence of "left-handed" materials, which have a negative refractive index (they bend light at a negative angle when it passes into them from a different medium) as well as other odd and potentially useful properties.
2003	The combination of conventional chemotherapy and new antiangiogenesis drugs—which starve cancer tumors of their blood supply by preventing them from growing blood vessels—proves effective with colon cancer patients.
2003	The Wilkinson Anisotropy Microwave Probe maps the universe showing the cosmic background radiation, the "afterglow" of the big bang, and pinpoints the age of the universe at 13.7 billion years.
Jan., 2004	The Mars Exploration Rovers, Spirit and Opportunity, land at different locations on the Martian surface and return unprecedented photographs of topographic features as well as geological data.
Dec. 26, 2004	A devastating tsunami, generated by an earthquake in the ocean near Indonesia, kills more than 200,000 in nations from Sri Lanka to Indonesia.

Jan. 27, 2005	Oxford University's climateprediction.net project announces evidence of a long-term increase in Earth's surface temperature in the range of 2° to 11° Celsius as a result of global warming.
Feb. 17, 2005	Two human skulls discovered in Ethiopia by Richard Leakey in 1967 are redated to 195,000 years old, the oldest known remains of modern human beings.
July 4, 2005	The Deep Impact spacecraft reaches Comet Tempel 1 and launches a 372-kilogram copper projectile into the comet's icy surface to collect data.
July-September, 2005	Xena, a body beyond Pluto that orbits the Sun, is discovered by astronomers at the University of Hawaii's Keck Observatory in July and its moon Gabrielle is discovered in September. The question of Xena's planetary status—like those of several other trans-Neptunian objects discovered since 1995—is debated by astronomers.
September, 2005	The U.S. National Snow and Ice Data Center and the National Aeronautics and Space Administration report "a stunning reduction" in Arctic sea ice, 20 percent below the mean average during Septembers from 1978 to 2001.

Web Sites

This appendix includes a wide variety of Web sites that range from providing basic information to exploring specific subjects in depth. Several of the sites are interactive; many provide additional links to more resources in their respective subject areas. Although URLs change over time, they are often rerouted to new Web addresses automatically; alternatively, a search on the sponsor listed will usually take the user to the site in question if the Web address has changed.

General Sites: Education, News, Reference

Bill Nye the Science Guy's Nye Labs Online
http://nyelabs.kcts.org

Conversion Factors
http://www.wsdot.wa.gov/Metrics/factors.htm

Dictionary of Scientific Quotations
http://naturalscience.com/dsqhome.html

Discovery Channel
http://discover.com

Eisenhower National Clearinghouse Resources Finder
http://www.enc.org/rf/nf_index.htm#rf

Electronic Journal of Science Education
http://unr.edu/homepage/jcannon/ejse/ejse.html

Environment News Network (ENN)
http://www.enn.com

How Stuff Works
http://www.howstuffworks.com

Internet Public Library Science and Technology Resources
http://www.ipl.org/ref/rr/static/scioo.oo.oo.html

Journal of Young Investigators
http://www.jyi.org

Library of Congress Science Reading Room
http://lcweb.loc.gov/rr.scitech

Livescience.com
http://www.livescience.com

MagPortal.com: Magazine Articles on Science and Technology
http://www.MagPortal.com/c/sci

National Academy of Sciences
http://www.nasonline.org/site/PageServer

National Aeronautics and Space Administration (NASA)
http://education.nasa.gov

National Geographic Society
http://www.nationalgeographic.com

National Institute for Science Education
http://www.wcer.wisc.edu/nise

National Science Foundation
http://www.nsf.gov

National Science Teachers Association
http://www.nsta.org

Nature Magazine
http://www.nature.com

New Scientist
http://www.newscientist.com

Newton's Apple Index
http://ericir.syr.edu/Projects/Newton

Nova (Public Broadcasting Service)
http://www.pbs.org/wgbh/nova

Odyssey Adventures in Science
http://www.odysseymagazine.com

On Being a Scientist: Responsible Conduct in Research
http://www.nap.edu/readingroom/books/obas

Popular Science Magazine
http://www.popularscience.com

Resources in Science and Engineering Education
http://www2.ncsu.edu/unity/lockers/users/f/felder/public/RMF.html

Scholarly Societies Project
http://www.lib.uwaterloo.ca/society/overview.html

Science Learning Network (SLN)
http://www.sln.org

Science Magazine
http://www.sciencemag.org/content/vol309/issue5743/twis.shtml

Science/Nature for Kids
http://kidscience.about.com

Science News
http://www.sciencenews.org

Science Online
http://www.scienceonline.org

Science Service Historical Image Collection
http://americanhistory.si.edu/scienceservice

Scientific American
http://www.sciam.com

Scout Report for Science and Engineering
http://scout.cs.wisc.edu/

Society for College Science Teachers
http://science.clayton.edu/scst

Statistical Reports of U.S. Science and Engineering
http://www.nsf.gov/sbe/srs/stats.htm

Temperature Conversion Calculator
http://www.cchem.berkeley.edu/ChemResources/temperature.html

U.S. House of Representatives Committee on Science
http://www.house.gov/science/welcome.htm

U.S. Senate Committee on Commerce, Science and Transportation
http://www.senate.gov/~commerce

Why Files: The Science Behind the News
http://whyfiles.news.wisc.edu

Yahoo! Science and Technology News
http://dailynews.yahoo.com

Archaeology

Ancient Technologies and Archaeological Materials
http://www.uiuc.edu/unit/ATAM/index.html

Archaeology Magazine Online
http://www.archaeology.org/main.html

Web Info Radiocarbon Dating
http://www.c14dating.com

WWWorld of Archaeology
http://www.archaeology.org/wwwarky/wwwarky.html

ASTRONOMY AND AEROSPACE

About.com Aerospace and Astronomy Sites
http://space.about.com

American Meteor Society
http://www.amsmeteors.org

Arctic Asteroid!
http://science.msfc.nasa.gov/headlines/y2000/ast01jun_1m.htm

AstroWeb–Astronomy Resources on the World Wide Web
http://www.stsci.edu/science/net-resources.html

Encyclodedia Astronautica
http://www.friends-partners.org/~mwade/spaceflt.htm

NASA Earth Observatory
http://earthobservatory.nasa.gov

NASA Human Spaceflight
http://spaceflight.nasa.gov/station/

NASA: Space Environment Center
http://www.sec.noaa.gov

National Aeronautics and Space Administration
http://www.nasa.gov

Orbital Elements
http://spaceflight.nasa.gov/realdata.elements/index.html

Science News About the Sun-Earth Environments
http://www.spaceweather.com

Sky and Telescope Magazine
http://www.skypub.com/skytel/skytel.shtml

Skyview
http://skyview.gsfc.nasa.gov

Solar Web Guide
http://www.lmsal.com/SXT/html2/list.html

Space News, Games, Entertainment
http://www.spacescience.com

Space Telescope Science Institute
http://www.stsci.edu/

Spacewatch Project, University of Arizona Lunar and Planetary Observatory
http://www.lpl.arizona.edu/spacewatch/index.html

Sunspot Cycle Predictions
http://science.nasa.gov/ssl/PAD/SOLAR/predict.htm

Terra: The EOS Flagship
http://terra.nasa.gov

U.S. Naval Observatory
http://aa.usno.navy.mil

Wide Web of Astronomy
http://georgenet.net/astronomy.html

Biographies

African Americans in Science
http://www.princeton.edu/~mcbrown/display/faces.html

American Indian Science and Engineering Society
http://www.aises.org

Biographies of Physicists
http://hermes.astro.washington.edu/scied/physics/physbio.html

4,000 Years of Women in Science
http://www.astr.ua.edu/4000WS/4000WS.html

Galileo and Einstein Home Page
http://galileoandeinstein.physics.virginia.edu

National Academy of Engineering (NAE) Celebration of Women in Engineering
http://www.nae.edu.cwe

Nobel Channel
http://www.nobelchannel.com

Nobel Foundation
http://nobelprize.org/

Nobel Prize Internet Archive
http://www.almaz.com

BIOLOGY

Association for Biology Laboratory Education "Hot" Biology Web Sites
http://www.zoo.toronto.edu/able/hotsites/hotsites/htm

Biolinks.com
http://www.biolinks.com

Biology in the News
http://www.nbii.gov/bionews

Cells Alive
http://www.cellsalive.com

Computer Enhanced Science Education, Whole Frog Project
http://george.lbl.gov/ITG.hm.pg.docs/Whole.Frog/Whole.Frog.html

e-Skeletons Project
http://www.eSkeletons.org

Ecological Society of America
http://www.esa.org/esaLinks.php

Electronic Introduction to Molecular Virology
http://www.uct.ac.za/microbiology/tutorial/virtut1.html

Evolution Website (BBC Education)
http://www.bbc.co.uk/education/darwin/index.shtml

Human Genome Project
http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml

Microbe Zoo—Digital Learning Center for Microbial Ecology
http://commtechlab.msu.edu/sites/dlc-mi/zoo

Microbiology Education Library
http://www.microbelibrary.org

Ongoing Biology
http://www.tilgher.it/ongoing.html

UCMP Exhibit Hall: Evolution Wing
http://www.ucmp.berkeley.edu/history/evolution.html

BOTANY

Agricultural Research Service Science 4 Kids
http://www.ars.usda.gov/is/kids

Ancient Bristlecone Pine
http://www.sonic.net/bristlecone/intro.html

Biotechnology: An Information Resource
http://www.nal.usda.gov/bic

Botanical Society of America
http://www.botany.org

Botany.com
http://www.botany.com

Carnivorous Plants
http://www.sarracenia.com/cp.html

Dr. Fungus
http://www.doctorfungus.org

Introduction to the Plant Kingdom
http://scitec.uwichill.edu.bb/bcs/bl14al.htm

What Is Photosynthesis?
http://photoscience.la.asu.edu/photosyn/education/learn.html

CHEMISTRY

About.com Chemistry
http://chemistry.about.com

Chem Team Tutorial for High School Chemistry
http://dbhs.wvusd.k12.ca.us/webdocs/ChemTeamIndex.html

Chem4Kids
http://www.chem4kids.com

Chemical Education Resource Shelf
http://www.umsl.edu/~chemist/books/

Chemical Heritage Foundation
http://www.chemheritage.org

Chemistry Teaching Resources
http://www.anachem.umu.se/eks/pointers.htm#Curriculum

ChemPen 3D–Classic Organic Reactions
http://home.ici.net/~hfevans/reactions.htm

ChemWeb.com
http://chemweb.com

Classic Chemistry, Compiled by Carmen Giunta
http://web.lemoyne.edu/~giunta

Introduction to Surface Chemistry
http://www.chem.qmw.ac.uk/surfaces/scc

IUPAC Compendium of Chemical Terminology
http://www.chemsoc.org/chembytes/goldbook/index.htm

Molecule of the Month
http://www.bris.ac.uk/Depts/Chemistry/MOTM/motm.htm

On-line Introductory Chemistry
http://www.scidiv.bcc.ctc.edu/wv/101-online.html

Science Is Fun
http://scifun.chem.wisc.edu/scifun.html

Computer Science and the Internet

Brain Spin: Technology for Students
http://www.att.com/technology/forstudents/brainspin

Computer Vision Handbook
http://www.cs.hmc.edu/~fleck/computer-vision-handbook

Greatest Engineering Achievements of the Twentieth Century
http://www.greatachievements.org

History of the Web
http://dbhs.wvusd.k12.ca.us/Chem-History/Hist-of-Web.html

Netdictionary
http://www.netdictionary.com

NetLib Repository
http://www.netlib.org

Resource Center for Cyberculture Studies
http://otal.umd.edu/~rccs

Robotics Institute
http://www.ri.cmu.edu

Thinkquest
http://library.thinkquest.org

Virtual Reality
http://www.cms.dmu.ac.uk/~cph/VR/whatisvr.html

EARTH SCIENCES

AgNIC Plant Science Home Page
http://www.unl.edu/agnicpls/agnic.html

ARGO-Observing the Ocean in Real Time
http://www.argo.ucsd.edu

Biota of North America Program
http://www.bonap.org

Botanical Ecological Unit
http://www.fs.fed.us/biology/plants/beu.html

Botanical Electronic News
http://www.ou.edu/cas/botany-micro/ben

Botanical Glossaries
http://155.187.10.12/glossary/glossary.html

Botany
http://www.nmnh.si.edu/departments/botany.html

Botany Online: The Internet Hypertextbook
http://www.biologie.uni-hamburg.de/b-online

Botany.com
http://www.botany.com

Centre for Plant Architecture Informatics
http://www.cpai.uq.edu.au

Delta
http://biodiversity.uno.edu/delta

Digital Tectonic Activity Map
http://denali.gsfc.nasa.gov/dtam

Electronic Sites of Leading Botany, Plant Biology, and Science Journals
http://www.e-journals.org/botany

Food and Agriculture Organization
http://www.fao.org

GardenNet
http://gardennet.com

Global Ice-Core Research
http://id.water.usgs.gov/projects/icecore

Hydrologic Information Center: Current Hydrologic Conditions
http://www.nws.noaa.gov/oh/hic/current

Igneous Rocks Tour
http://seis.natsci.csulb.edu/basicgeo/IGNEOUS_TOUR.html

Index Nominum Genericorum
http://rathbun.si.edu/botany/ing

Integrated Taxonomic Information System
http://www.itis.usda.gov

International Association of Volcanology and Chemistry of Earth's Interior
http://www.iavcei.org

International Organization for Plant Information
http://iopi.csu.edu.au/iopi

International Plant Names Index
http://www.ipni.org

Internet Directory for Botany
http://www.botany.net/IDB

MedBioWorld
http://www.medbioworld.com/bio/journals/plants.html

National Earthquake Information Center
http://wwwneic.cr.usgs.gov

National Oceanic and Atmospheric Administration
http://www.noaa.gov

Natural Perspective
http://www.perspective.com/nature/index.html

Plant Facts
http://plantfacts.ohio-state.edu

Plant Information Systems
http://www.wes.army.mil/el/squa/cdroms.html

Plants Database
http://plants.usda.gov./topics.html

Topozone
http://www.topozone.com

U.S. Geological Survey
http://www.usgs.gov

Virtual Geosciences Professor
http://www.uh.edu/~jbutler/anon/anonfield.html

Virtual Library of Botany
http://www.ou.edu/cas/botany-micro/www-vl

Volcano World
http://volcano.und.nodak.edu

W3 Tropicos
http://mobot.mobot.org/W3T/search/image/imagefr.html

Woods Hole Oceanographic Institution
http://www.whoi.edu

World-Wide Earthquake Locator
http://www.geo.ed.ac.uk/quakes/quakes.html

Genetics

BioMedNet
http://reviews.bmn.com/?subject=Genetics

DNA from the Beginning
http://www.dnaftb.org/dnaftb

Dolan DNA Learning Center, Cold Spring Harbor Laboratory
http://www.dnalc.org

Genetics Society of America
http://www.genetics-gsa.org

Genome News Network
http://www.genomenewsnetwork.org/index.php

Kimball's Biology Pages
http://biology-pages.info

MedBioWorld
http://www.medbioworld.com

MendelWeb
http://www.mendelweb.org

National Center for Biotechnology Information
http://www.ncbi.nlm.nih.gov

National Public Radio, the DNA Files
http://www.dnafiles.org/home.html

Nature Publishing Group
http://www.nature.com/genetics

U.S. Department of Energy, Genomics Image Gallery
http://www.ornl.gov/sci

U.S. Department of Energy Office of Science, Virtual Library on Genetics
http://www.ornl.gov/TechResources/Human_Genome/genetics.html

University of Massachusetts, DNA Structure
http://molvis.sdsc.edu/dna/index.htm

University of Utah, Genetic Science Learning Center
http://gslc.genetics.utah.edu

History, Society, and Culture of Science

American Physical Society: A Century of Physics
http://timeline.aps.org/APS/home_HighRes.html

Art of Renaissance Science
http://www.pd.astro.it/ars/arshtml/arstoc.html

Case Studies in Science
http://ublib.buffalo.edu/libraries/projects/cases/case.html

History of the Light Microscope
http://www.utmem.edu/personal/thjones/hist/hist_mic.htm

Important Historical Inventions and Inventors
http://www.lib.lsu.edu/sci/chem/patent/srs136_text.html

Links to Science, Technology, and Society-Related Information Sources
http://www2.ncsu.edu/ncsu/chass/mds/stslinks.html

Science in Our Daily Lives
http://www.lib.virginia.edu/science/events/Sci_Daily_Life.html

Inventions

Invent America!
http://www.inventamerica.com

Invention Convention/National Congress of Inventor Organizations
http://www.inventionconvention.com

Inventors Museum
http://www.inventorsmuseum.com

Inventors Web Site
http://inventors.about.com

Kids Inventor Resources
http://www.InventorEd.org/k-12/becameinv.html

Lemelson-MIT Awards Program Invention Dimension Web Site
http://web.mit.edu/invent/index.html

National Collegiate Inventors and Innovators Alliance
http://www.nciia.org

National Inventors Hall of Fame
http://www.invent.org/book/index.html

Tips for Parents of Young Inventors (Young Inventors Fair Web Site)
http://www.ecsu.k12.mn.us/yif/tips.html

United States Patent and Trademark Office
http://www.uspto.gov

"What It Takes to Be an Inventor": 3M Collaborative Invention Unit
http://mustang.coled.umn.edu/inventing/Inventing.html

Mathematics

Clay Mathematics Institute
http://www.claymath.org

Geometry in Action
http://www.ics.uci.edu/~eppstein/geom.html

Math Archives
http://archives.math.utk.edu

Mathematical Sciences Research Institute
http://www.msri.org/index.html

Metamath Proof Explorer
http://www1.shore.net/~ndm/java/mmexplorer1/mmset.html

Medicine and Nutrition

American Medical Association
http://www.ama-assn.org

BioMedNet
http://www.biomednet.com

Centers for Disease Control and Prevention
http://www.cdc.gov

Consumer Health Information Service
http://hml.org/CHIS/index.html

Healthlink USA
http://www.healthlinkusa.com

Heart: An Online Exploration
http://sln.fi.edu/biosci/heart.html

Human Anatomy Online
http://www.innerbody.com/htm/body.html

Kids Health
http://www.kidshealth.org

Martindale's Health Science Guide
http://www-sci.lib.uci.edu/HSG/Ref.html

Medicine Net
http://www.medicinenet.com/script/main/hp.asp

Medicine Through Time (BBC)
http://www.bbc.co.uk/education/medicine

Medline Plus
http://medlineplus.gov

Medscape
http://www.medscape.com/px/urlinfo

MEDtropolis Home Page
http://www.medtropolis.com

National Library of Medicine
http://www.nlm.nih.gov

Neuroscience for Kids
http://faculty.washington.edu/chudler/neurok.html

On-line Medical Dictionary
http://www.graylab.ac.uk/omd

WebMD
http://www.webmd.com

World Health Organization
http://www.who.int

Museums

American Museum of Natural History
http://www.amnh.org

American Museum of Science and Energy, Oak Ridge, Tennessee
http://www.amse.org

California Science Center
http://www.casciencectr.org

Carnegi Museum of Natural History
http://www.CarnegieMuseums.org/cmnh

DNA Learning Center, Cold Springs Harbor
http://vector.cshl.org

Exploratorium
http://www.exploratorium.edu

Field Museum of Natural History in Chicago
http://www.fmnh.org

Franklin Institute Science Museum
http://sln.fi.edu/tfi/welcome.html

Further Explorations
http://www.explorations.org/further_explorations.html

Museum of Science and Industry
http://www.msichicago.org

National Air and Space Museum
http://www.nasm.si.edu

Peabody Museum of Natural History
http://www.peabody.yale.edu

Science Museum of Minnesota, Thinking Fountain
http://www.sci.mus.mn.us

SciTech, the Science and Technology Interactive Center
http://scitech.mus.il.us

Smithsonian Institution
http://www.si.edu

U.S. Space & Rocket Center
http://www.spacefun.com

WebExhibits
http://www.webexhibits.com

Paleontology

Coelacanth: The Fish Out of Time
http://www.dinofish.com

Paleonet
http://www.ucmp.berkeley.edu/Paleonet

PaleoQuest
http://paleoquest.cet.edu

So You Want to Be a Paleontologist?
http://www.cisab.indiana.edu/~mrowe/dinosaur-FAQ.html

Willo, the Dinosaur with a Heart
http://www.dinoheart.org

Physics

American Association of Physics Teachers
http://www.aapt.org

American Institute of Physics Center for the History of Physics
http://www.aip.org/history

Elemental Data Index
http://physics.nist.gov/PhysRefData/Elements/cover.html

Exploring Gravity
http://www.curtin.edu.au/curtin/dept/phys-sci/gravity

Gravity Probe B: The Relativity Mission
http://einstein.stanford.edu

Internet Pilot to Physics
http://physicsweb.org/TIPTOP

Particle Adventure
http://www.particleadventure.org

PhysicsEd: Physics Education Resources
http://www-hpcc.astro.washington.edu/scied/physics.html

PhysLINK
http://www.physlink.com

Playground Physics
http://www.aps.org/playground.html

Professor Bubbles' Official Bubble Home Page
http://bubbles.org

Unsolved Mysteries
http://www.pbs.org/wnet/hawking/mysteries/html/myst.html

Visual Quantum Mechanics: Online Interactive Programs
http://phys.educ.ksu.edu/vqm/index.html

SPACE SCIENCE

Air and Space Magazine
http://www.airspacemag.com

Amateur Radio on the International Space Station (ARISS)
http://www.arrl.org/ARISS/

Ames Research Center
http://www.nasa.gov/centers/ames

Ames Research Center: History Office
http://history.arc.nasa.gov

Ames Research Center: Multimedia
http://www.nasa.gov/centers/ames/multimedia

Apollo: A Retrospective Analysis
http://www.hq.nasa.gov/office/pao/History/Apollomon/cover.html

Apollo Program
http://spaceflight.nasa.gov/history/apollo

Apollo Project Archive
http://www.apolloarchive.com

Association of Space Explorers
http://www.space-explorers.org

Astronaut Biographies
http://www.jsc.nasa.gov/Bios

Astronomy Café, The
http://www.astronomycafe.net

Astrophysics Data System
http://adswww.harvard.edu

Cassini-Huygens Mission
http://www.nasa.gov/mission_pages/cassini/main

Chandra X-Ray Observatory Center
http://chandra.harvard.edu

Chronology of Space Exploration, Russian Space Web
http://www.russianspaceweb.com/chronology.html

Coalition for Space Exploration
http://www.spacecoalition.com

Compton Gamma Ray Observatory
http://cossc.gsfc.nasa.gov/cossc

Dawn Mission
http://dawn.jpl.nasa.gov

Deep Impact
http://deepimpact.jpl.nasa.gov

Deep Space Network
http://deepspace.jpl.nasa.gov/dsn

Destination Earth
http://www.earth.nasa.gov

Discovery Program
http://discovery.nasa.gov

Earth Observing System
http://eospso.gsfc.nasa.gov

Earth Observing System Data Gateway
http://delenn.gsfc.nasa.gov/~imswww/pub/imswelcome

European Space Agency (ESA)
http://www.esa.int

Galaxy Evolution Explorer
http://www.galex.caltech.edu

Gamma-ray Large Area Space Telescope (GLAST)
http://glast.gsfc.nasa.gov

Gemini Program
http://www-pao.ksc.nasa.gov/kscpao/history/gemini/gemini.htm

Glenn Research Center
http://www.nasa.gov/centers/glenn

Goddard Space Flight Center (GSFC)
http://www.nasa.gov/centers/goddard

Great Images in NASA
http://grin.hq.nasa.gov

History Timelines
http://www.hq.nasa.gov/office/pao/History/timeline.html

Human Space Flight
http://spaceflight.nasa.gov/home

International Space Station
http://www.nasa.gov/mission_pages/station/main

Jet Propulsion Laboratory (JPL)
http://www.jpl.nasa.gov/

Johnson Space Center (JSC)
http://www.nasa.gov/centers/johnson

Kennedy Space Center
http://www.nasa.gov/centers/kennedy

Konstantin E. Tsiolkovsky State Museum of the History of Cosmonautics
http://www.informatics.org/museum

Langley Research Center (LRC)
http://www.nasa.gov/centers/langley

Lunar and Planetary Science
http://nssdc.gsfc.nasa.gov/planetary/planetary_home.html

Lunar Exploration Timeline
http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html

Lyndon B. Johnson Space Center
http://www.nasa.gov/centers/johnson

Manned Spacecraft Gallery
http://www.lycoming.edu/astr-phy/fisherpdg1

Mars Exploration Program
http://mars.jpl.nasa.gov/

Marshall Space Flight Center
http://www.nasa.gov/centers/marshall

Mercury, Project
http://www-pao.ksc.nasa.gov/kscpao/history/mercury/mercury.htm

Mir Space Station, Russian Space Web
http://www.russianspaceweb.com/mir.html

NASA
http://www.nasa.gov

NASA: History Office
http://history.nasa.gov/

NASA: Image Exchange (NIX)
http://nix.nasa.gov

NASA: Science Mission Directorate
http://science.hq.nasa.gov/

NASA: Space Science
http://spacescience.nasa.gov

New Millennium Program
http://nmp.jpl.nasa.gov

Origins of the Universe
http://origins.jpl.nasa.gov

Planetary Society, The
http://planetary.org

PlanetScapes
http://planetscapes.com

Satellite Tracking in Real Time
http://science.nasa.gov/realtime

Skylab Program
http://www-pao.ksc.nasa.gov/kscpao/history/skylab/skylab.htm

Solar System Exploration
http://sse.jpl.nasa.gov

Spaceline.org History of Rocketry
http://www.spaceline.org/rockethistory.html

Spitzer Space Telescope
http://www.spitzer.caltech.edu/spitzer

Stardust Project
http://stardust.jpl.nasa.gov

Stennis Space Center, John C.
http://www.nasa.gov/centers/stennis

TDRSS Satellite System
http://msp.gsfc.nasa.gov/tdrss/tdrsshome.html

Ulysses
http://ulysses.jpl.nasa.gov

Virtual Space Museum (of Cosmonautics)
http://vsm.host.ru/emain.htm

Wilkinson Microwave Anisotropy Probe
http://map.gsfc.nasa.gov

WEATHER, CLIMATE, AND NATURAL DISASTERS

Environmental Protection Agency, Global Warming Site
http://www.epa.gov/globalwarming

Global Volcanism Program
http://www.volcano.si.edu/gvp/index.htm

Hurricane and Storm Tracking
http://hurricane.terrapin.com

Lightning Imaging Sensor Data
http://thunder.msfc.nasa.gov/data/lisbrowse.html

National Drought Mitigation Center
http://enso.unl.edu/ndmc

National Snow and Ice Data Center
http://www-nsidc.colorado.edu/NSIDC

National Weather Service
http://www.nws.noaa.gov

Nova Online: Flood!
http://www.pbs.org/wgbh/nova/flood

Tornado Project Online
http://www.tornatoproject.com

Tsunami!
http://www.geophys.washington.edu/tsunami/intro.html

ZOOLOGY

AmphibiaWeb
http://elib.cs.berkeley.edu/aw

Animal Diversity Web
http://animaldiversity.ummz.umich.edu

Endangered Species Update
http://www.umich.edu/~esupdate

Extinction Files
http://www.bbc.co.uk/education/darwin/exfiles/index.htm

FishBase
http://www.fishbase.org

Ichthyology Web Resources
http://www.biology.ualberta.ca/jackson.hp/IWR/index.php

Living Links
http://www.emory.edu/LIVING_LINKS

National Marine Mammal Laboratory's Education Web Site
http://nmml.afsc.noaa.gov/education

NetVet and the Electronic Zoo
http://netvet.wustl.edu

North American Bird Conservation Initiative
http://www.bsc-eoc.org/nabci.html

Northern Prairie Wildlife Research Center
http://www.npwrc.usgs.gov

Satellite Tracking of Threatened Species—NASA
http://sdcd.gsfc.nasa.gov/ISTO/satellite_tracking

Virtual Creatures
http://k-2.stanford.edu/creatures

Welcome to Coral Forest
http://www.blacktop.com/coralforest

World Wildlife Fund
http://www.wwf.org

—*Elizabeth Schafer, updated by Christina J. Moose*

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