

DISCOVERING
THE
NANOSCALE

Edited by
Davis Baird
Alfred Nordmann
Joachim Schummer

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DISCOVERING THE NANOSCALE

This One



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Introduction

Science and engineering, industry and politics, environmentalists and transhumanists are *Discovering the Nanoscale*. Public debate is widening, policy makers are demanding explicit consideration of ethical, legal, and social aspects, and popular books are explaining the achievements and promises of nanoscience. It may therefore seem surprising that this is the first collection of studies that considers nanoscience and nanotechnologies from the critical perspective of Science and Technology Studies (STS).

This is less surprising, however, when one appreciates that such a critical perspective needs to be historically informed and often involves intimate acquaintance with the research process. Accordingly, this book on the historical, analytical, and ethical study of nanoscience and -technology – ^{nano}STS, for short – was several years in the making. Though it presents only first results, these results for the most part stem from sustained investigations of nanoscience and nanotechnologies and of the contexts that are shaping their development.

Nanoscience and technologies are developing very quickly, and for this reason both pose a challenge to the more reflective approach commonly taken by science studies, while at the same time requiring the perspective provided by science studies scholars. Indeed, this book serves as a corrective to two commonly held, but equally mistaken beliefs.

First, many are convinced that nothing meaningful can be said at this early stage of their development about the social and ethical implications of nanotechnologies. While, indeed, not much has come out of nanoscale research as of yet to warrant critical assessment, one can already see what programmatic attitudes go into nanoscale research, what metaphors are shaping it, and what conception of nature is implicit in its vision. This volume shows that all of this is already open to analysis and questioning.

The second common misconception points in the opposite direction. It is often assumed that in order to consider ethical, legal, and social aspects of nanotechnologies it is sufficient to know a bit of the science and to have some ethical intuitions. This collection of papers establishes that this is not enough but that one also needs to appreciate nanoscale research and development in the larger context of the changing relations of science, technology, and society.

Most public discussion of nanotechnologies, including that of ^{nano}STS, concerns what Arne Hessenbruch in this volume calls the “negotiation of novelty”. To be sure, nothing would be “wrong” with nanoscience or nanotechnologies, if they turned out to be far less novel and far more normal than some of their propagandists are making them out to be. Indeed, for purposes of rational political discourse it is important to treat them not as unfathomably new but as just so many ordinary innovations that need to be discussed and perhaps regulated in the political sphere, and that await to be accepted, rejected, or modified by consumers in the marketplace like all other innovations.

And yet, even if the research, development, diffusion, and appropriation of nanotechnologies ought to be considered in normal rather than mystifying terms, it cannot be denied that, indeed, nanotechnology may herald large changes in a variety of areas from manufacturing to the way research is done to how we conceive ourselves as humans. Even if nanosciences and nanotechnologies are not in principle new but continue familiar trajectories of materials science, synthetic chemistry, solid state physics, surface science, molecular biology, electrical, mechanical, and chemical engineering, and so on, their current prominence and visibility are symptomatic of cultural changes in science and technology and of

societies at large. Independent of the issue of novelty, understanding those changes is what nanoSTS is particularly concerned with.

The present volume is the first offspring of an emerging international community of nanoSTS scholars. Starting with a pair of conferences in Columbia, South Carolina, and Darmstadt, Germany (March and October 2003), scholars from a wide array of disciplines assembled together, including philosophers, historians, and sociologists of science and technology, scholars from art, literature, communication, media, policy, and legal studies, as well as nanoscientists and nanoengineers. Further conferences have been held since or are forthcoming, both in the US and Europe, on more specific topics, such as imaging and imagining nanotechnology and ethical issues. Many research groups are being established in different countries to study social and ethical implications of nanotechnology. Two journals, *Hyle* and *Techne*, specialized in philosophy of chemistry and philosophy of technology, respectively, are preparing a joint special issue on “Nanotech Challenges” for fall 2004. A website at the University of South Carolina has been set up to provide various resources (www.cla.sc.edu/cpeccs/nirt/), including an online bibliography of which we publish the current version here.

For the present volume, we made a selection of 25 papers from more than 40 contributions to the mentioned pair of inaugural conferences. The succession of conferences assured that the contributors could speak to and learn from each other before they prepared their final papers. Despite their various disciplinary backgrounds, contributors assembled around six main topics that provide the structure of this book. The very first question is how to characterize nanoscale research, especially in regard to established science and engineering disciplines (I). This leads to the problem regarding the theoretical and methodological basis of nanoscience or nanotechnology and what it might be (II). In terms of scientific practice, the production and interpretation of nanoscale images has been central to nanoscale research from its very beginning (III). Also, from its very beginning, nanotechnology has been defined by way of the rhetoric and metaphors used to propagate it to a wider public (IV). Moving outward from the consideration of research to its societal contexts, the contributions finally consider the politics of nanotechnology (V) and ethical issues (VI).

Since researchers from most of the classical science and engineering disciplines are currently engaged in nanoscale research at rapidly increasing numbers, nanoscale research is arguably a broad scientific movement across the disciplines. Is that going to undermine the identities of the disciplines and the disciplinary landscape as we know it? Does nanoscale research require a complete re-organization of our received knowledge structure? In Part I of this volume, “Configuring the Disciplines”, five papers provide different answers to these questions. Based on empirical findings, JOACHIM SCHUMMER argues that each discipline currently does its own nanoscale research without much interaction, because different disciplinary perspectives on the nanoscale and different technological paradigms prevent the politically desired interdisciplinarity. Opposed to the segmentation of nanodisciplines, two authors suggest quite different unification views. JAN SCHMIDT sees in nanotechnology the attempt to establish a fundamental technology that is guided by a misguided technological reductionism and driven by physicists. GEORGE KHUSHF suggests a systems-theory approach that allows for the nonreductionist convergence of nanotechnology, biotechnology, information technology, and cognitive science in which also the humanities find their appropriate place. Instead of taking a bird’s eye view, two papers explore the disciplinary issues in detailed case studies. In his analysis of a debate between two research schools in molecular electronics, ALFRED NORDMANN identifies a shift of nanoscience from classical theory-driven science towards a new form of technoscience that differs from classical science as much as from engineering. Finally, MICHAEL GORMAN,

JAMES F. GROVES, and JEFF SHRAGER present a model of successfully interdisciplinary collaboration between the humanities and nanoengineers for scientific research that is directed towards socially beneficial results.

Despite popular portraits of moving atoms around like balls and sticking them together with ultra-precision, successful nanoscience and nanotechnologies depend on advanced theories of molecular, atomic, and sub-atomic behavior that are traditionally provided by chemistry and physics. Is the classical canon of theories and theoretical methods sufficient to cope with the challenges posed by the nanotechnology movement, by its strong technological orientation across the disciplines? In Part II, “Searching for Theories of the Nanoscale”, three papers explore how nanoscientific approaches differ from mathematical physics. PIETER VERMAAS argues that, since a theory of nanotechnology requires describing technological functions that cannot be derived from quantum mechanics, new/particular interpretations of quantum mechanics are required. JOHANNES LENHARD points out that nanoscience, because it relies heavily on computer simulations that combine epistemological features of theory and experimentation, is set apart from the received methodology of physics. OTÁVIO BUENO goes beyond physics and argues that John von Neumann’s theory of automata and self-reproduction is the historical and methodological background of Eric Drexler’s “theoretical applied science” approach to self-assembling devices.

More perhaps than any other field of research, nanotechnology lives from the production and mediation of images. Binnig’s and Rohrer’s Nobel prize winning invention of the scanning tunneling microscope (STM) in 1981 and IBM’s logo written with pointy bright-blue xenon atoms on a smooth dark-gray nickel surface have been made visually compelling highlights of standard narrations of nanotechnology. In part III “Imaging the Nanoscale”, five papers analyze from historical, sociological, epistemological, and artistic points of view images of the nanoscale and the instruments used for their production. They all question popular understandings of the role of STMs in nanotechnology and of “seeing atoms”. The first three papers by CYRUS MODY, ARNE HESSENBRUCH and DAVIS BAIRD & ASHLEY SHEW each provide detailed historical narratives of scanning probe microscopy, of the various researchers, communities, companies, and politics involved in its development. Mody concludes that, although the connection to nanotechnology had been contingent, probe microscopists were trying to create their own nano field. Hessenbruch analyses the negotiation of novelty of the instruments’ capacities and suggests that this is part of the visionary rhetoric that is generally required nowadays to promote science in the public sphere. BAIRD & SHEW argue that the commercialization and black-boxing of scanning probe microscopes represents an epistemological shift characteristic of post-academic science. The two remaining papers focus on the role of visual images. JOSEPH PITT critically analyses the notion of “seeing atoms” with STMs and argues for a metaphorical reading, because visualization by scientific instruments fundamentally differs from actual seeing. CHRIS ROBINSON relates nanotechnological image production to the broader culture of visual arts, warns of uncritical image use, and suggests distinguishing carefully between schematics, documentation, fantasy, and fine art.

Apart from visual images, the language used by nanoscale researchers, visionaries, and politicians in public speeches and publications for broader readerships plays an important role in propagating nanotechnology and negotiating its identity. The term “nano” itself has become a buzz word, prefixed to almost any other term to build compound words that indicate little more than the author’s commitment to the nano movement. Powerful old metaphors have been incorporated into the nano discourse and new ones are being created to communicate specific messages. Part IV “Communicating Nanotechnology” presents four critical analyses of the rhetoric of nanotechnology. DAVID BERUBE provides a rhetorical analysis of Eric Drexler’s publications on molecular nanotechnology with emphasis on how risks have been communicated to a broader readership. In his discourse analysis of the

emerging field of nanomedicine, ANDREAS LÖSCH investigates how innovation is negotiated within research communities by referring to different notions, such as miniaturization (the top-down approach) and hybridization of nature and technology. GREGOR SCHIEMANN examines how the US brochure “Shaping the World Atom by Atom” exploits the common sense distinction between nature and technology as an effort to legitimize nanotechnology to the public. ASTRID SCHWARZ, by carefully distinguishing different concepts of sustainability, points out the inconsistencies in the public discourse on nanotechnology.

Given the strong political efforts – through enormous governmental funding, the foundation of numerous national initiatives, and the competition for global leadership – nanotechnology almost appears like a creation by politicians. Part V “Examining the Politics of Nanotechnology” addresses such questions as: What specific interests are guiding the politics of nanotechnology? How can the political control of nanotechnology be further democratized? Based on her survey of the history of research policy in the US, ANN JOHNSON argues that the current focus on nanotechnology is only the final step of a two-decade long shift towards commercially exploitable research at the expense of pure science. From a sociological point of view, HANS GLIMMEL analyzes the development of the US National Nanotechnology Initiative, its actors and their responses to critical concerns, as well as the role conceived for the social sciences. JODY A. ROBERTS, with reference to prior legal studies on the regulation of nanotechnology, discusses several approaches to increase and decrease public participation in the creation, acceptance, and use of nanotechnology. EDWARD MUNN argues for democratic deliberation about nanotechnology and a culture in which the role of experts is restricted to the promotion of informed decision-making by the citizens.

Since nanotechnology emerged from the efforts of visionaries, promises of unprecedented benefits have been accompanied by warnings of great threats, such that the demand for “Societal and Ethical Implications of Nanotechnology” has become an essential component of the nano movement. This has made philosophers and ethicists quite reluctant to engage in such visionary speculations. It is time, however, to approach the field from perspectives that are detached from the visionary propagation of nanotechnology. Part VI “Exploring Ethical Dimensions” therefore comprises four papers that deal with ethical issues that are likely to arise in the near future. JÜRGEN ALTMANN & MARK GUBRUD focus on possible military applications of nanotechnology and argue that they would undermine current arms-control treaties, humanitarian laws, and military stability, such that new arms control measures are required now. EMMANUELLE SCHULER claims that, against the background of current scientific knowledge, the perceived risks of nanoparticles for health and the environment are overestimated and overrated. WADE ROBISON distinguishes between ethical issues that are internal to the practice of nano-engineers, like error-provocative designs, and those that are external and result from misguided application, like constraints of health risks, and environmental harm. JAMES MOORE and JOHN WECKERT, while acknowledging the uncertainties in defining the terrain of nanotechnology, discuss the ethical issues of privacy, human longevity, and “runaway nanobots” that will arise if certain promises come true.

As Arne Hessenbruch and Ed Munn point out, the negotiation of novelty hinges on contentious claims. To the extent that the papers in this volume sift through such claims and end up taking a stance regarding the novelty and particular interest of nanoscience and nanotechnologies, they leave us with contentious claims of their own. Whether they mark beginnings of ^{nano}STS research trajectories or present results of sustained investigations, all of them invite dissent. What this book therefore needs most are readers willing to take on the various claims and counter-claims of the book, to examine them carefully and critically and to constructively move the field ahead. Only then can we say to have “discovered the

nanoscale” as an important and contentious territory for Science and Technology Studies. Inasmuch as nanoscience and nanotechnologies challenge our ways of thinking, judging, and acting, ^{nano}STS helps developing a better understanding of who we are, which times we live in, and what science and technology mean in contemporary culture.

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Interdisciplinary Issues in Nanoscale Research

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Abstract. Great expectations and promises rest on interdisciplinarity in nanoscale research. Yet, although many science and engineering disciplines actually began to engage in this field, it is only poorly understood what interdisciplinarity actually is and what factors hinder and promote it. Part I provides an introduction to interdisciplinarity, its cognitive and social elements, and its related concepts, such as multi- and transdisciplinary or super-interdisciplinary. Part II first presents empirical findings about the actual weakness of interdisciplinarity in current nanoscale research and then discusses two of the main conceptual reasons for this. I argue that definitions of nanoscale research are too vague to provide interdisciplinary integration and that current nanotechnological visions include discipline-rooted and metaphysically opposed technological paradigms, such as ‘self-assembly’ vs. ‘atom-by-atom-manipulation’, that pose strong barriers to interdisciplinary research.

Introduction

Nanoscale research is currently attracting tremendous attention from both the general public (Schummer 2005) and from a large variety of science and engineering disciplines (Schummer 2004). The attraction is largely fostered by technological visions, the promises of new scientific discoveries, and huge governmental funds. Such a melting pot of various disciplines promises to be a great opportunity for innovative research through synergetic effects, provided that researchers from different disciplines find a common basis required for interdisciplinary research. If that is missing, however, disintegration is to be expected and researchers will at best do their disciplinary research business as usual, though under a new label. Therefore, the understanding and mediating of interdisciplinarity is a crucial factor in the future success of nanoscale research. Yet, although every report on nanoscale research highlights the necessity of interdisciplinarity,¹ little effort at understanding interdisciplinarity has been made. To the contrary, there is currently a naive rush from badly understood interdisciplinarity towards new visions of super-interdisciplinarity to be centered on nanotechnology (Roco & Bainbridge 2002).

A sort of longish introduction, the first part of this paper presents some general ideas about interdisciplinarity and its related concepts, such as discipline, multi- and transdisciplinary or super-interdisciplinary. The second part starts with a summary of scientometric findings about multi- and interdisciplinarity in current nanoscale research (Schummer 2004). Since these findings suggest that interdisciplinary nanoscale research is indeed in a bad shape, the rest of the paper analyzes two specific reasons for this. On the one hand, I argue that current definitions of nanoscale research, which are mainly based on the size of objects, are too vague to provide any integrative function. On the other hand, I point out that certain discipline-rooted technological paradigms, such as ‘self-assembly’ and ‘atom-by-atom-manipulation’, which are currently employed in nanotechnological visions, are

barriers to interdisciplinarity insofar as they include metaphysical oppositions that disintegrate rather than integrate the disciplines.

1. Elements of Interdisciplinarity

1.1 *A Brief Survey of the Literature*

Strangely enough, the literature on interdisciplinarity is multidisciplinary rather than interdisciplinary (for the distinction, see below). It includes scholars from science education, sociology of science, history of science, and philosophy of science.²

As we shall see, ‘discipline’ has strong educational connotations. A great part of the literature on interdisciplinarity therefore belongs to professional education and arose from debates about reforms of tertiary education to be based on a broadened scope of general knowledge, like a *studium generale*.³ Other literature stems from sociology of science and science policy studies. Not surprisingly, scholars in these fields focus on sociological and organizational aspect of interdisciplinarity while neglecting to some extent the cognitive side. Much more integrative perspectives can be found in the numerous detailed case studies of interdisciplinary research and discipline formation by historians of science.⁴

When sociology and history of science merge, this frequently results in ‘Big Philosophical Pictures’. A favorite topic is the allegedly new or hoped-for interdisciplinarity between science and technology in problem-based research, for which historical claims have been made and new terms introduced, like ‘Technoscience’, ‘Mode 2 of Knowledge Production’. Such approaches may belong to philosophy insofar as they engage in metaphysical and epistemological debates about modernism/postmodernism or realism/constructivism rather than the historiography of science. In fact, they, more or less explicitly, oppose the other Big Philosophy Picture of interdisciplinarity, the ambitious Unity of Science Project launched by Logical Positivists in the 1930s. Claiming that the disciplinary languages of all sciences can and should be based on or reduced to the language of physics, the Unity project reduced interdisciplinary relations to the reduction of all sciences to physics. With their bias towards physics, modern philosophers of science (or rather, of physics) favored physicalistic reductionism as the only interdisciplinarity relation, be it on the level of descriptive language, theories, so-called meta-theories, ontologies, or methods.⁵

It might be recalled, however, that the cognitive relations between the sciences, or more generally the structure of our overall knowledge, has been a central topic of philosophy ever since at least Aristotle. Behind that stands the classical idea that the ideal structure of our knowledge does or should correspond to the structure of our world – a position that has frequently recurred as either epistemological realism or metaphysical idealism. By emphasizing the impact of social dynamics on the structure of our knowledge, social constructivists could easily challenge the classical idea, particularly in its epistemological variant, with case studies on the social dynamics of the disciplinary structure, provided that the disciplinary structure determines the structure of knowledge. This has made interdisciplinarity a hot topic, although full of ambiguity as to whether ‘discipline’ is considered a cognitive or a social category and as to whether epistemological claims are meant to be descriptive or normative.

1.2 *What is a Discipline?*

In its original Latin meaning, which is still preserved in current English as well as in other European languages, the term ‘discipline’ (from Latin, ‘*disciplina*’) refers to a body of knowledge that is taught in a certain school. Students (disciples) learn a certain doctrine (a discipline) by obeying strict (disciplinary) rules of a school (discipline) and by practicing

self-control (discipline). There is no disciplinary knowledge without a social context of transmission and education and a social body that thereby reproduces itself. Modern scientific disciplines do not differ much from that, except that they do not simply preserve but increase and modify a body of knowledge through scientific research – which requires even stricter methodological rules to preserve the continuity of the social body. Thus, a scientific discipline, as I will use the term in the following, comprises both cognitive and social aspects: (1) a body of knowledge, including concepts and beliefs (knowledge of objects), methods for increasing and securing knowledge (knowledge of methods), and values about judging the quality and importance of knowledge (knowledge of values); (2) a social body with effective rules and means for increasing, communicating, and teaching the body of knowledge as a way of self-reproduction.

1.3 Multi-, Inter-, Transdisciplinary, and Super-interdisciplinary

The terms ‘multidisciplinary’, ‘interdisciplinary’, and ‘transdisciplinary’ have been used to describe research activities, research problems, research institutions, teaching, or a body of knowledge, each with an input from at least two scientific disciplines. Although confusion still abounds, there is some agreement that ‘multidisciplinary’ describes a rather loose, additive, or preliminary relation between the disciplines involved, whereas ‘interdisciplinary’ requires stronger ties, overlap, or integration. In some diachronic models, multidisciplinaryity is a preliminary step toward interdisciplinarity, which can go as far as to either unify two or more disciplines or to create a new ‘interdisciplinary’ (hybrid) discipline at the interface of the mother disciplines. Transdisciplinarity is a diachronic (if not a political or ‘antidisciplinary’) concept to describe a state of research or knowledge that transcends disciplinary boundaries, with continuous input from various disciplines but without any inclination to consolidate into a new (hybrid) discipline. On the opposite side of this is ‘super-interdisciplinarity’, a term used to describe a new unity of all or at least of many sciences.

1.4 Cognitive Elements and Strategies of Interdisciplinarity

Cognitive elements of interdisciplinarity follow from our definition of a discipline. People from different disciplines involved in a common interdisciplinary research project must share a common knowledge basis, consisting of knowledge of objects, methods, and values. As long as there are different disciplines in the proper sense, the common basis can only consist in more or less overlap, because disciplines greatly differ in their knowledge of objects, in their methods for increasing and securing knowledge, and in their values about judging the quality and importance of pieces of knowledge. There are three approaches to increase overlap.

(1) *Reductionism* tends to ignore the differences of knowledge bodies by inventing hierarchies, such that the knowledge on one level can be reduced to the knowledge on a more basic level. The price of reductionism, which has been favored by many philosophers of science (of physics), is that their picture of scientific knowledge has lost any descriptive value with regard to the actual sciences other than physics.

(2) *Simplification* is a strategy that largely relies on the common ground of everyday knowledge. Because we share to some extent a common experience, an ordinary language, a rich source of common metaphors and pictures, this is a useful point to start with. Since ordinary knowledge does not capture the sophisticated structures of disciplinary knowledge, crude over-simplifications and particular efforts at using visual forms of communication are typical approaches that are all too apparent in current nanotechnology. The risk of simplification is that people stick to artificial problems and solutions, created from oversimplification, and that they do not recognize that simplification can only be a preliminary step towards serious research.

(3) *Translation or Mediation* requires a translator who should ideally be educated in all the disciplines involved. This would certainly be the best solution if mediators were available and socially accepted, neither of which is the case. Alternatively, scientific education could provide a broad scope of multidisciplinary teaching to students, such that everybody involved in interdisciplinary research has at least a basic understanding of the other disciplines. However, the general trend of tertiary education is heading in the opposite direction, which leads us to social elements of interdisciplinarity.

1.5 Social Elements of Interdisciplinarity

Long before the formation of a new discipline comes the step from multi- to true interdisciplinarity. It requires a considerable effort of social integration that involves new infrastructures for communication, collaborative research, publication, and teaching. While these aspects have been dealt with at length in the sociology and science policy literature, I would like to point out two further interrelated factors of social integration that are frequently overlooked because they appear to be only about cognitive integration. Both play a growing role in current nanoscale research; they are the historiography of the field and its visions. As they look into the past and into the future, both frequently appear in the same sort of texts authored by leaders in the field, namely in introductory, review, and editorial essays.

By identifying the founders and heroes of a field, both the field and the community are shaped, if not created.⁶ In addition, references to early and widely accepted authorities add seriousness and attractiveness to the field. A powerful tool of discipline formation, self-historiography frequently appears at the earliest state when research is just at the beginning. Two famous historical examples are Priestley's history of electricity from as early as 1767 and Ostwald's history of electrochemistry from 1896. Moreover, historiography takes a dynamic view of the field. It first places current activities into the overall historical development, and thereby provides historical meaning, significance, and links to the current works of researchers. Secondly, it calls for, or is even recruited for, extrapolation to the future, thereby giving plausibility to visions as the natural outcome of the historical development. That is why historiography and the formulation of visions frequently appear closely together.

Visions add further meaning, orientation, and links to particular research projects. Expressed in simple terms with reference to general human needs, visions provide quick answers to why-questions of a general audience – questions which researchers in highly specialized fields have difficulties to answer otherwise. By sharing the same visions, researchers of different fields can see each other as working on the same project or even belonging to the same community. This is the positive aspect of the current production of nanotech visions. Later we will see that visions can also pose barriers to interdisciplinarity.

2. The Bases of Interdisciplinarity in Current Nanoscale Research

In this part, I first present some scientometric results about the disciplinary structure of current nanoscale research and then discuss two elements on which expectations of successful interdisciplinary research largely seem to be based: the length scale of objects and technological visions about future success. The idea behind that seems to be straightforward: in order to integrate a bunch of scientific and engineering disciplines into one project, they must first study the same objects and secondly have the same vision of what the research should aim at technologically – interdisciplinary collaboration will then follow automatically. We will see that this is not that easy.

2.1 Multidisciplinarity and Interdisciplinarity in Nanoscale Research Journals

The journals in which nanoscale research is published are a good source to analyze its multi- and interdisciplinary structure. Although much of nanoscale research is still published in classical disciplinary journals, there are already eight journals devoted to the new field.⁷ In the following, I will focus on two journals: *Nanotechnology*, published since 1990 by the UK based Institute of Physics, with 150 regular papers in 2002; and *Nano Letters*, published since 2001 by the American Chemical Society, with 281 papers in 2002. Both journals define their field quite similarly as nanoscience and nanotechnology, and both have an explicit interdisciplinary mission ventilated in their Aims-and-Scope sections.

If one looks at the disciplinary affiliation of the authors, as I have done with 100 papers of each journal (see Figure 1), the combined results present a rich spectrum of all the disciplines involved in nanoscale research, *i.e.*, physics, chemistry, materials sciences, electrical engineering, chemical engineering, and so on. In contrast, in a typical disciplinary journal, *e.g.* the *Journal of the American Chemical Society* (JACS), about 80% of the authors are from the ‘mother discipline’, with some 20% from neighboring disciplines. From that we may conclude that nanoscale research is in fact multidisciplinary.

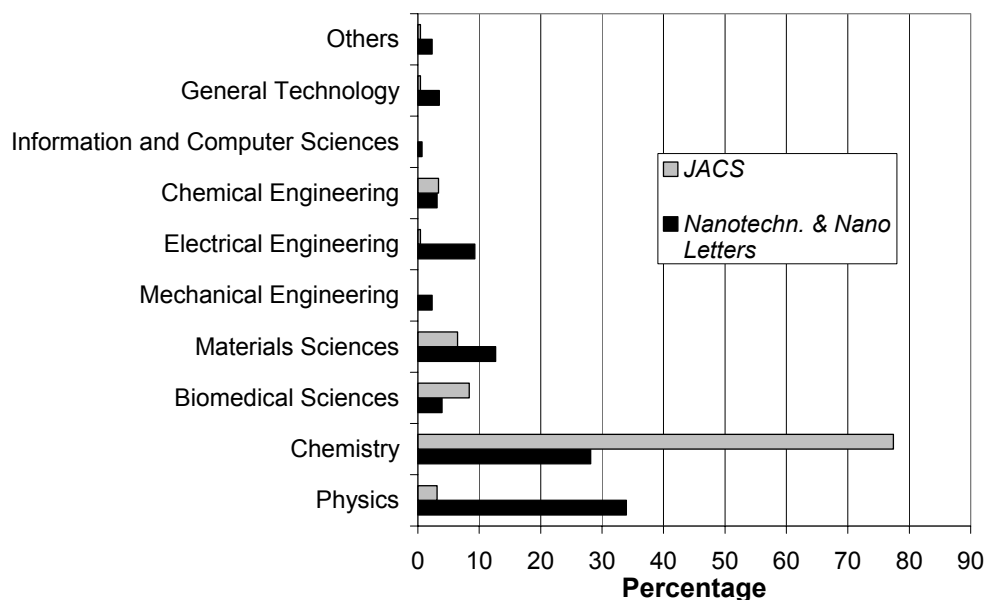


Figure 1. Disciplinary affiliation of authors publishing in ‘nano journals’ (*Nanotechnology* and *Nano Letters*) as opposed to the disciplinary *Journal of the American Chemical Society* (JACS) (data from Schummer 2004).

Yet, the disciplinary landscape becomes more divided when we analyze each of the two journals separately (see Figure 2). It turns out that we have a ‘nanophysics’ journal with almost half of the authors from physics; and a ‘nanochemistry’ journal with almost half of the authors from chemistry. Also, both journals show some preferences for favorite ‘guest disciplines’ – particularly the physics journal for electrical engineering and chemistry, and the chemistry journal for physics and materials sciences. Still, the overall picture of each journal is more multidisciplinary than disciplinary journals like JACS.

However, a multidisciplinary journal does not necessarily contain interdisciplinary research, since each discipline could publish its papers separately. Interdisciplinary research requires that scholars from different disciplines collaborate to become co-authors of one paper. On average, a paper in nanoscale research has 4.5 authors from 2-3 different institutions; in this regard, it does not much differ from a typical disciplinary journal like JACS.

The question is if the different institutions belong to different disciplines, instead of being located just in different cities. A simple measure for interdisciplinarity of a journal is the number of papers with authors from more than one discipline, the *interdisciplinarity rate* (see Table 1). The surprising result here is that our nanoscale research journals, though being more multidisciplinary, are hardly more interdisciplinary than a typical disciplinary journal like JACS.

I will now discuss two possible reasons why multidisciplinary of nanoscale research does not lead towards interdisciplinarity.

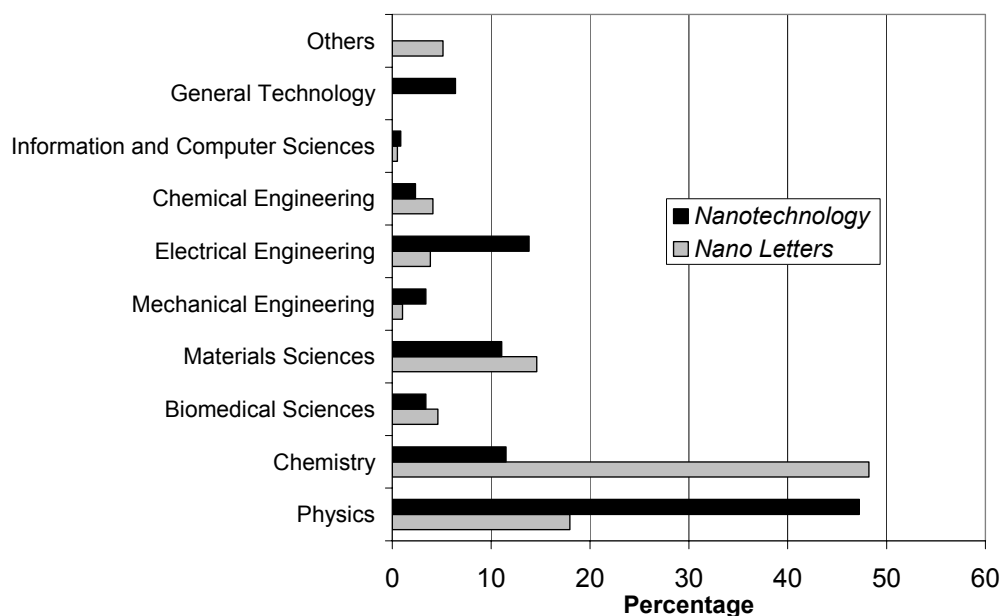


Figure 2. Disciplinary affiliation of authors publishing in *Nanotechnology* and in *Nano Letters* (data from Schummer 2004).

Table 1. Interdisciplinarity rates and main bi-disciplinary collaboration

Journals	Interdisciplinarity rate (%)	Main bi-disciplinary collaboration
<i>Nanotechnology</i>	37	Physics & Chemistry (6%)
<i>Nano Letters</i>	37	Chemistry & Physics (12%)
<i>JACS</i>	30	Chemistry & Materials Science (9%) Chemistry & Biomedical Sciences (9%)

2.2 The Scale of Objects as a Common Basis

Definitions of nanoscale research define this field almost tautologically by the nanometer size of its objects. For instance, the US committee on Nanoscale Science, Engineering and Technology (NSET) defines nanotechnology as:⁸

Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.

Since that is a precise length range, one might think that the definition of research objects is sufficiently clear. However, while it clearly defines a field of optical research, *i.e.* electromagnetic waves from far UV to soft X-ray, it is difficult to find any kind of matter that would not qualify as an object of such nanoscale research. The only candidates that come to mind are the small molecules and simple ideal crystals that fill introductory textbooks of chemistry – but even those have critical nanometer lengths in the gas phase at appropriate pressures, for example the mean free path length. Nowadays chemists produce more than fifteen million new substances per year, of which virtually all have molecular or crystallographic lengths larger than 1 nm.⁹

Table 2. Examples of commonly known substances with crystallographic lengths in the nanometer scale (data from <http://www.reciprocalnet.org>)

Substance Name	Empirical Formula	Biggest crystallographic unit cell length
Formic acid	CH ₂ O ₂	1.02410 nm
Buckminsterfullerene	C ₆₀	1.40410 nm
Glucose	C ₆ H ₁₂ O ₆	1.48400 nm
Gypsum	H ₄ CaO ₆ S	1.52010 nm
Vitamin C	C ₆ H ₈ O ₆	1.71000 nm
Alanine	C ₃ H ₈ CINO ₂	1.75900 nm
Sulfur	S ₈	2.43360 nm
Vanillin	C ₈ H ₈ O ₃	2.50990 nm
Cholesterol	C ₂₇ H ₄₆ O ₁	3.42090 nm
Vitamin D3	C ₂₇ H ₄₄ O	3.57160 nm
Pepsin		29.01000 nm

Against the rhetoric of novelty, Table 2 provides a few examples of commonly known substances with crystallographic lengths in the 1-30 nm range. The celebrated ‘nano-substance’ buckminsterfullerene is only slightly bigger than the simplest organic acid, formic acid, and smaller than everyday substances like sugar (glucose), gypsum, or vitamin C, which has long been produced at large industrial scale. Even elements, such as sulfur, arsenic, antimony, and bismuth, crystallize with characteristic lengths in the nanometer scale. Typical substances of 20th-century organic chemistry, here exemplified by the flavor vanillin, the steroid cholesterol, and vitamin D3, are in the range of 2-4 nm. Depending on the number and constitution of their ‘building blocks’, amino acids, proteins cover a large range of lengths. Simple amino acids, such as alanine, already crystallize with lengths in the 1-2 nm range. The small-to-medium-sized protein pepsin, first isolated by Theodor Schwann in 1836, is almost 30 nm large.

Besides chemistry, almost every other branch of the experimental sciences and technologies deals with material objects structured at the nanoscale. Since it applies ubiquitously, the nanometer scale is insufficient to define any particular or new kind of research.

There is a popular view of the sciences, according to which a hierarchy of material objects is mirrored by a hierarchy of the disciplines: the basic science (called physics) deals with the smallest objects, elementary particles or atoms, that are the building blocks of the objects of the next level, namely molecules which define the field of chemistry. Next comes biology that deals with living beings that are made up of molecules, and finally, if you wish, sociology. Not surprisingly, that originally pre-modern view found expression in the 19th century, when the rapid formation and differentiation of scientific disciplines broke up old dreams of the unity of science. No doubt, creating a new unity of the sciences by conceiving a division of labor according to the scale of their objects served as a sedative for those who wished to hold on to such unity. However, this never had the slightest basis in

the actual practice of the sciences. All of our sciences deal or could deal with objects of all length scales, ranging at least from picometers to meters. All combine various micro- and macro-perspectives, and sometimes, as in bulk properties of substances, the size of objects does not even matter.

Regarding the issue of interdisciplinarity, the good news is that, unlike the pre-modern view of science, different disciplines can and do share research objects of the same size – indeed almost every interdisciplinary research is based on sharing the same objects. The bad news is, however, that the lengths scale of objects has never been the main criterion to define a research field; that the nanometer scale is anything else than new, as the phrase ‘intermediate size’ suggests; and that a shared scale of objects is hardly sufficient to integrate different disciplinary perspectives.

Give a macroscopic object, say an old coin, for professional investigation to a chemist, an economist, and a historian, and you will hardly notice that they speak about the same object. This is even worse with objects beyond human perception, because here our common ordinary life practices of characterizing and referring to objects fail. In the molecular world, we need sophisticated instruments for characterization. And instead of pointing to an object of common reference, it is symbolic, theory-derived representations to which we must at first refer in scientific communication. If a chemist, a biologist, and a physicist talk about a certain kind of molecule, they may have some idea of sharing a common object because they have shared some basic education at school. Yet, as professionals, each has a different understanding of what a molecule is and what its essential features are. The chemist might analyze the molecule in terms of functional groups or reactivity sites, the biologist might be looking for biological information or biological functionality, whereas the physicists could be interested in spatial structure or electromagnetic properties.

One need not be a constructivist to accept that the scientific objects of different disciplines considerably differ from each other because each discipline has another cognitive, instrumental, and problem perspective on objects. As a realist one can claim that all perspectives can be focused on the same ‘bare object’ – yet what matters in science are not ‘bare objects’, nor the notorious Building Blocks of Everything, but scientific objects that considerably differ from discipline to discipline.

One might object that I have stuck to conventional science and ignored the important new features that appear at the so-called ‘threshold’ of the nanoscale and which deserve to create a new research field on its own. After all, by varying the size of material objects at the nanoscale, we can tune many properties that depend on the electronic structure at the objects’ surface, like electromagnetic or catalytic properties. And by furthering supramolecular chemistry or by modifying the basic systems of genetic engineering, we could create new machine-like devices with new functionalities. That is all true, and promising indeed. However, just as the understanding of what a molecule is differs considerably between chemists, biologists, and physicists, so does their understanding of what a larger nanoscale object is. The size of objects simply does not matter. It is their disciplinary perspective that render their objects different from or similar to each other, as a chemical reaction site or reactor, as a mechanical or electrical device, as a self-reproducing or information transmitting entity, and so on. In short, the idea that the common size of research objects might be a sufficient ground for the integration of various disciplines is misleading.

2.3 Technological Paradigms Underlying Nanotech Visions

Most reports about the prospects of nanoscale research refer to such values as health, wealth, security, and ‘environment’. These are so general that almost everybody would subscribe to them, regardless of their disciplinary professions. Through their appeal to general values or basic human needs, technological visions can provide some integration of different disciplinary perspectives. Yet, once the visionary ways by which such basic values

could or should be realized technologically are spelled out, disciplinary distinctions appear. Scholars from different disciplines rely on different ‘technological paradigms’. On a very general level, a technological paradigm determines the scope of what is considered technologically feasible and how to approach a technological problem. Technological paradigms usually rest on past successful approaches within the discipline; they are applied to new issues by analogical or metaphorical reasoning rather than by deduction or scientific prediction; and they incorporate metaphysical concepts such as nature or the human-nature relationship.

Current prospects and visions of nanotechnology refer to several different technological paradigms, of which for reasons of brevity I discuss only the two most frequently mentioned: ‘atom-by-atom-manipulation’ and ‘self-assembly’ or ‘self-organization’.

‘*Atom-by-atom-manipulation*’ was fostered when scanning probe microscopes (STM, AFM, etc.) turned from mere surface imaging instruments (since about 1981) into surface imaging and ‘manipulation’ instruments (since 1986), such that individual atoms could be moved and monitored almost simultaneously. Extending the approach to three dimensions, visionaries like E. Drexler conceived atom-by-atom-manipulation as the making of any molecular structure from individual atoms by sticking them together with ultra-atomic precision, once a suitable device – a so-called ‘universal assembler’¹⁰ – has been manufactured. The technological paradigm behind this vision of a new way of doing synthetic chemistry is clearly derived from mechanical engineering by extrapolating high-precision manufacturing to the subatomic scale. (Correspondingly, Drexler’s vision of ‘self-assemblers’ repeats the historical step from the manufacturing of machines to that of tool making machines.) Indeed, the most advanced approach in this field, namely micro-lithography, is also called the ‘top-down approach’ of nanotechnology. ‘Atom-by-atom-manipulation’ promises nanotechnological success by keeping to mechanical engineering’s virtues of high-precision and complete human control over the technological process and also over the matter involved, to the extent that one might worry about the role of chemical bonding in this picture.

‘*Self-assembly*’, although having a much longer history, became a new mode of both conceptualizing chemical processes and doing synthesis in the 1980s when chemists noticed that, under certain experimental conditions, complex series of reaction steps take place, leading to larger and more complex molecular structures than would be available by classical chemical synthesis. In self-assembly, the intermediary product of the first reaction step triggers or catalyses the second one which in turn favors a third step, and so on, in a rapid series of reactions leading to a complex product. It is the art of the chemists, as they see it, to initiate the series of steps by favorable conditions that direct the entire process toward the desired nanoscale product. Besides conventional conditions, the crucial starter can be a ‘template’ molecule that functions like a mould or a model for the self-assembly of components. The term ‘self-assembly’ already reveals that chemists consider a second agency to be at work here that is usually referred to as ‘Nature’. And since they find many models of such processes in living beings, they frequently describe the approach of ‘chemical synthesis by self-assembly’ as based on ‘learning from Nature’ or ‘biomimetic’. This is only one of many instances in which that fundamental notion of alchemy, indeed its basic technological paradigm, is still influential in today’s chemistry (Schummer 2003).

The difference between the two technological paradigms could not be greater. ‘Atom-by-atom-manipulation’ highlights the virtues of high-precision and total human control over the whole material process (‘nature’), which would require complete deterministic understanding of all possible events in classical mechanical terms. ‘Self-assembly’ focuses on virtually selected starting conditions and relies, for the rest, on the virtues of ‘Nature’. Although an understanding of ‘self-assembly’ in terms of chemical thermodynamics and kinetics is important, a complete deterministic understanding is usually regarded beyond reach, and not necessarily required for synthetic success. In fact, many chemists consider

‘self-assembly’ smarter and superior to the almost two century old approach of classical chemical synthesis, which is a kind of ‘atomic-group-by-atomic-group-manipulation’ based on the non-mechanical theory of chemical structures and reaction mechanisms.

Since both technological paradigms play a leading role in current nanotechnology, it is hard to see how research approaches guided by such opposing views could ever merge toward interdisciplinary collaboration. The recent Drexler-Smalley debate, their mutual misunderstandings and misconceptions, provides an excellent example of how chemists and mechanical engineers can be talking at cross-purposes, each relying on their own technological paradigm.¹¹ The debate illustrates that metaphysical notions rooted in history and disciplines pose strong barriers not only to interdisciplinarity and mutual understanding. They can also cause hostility if each party denies the other the expertise due to the ‘wrong’ technological paradigm.

3. Conclusion

Given the need for interdisciplinarity in nanoscale research, the current situation is not very encouraging. Despite their multi-disciplinary appearance, newly launched ‘nano journals’ contain hardly more interdisciplinary research than typical mono-disciplinary journals. Obviously, interdisciplinarity is much more difficult to achieve than multidisciplinary. In this paper, I have pointed out two of the cognitive reasons. First, the widely proclaimed common ground – the nanometer scale of objects – is too weak to integrate different disciplinary perspectives. Second, nanotech visions that are meant to orient researchers towards common goals refer to technological paradigms that are rooted in different disciplines and may, in contrast, pose strong barriers to interdisciplinarity. My conclusion is that the present situation requires serious thinking and rethinking about the cognitive conditions and possibilities of interdisciplinarity in nanoscale research.

My critical conclusion comes at a time when political ambitions, at least in the US, further extend the reach of interdisciplinarity (Roco & Bainbridge 2002, Khushf 2004). Nanotechnology, wrongly considered a homogenous field, is supposed to be one of four fields that combine to form the future scientific landscape, the other three being biotechnology, information science, and cognitive science. The result shall be a super-interdisciplinary structure of the whole of science, including technology, social sciences, and the humanities – a new unity built on the pragmatic goal of improving human performance instead of the dismissed idea of physicalistic ‘reductionism’. Although that vision complies with ‘anti-disciplinary’ and anti-reductionist ideas advanced in recent science studies, the actual situation in current nanoscale research gives rise to serious doubts (see also Schummer 2004). Instead of discussing such Big Pictures, detailed philosophical work is needed to understand both the chances of and the barriers to interdisciplinarity caused by the similarities and differences between the disciplines.

Acknowledgment

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Notes

- ¹ For a report that calls for interdisciplinarity even in its title, see Malsch 1997.
- ² Still the best survey with extensive bibliography is Klein Thompson 1990; a more recent bibliography has been prepared by Brandl 1996. Recent monographs and anthologies include Kline 1995, Klein Thompson 1996, Galison & Stump 1996, Umstätter & Wessel 1999, Weingart & Stehr 2000, Kabisch, Maaß & Schmidt 2001, Moran 2002; see also the ongoing online discussion of papers published since April 2003 by Interdisciplines [<http://www.interdisciplines.org/interdisciplinarity>].
- ³ A great many books with ‘interdisciplinary’ in their titles result from *studium generale* lecture series on some topic with speakers from different disciplines. All of these books that I have seen are really multidisciplinary, that is, a collection of disciplinary essays without any reference to each other.
- ⁴ For nanoscale research the most relevant recent case study is on the discipline formation of materials science since about 1960, see Bensaude-Vincent 2001.
- ⁵ For an excellent account of the manifold ‘fallacies of projection’ from physics to other discipline, see Kline 1995, particularly part 4.
- ⁶ For a case study on the historiography of psychology, see Geuter 1983.
- ⁷ The results of this section are taken from a much more comprehensive scientometric study of eight nano journals, which also includes details on various methods of measuring interdisciplinarity (Schummer 2004).
- ⁸ NSET, February 2000 (http://www.nsf.gov/home/crssprgm/nano/omb_nifty50.htm).
- ⁹ More exactly, Chemical Abstracts registered 15,459,282 new substances in 2003 of which 13,808,462 were biosequences (CAS 2004, p. 7).
- ¹⁰ Drexler (1986, chapter 1). Unlike Drexler, Stephenson (1995) uses the term ‘matter compiler’ which refers to computer science rather than to mechanical engineering.
- ¹¹ See *Chemical & Engineering News*, 81 (2003), No. 48, pp. 37-42 [<http://pubs.acs.org/cen/coverstory/8148/8148counterpoint.html>]

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A Hierarchical Architecture for Nano-scale Science and Technology: Taking Stock of the Claims About Science Made By Advocates of NBIC Convergence

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Abstract. Leaders of nanoscale science and technology advance a systems theoretic model as an alternative to scientific reductionism. Within this essay, I seek to formulate their concerns in a more philosophical idiom, and thereby provide a basis for a common discourse about the nature, values, and limits of current science. This will be of special importance as we contemplate the radical capacities for human enhancement made possible by converging technologies.

The evolution of a hierarchical architecture for integrating natural and human sciences across many scales, dimensions, and data modalities will be required. Half a millennium ago, Renaissance leaders were masters of several fields simultaneously. Today, however, specialization has splintered the arts and engineering, and no one can master more than a tiny fragment of human creativity. The sciences have reached a watershed at which they must unify if they are to continue to advance rapidly. Convergence of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale. (Roco & Bainbridge 2002, p. x)

Introduction*

A new capacity to measure and directly manipulate matter at the nano-scale establishes the conditions for a convergence between physics, chemistry, biology, and the engineering disciplines that use these sciences to address human needs. On the basis of this nano-scale convergence, a higher level convergence is made possible, one which offers great promise for human enhancement. At this higher level, nano-science and technology merges with biomedicine, information technology, and cognitive science. In order to seed the development of this NBIC convergence (Nano, Bio, Info, and Cogno), and to assure that it is appropriately directed for human enhancement, a major public/private partnership is being formed. Millions of dollars will be used to establish and organize the infrastructure needed.

The principal architects of the convergence effort argue that one of the “substantial intellectual barriers” to success involves the development of a new model of science, one which enables the appropriate integration of disciplines that are fragmented, and which moves us beyond outmoded, reductionist assumptions. They suggest that hierarchical, sys-

tems theory can provide the needed framework of integration, and they call for work in the formulation of this systems theoretic alternative.

Embodied within the claims of the convergence advocates is a notion of science and the history of science. There are three distinct components: (1) that there is an old approach to science and engineering, in which knowledge is fragmented, pure and applied domains are distinct, and a reductionist approach is taken to the relation between disciplines; (2) that new research and tools in science, especially those associated with nano-scale science and technology, lead to a convergence of disciplines, a holistic approach to knowledge, and a more intimate intertwining of fundamental science and engineering; and (3) that hierarchical, systems theory can provide the framework for the integrated paradigm needed for this new science.

Many scientists and philosophers of scientists – including several contributors to this volume – are skeptical about each of these claims. Regarding the first claim, there is an interesting split between scientists and philosophers of science, with the former still having much confidence in reductionist approaches to knowledge and the latter believing that a full reductionism never characterized the theory or practice of any science, and thus that it is a myth that distracts one from a genuine history of any scientific development. In either case, there is a skepticism about the claim that we are moving away from such a reductionism. Regarding the second claim, both scientists and philosophers of science are skeptical about the uniqueness of the nano-scale. “Nano-” is seen as a ruse, drawing on the hype associated with visionaries such as Drexler, in order to get increased funding for what are otherwise very conventional projects. And regarding the third claim, there is a belief that no new notion of science is needed – whether based on systems theory or any other theory – because science never draws on such general notions for its practice anyway. Instead of such an overly general and unhelpful notion of the scientific enterprise, we should look at what is actually taking place within the disciplines, at the boundaries between the disciplines, and in the trading zones where knowledge and technology are produced.

Such nano-skeptics are likely to read the NBIC convergence claims as examples of rhetoric, whose sole purpose is to elevate otherwise conventional practices above peer-efforts, and thus to obtain higher levels of funding and prestige. Rather than give credence to the three claims outlined above, the skeptics shift the focus to the advocacy of human enhancement, seeing there the revolutionary program. Further, many are suspicious of that program. An overview of NBIC convergence claims and efforts thus shifts into a social/political criticism of the implicit ideology.

While there is undoubtedly a need for a more sustained analysis of the enhancement efforts, and there is also some truth in the nano-skeptic’s analysis, I also believe that core considerations are either overlooked or misrepresented. Further, I think that the claims of Roco and others about the older approach to science, the newness of nano-, and the value of systems theory are all defensible. I will thus provide a reconstruction of the three claims, attempting to specify the content at issue, and also defend these claims in their reconstructed form. I will also suggest there are opportunities for establishing a rich dialogue between the sciences and humanities, which are directly intertwined with the claims that are at issue.

1. Some Preliminary Distinctions

In order to defend the NBIC claims about science, we need to distinguish between what scientists actually do and how they conceptualize what they are doing. While it is true that scientists never had, or could have, a simple hierarchy of disciplines, independence of pure and applied considerations, and so on, this does not mean the reductionist model didn’t guide the way scientists conceptualized their own activity, reported their data, etc. In other

words, when I give content to the so-called older approach to science – the reductionist model – I am not suggesting that science used to be like that and now it is different.

The reductionist model served a heuristic function for the scientist in conceptualizing his or her own activity. When Roco and others say we need a new approach to science and engineering, I will thus interpret them as saying we need a new model of the general activity of science – that something has changed such that the reductionist model no longer can serve its heuristic role. I will then specify the content of nano-scale work that is unique and that demands an alternative conceptualization.

Some will ask why a general model of science is needed at all. What is the heuristic value of such a model? To answer this, we need to distinguish between the different ways that scientists and philosophers use models. Modeling is obviously a major focus in current science studies. The focus is usually on the way scientists use models. Here a model is of whatever the scientist studies, and philosophers ask how such models are constructed, what they denote, how they are modified, and so on.

When philosophers consider how scientists use models they are modeling the modeling activity of the scientists. The domain is science itself, and the philosopher of science seeks to understand this in ways that are similar to how scientists understand their domain, whatever that may be. Such meta-models – namely, the philosopher’s model of the activity of science – incorporates within it an account of the first level of modeling.

In order to appropriately interpret the claims of NBIC advocates, we must see that both the scientist and the philosopher engage in meta-modeling, but the function of their meta-models is different. For the scientist, the meta-model serves as a heuristic for the development of their models, while the philosopher is more directly concerned with meta-models that are isomorphic to the scientist’s actual activity. Different criteria must thus be used in judging the diverse meta-models, and, given the alternative projects, competing accounts are fully compatible. In fact, the divide between scientists and those in science studies is partly a reflection of the diverse criteria they use for assessing their meta-models.

In what follows, I consider the notions of science that might inform the understanding and organizing activity of those involved in nano-scale science and technology and the broader NBIC convergence efforts. However, I will suggest that the systems theoretic alternative advocated by the scientists offers opportunity for consilience with meta-models advocated by philosophers, and, to this extent, there is a move from a meta-model that is less appropriate (in the philosophy of science sense) to one that is more appropriate.

Advocates of the NBIC convergence are convinced that a new view of science and engineering is needed. To assess whether this is the case and why, it is first necessary to consider the old view of science, and why it is inadequate. To this end, I now review the old meta-model, which involves a classical account of reduction, dualism, and linear causal relations. While this traditional understanding of science is generally rejected by scientists working in areas such as quantum theory and complexity, the reductionist program still characterizes the view of many other scientists (Wilson 1998). And it has been a valuable meta-model for the scientist – not because it is “true”, but because it has served as a useful heuristic for organizing the activity of science. (To this extent it is analogous to a frictionless surface; *i.e.*, helpful for highlighting certain features valuable in analysis, but only of use as a first approximation.)

After my initial survey of the project of reduction, characteristics of nano-scale science and technology will be considered. Through this review, it will become clear that the assumptions about reduction no longer serve as a useful heuristic, since they contradict core features of this new science. A new view of science and engineering is indeed needed. However, the alternative cannot be a simple rejection of the reductionist project. Instead, features of reduction must be taken together with a more holistic analysis that accounts for irreducible complexity and fosters interconnections between the multiple scales and levels

of disciplinary interaction. (As Roco puts it, we need an integration of left-brain reductionism with right-brain assembling views, 2002, pp. 73-74.) Instead of an either/or between reduction and holism, we need a both/and. Systems theory can provide the needed framework for this integration.

2. The Old View of Science: the Grand Project of Reduction and Unification

Scientists generally do not spend much time reflecting on the nature of the scientific enterprise itself; or, if this puts it too strongly, they at least do not worry about the nature of science in the way a philosopher would. Generally, they do not need to. Consider, for example, the activity of a molecular biologist. She can happily work on understanding a given protein and its function, simultaneously probing multiple levels of explanation, while being completely oblivious to the broader debate on holism vs. reduction in biology, or on the nature of the biological sciences more generally. Sometimes a logic of function unique to biology is presupposed, sometimes not. And it does not matter, since everything is on the way and interim. Slowly different things jump together, diverse domains of investigation converge, and the sense of being on the right track is clear. It all seems to work. So why spend the time reflecting on the nature and character of this endeavor?

While most scientists spend little time reflecting on the nature of science, this does not mean they do not generally have a view on the matter. In fact, as I outline below, scientists often espouse a classical, nineteenth century view of their enterprise. This involves the assumption that science follows a method that controls for bias and enables one to get at the objective world, and that the world is, in the end, composed of tiny parts, which are assembled to give the full array of complexity we see in the world. Higher levels of complexity are explained by breaking them into lower levels, and then showing how the higher levels can be built up from the lower ones. I will call this the project of a grand reduction. Whether or not a philosophy can be sustained that consistently upholds the notions of “objectivity”, “scientific method”, or “reduction” is not usually of concern to the scientist.

Captivated by the ideal of such a science, earlier philosophers of science attempted to reconstruct this project and its assumptions on a more rigorous foundation. (There are many different attempts at such reconstruction, ranging from the mechanical materialists of the 1850s-1880s to the logical positivists in the first half of the twentieth century.) While philosophy of science in the latter part of the twentieth century can be regarded as the breakdown of nearly all features of this project of reconstruction, many scientists still hold to such an ideal, highlighting an interesting tension between scientists and philosophers of science. (I will return to this contrast later, when we consider the relation between science and the humanities, and how systems theory makes possible a convergence of perspectives.) In presenting the older ideal, I will merge what might be considered “common sense” among many scientists (Popper 1979) with some of the features of the earlier philosophical reconstruction (Suppe 1977), in order to give a fuller picture of what the project of reduction entails.

When leaders of the NBIC convergence call for a new view of science and engineering, it seems clear that they regard the features of the grand reduction as the old view (Roco 2002). In summarizing this old view, I highlight four areas which will be challenged – or should I say “augmented” – by nano-scale science and technology, and a systems theoretic framework for that science. These four areas concern the hierarchy of the sciences, a complementary understanding of the nature and method of scientific investigation, a particular view of causality, and a set way of relating pure and applied sciences. Perhaps the most prominent recent statement of these features has been provided by E.O. Wilson (1998). I follow his formulation in much of my account. The project of the grand reduction can thus be understood as follows.

2.1 The Hierarchy of the Sciences and the Hierarchy of Nature

Advances in science have come by analysis. Wholes are broken into parts, which are understood with increased clarity, first in terms of a differential system of the whole and then in terms of an independent understanding of each part. Parts then become new wholes and the process of analysis continues ever downward. Worlds within worlds are discovered. With this tunneling, the universe is ever divided. Disciplinary fragmentation is partly a reflection of the success of this process.

Organizing the fragmented landscape has been an established hierarchy of disciplines. Physics owns the base. Chemistry builds on physics, biology on both, and the human sciences (psychology, sociology, economics) build upon the biological. With this hierarchy comes a broader vision of reassembling the scattered pieces. Radiating upward and outward from the subatomic particles of the physicist are the elements, compounds, and molecules of the chemist, and from there the macromolecular constituents of cells, tissue, organs, organ systems, and upward to the organisms and the psychological and social organization of these organisms. So nature emanates outward: ecosystems, earth systems, solar system, and so on, all the way to the cosmos. Similarly, there is a radiation outward in time, from the femtosecond vibrations at the subatomic level outward to the evolution of life and the cosmos itself. The hierarchy of scientific disciplines thus reflects the hierarchy of nature.

While these hierarchies are acknowledged by all, what characterizes the grand project of reduction is the belief that the higher level wholes can be fully understood in terms of their constituent parts; that they are no more than that sum. The goal of each science is then to provide the needed synthesis, reconstructing in the intellectual domain of science that pattern by which the whole is assembled chink by chink from its base elements in the natural world. Scientific knowledge is thus a mirror of nature, reconstructing in its theoretical models a pattern that is isomorphic with the natural order. And, most significantly for the project of reduction, the reconstruction proceeds upward and outward from the simplest components. Thus physics, concerned with the most fundamental aspects of the world, is not dependent on any of the other sciences. Chemistry, however, depends on physics, but not on the sciences above it in the hierarchy. So each higher level is independent from those above it, but dependent on those below it. There is thus an asymmetrical relation of dependence among the sciences. All higher levels are *in principle* reducible to the core terms found in the lower ones. If they are not yet *in fact* reducible, that simply points to the work that yet needs to be done within the sciences. Ultimately, all scientific knowledge is reducible to the principles of physics (Wilson 1998, p. 60). (Sometimes it is said that “all science is reducible to physics *and chemistry*”, but on this account chemistry must in the end be reducible to physics, *i.e.*, to a knowledge of fundamental forces, subatomic particles and their interactions, etc.)

2.2 The Nature of Science and its Method

Complementing the hierarchy of nature and the sciences is a specific conceptualization of the scientific method. The scientist comes as a neutral observer, without any interests or values that might distort what is perceived and understood (Martin 1997). In order to assure this neutrality, a form of investigation is advanced, which builds in checks against bias. These checks are integral to the distinction between being objective and subjective. Objectivity is understood in a double sense: (a) that which is independent of the subject and characterizing the world independent of the observer, and also (b) that stance of the scientist that enables her or him to get at the world of nature as it is, rather than as the scientist wants it to be. There is thus a dualism between object (of investigation) and subject (who investigates); between objectivity (a neutral, open stance toward understanding nature as it is in

itself) and subjectivity (an interested, and thus biased approach to investigation); and between fact (characterizing nature) and value (characterizing the subject).

The scientific method involves an empirical stance, and structures investigation so that simple causal relations can be isolated. First in the process of study is the reformulation of a poorly structured problem or question into a well structured one. This involves framing questions in such a way that experiment can answer them. Preliminary data serves as the basis for the formulation of a hypothesis, which is then tested by a controlled trial. “Data” is linked to simple observables (the pure empirical moment); namely, that “information of sense” which is uninfected by the interests, ideology, or values of the scientist (following Ernst Mach, this was the ideal for the positivist; Suppe 1977). The test of whether something constitutes such an “observable” is intersubjectivity: will all similarly situated individuals see this in the same way, regardless of their broader commitments? Just as the world is constructed from simple parts, so too is knowledge. The data of sense is organized by mathematical/logical rules to provide empirical generalizations; namely, laws. Multiple empirical laws are themselves grouped, yielding higher level generalizations. At the broadest level, foundational principles or axioms are formulated that account for the content given in the empirical generalizations. Through these higher level generalizations and theories, otherwise disconnected domains jump together or converge. The classic example of this is found in the merging of terrestrial and celestial mechanics; through Newton’s three laws, the empirical laws of Galileo (terrestrial mechanics), and Kepler & Brahe (celestial mechanics) merge.

2.3 Causality, Explanation, and the Determinate World

Embodied within the classical notions of the scientific method are certain assumptions about causality and the character of the natural world (Weiss 1971). Every effect has a cause. To “explain” something, *e.g.*, some natural state or event, involves elucidating its necessary and sufficient conditions. Certain laws capture causal relations, so the explanation involves bringing the state/event to be explained under one of these “covering laws”.

Ultimately, higher level phenomena are to be explained in terms of lower level components and their interactions. Lower level interactions, in turn, can be understood in terms of part-part relations; in other words, the wholes can be explained in terms of part functions, each of which can be isolated and sufficiently explained in its own terms. This capacity to discretely consider each component and its interactions is itself intertwined with the controlled experiment integral to scientific method. One can isolate the variable of interest, control for all else, and then discover the causal relation between this variable and others of interest. Explanation is thus linked to elucidating the “mechanism” involved.

A good example of the reduction can be found in biology, where, as Watson *et al.* (1992) note: “By now there exists an almost total consensus of informed minds that the essence of life can be explained by the same laws of physics and chemistry that have helped us understand, for example, why apples fall to the ground and why the moon does not...” Or, put in a more formal way, the reductionist position in biology can be defined as affirming that all aspects of biology can be defined in terms of an underlying mechanism. “Mechanism may now be defined as the view that every event E , which is describable as a biological event, is numerically the same as the set of events E_1, E_2, \dots, E_n , in which each E_i exemplifies no laws that are not also exemplified in nonbiological systems ...” (Bechner 1967). The same is true for psychology, sociology, etc.: all phenomena can be broken into discrete parts and linear causal relations between these parts, which, in turn, can be taken as explaining (through the elucidation of mechanisms) what happens at the higher level.

2.4 The Relation between Pure and Applied Domains

The distinction between pure and applied science is a corollary of the dualism between fact and value. Pure science simply describes the world as it is, independent of the knower. “An applied science, by contrast, seeks to realize certain ends, and it draws on the pure sciences for the knowledge base and skills necessary to accomplish this” (Hempel 1960). Thus, for example, chemical engineering applies the concepts found in chemistry to synthesize desired products (often on a large scale); medicine applies knowledge of physics, chemistry and biology to the treatment of disease. In each case, the “basic sciences” (a term from medical education, characterizing the scientific foundations of practice, primarily learned in the first two years of medical school) enable one to understand the causal interactions of basic elements. The “application” of this knowledge in engineering or medicine involves an intervention in this causal sequence, or a construction of alternative conditions, for the purpose of advancing interests that lie outside of the science itself.

While “science” proper – *i.e.*, the “pure” activity – is independent from the diverse interests and values of individuals and society (at least in the content of its knowledge), their application presupposes such values. People want to accomplish things within the world. They have goals. These can be pursued in an ad hoc manner, or one can use the means-end reasoning of the scientist. The applied sciences are “mixed”, in that they combine the extra-scientific ends/values with the capacity to causally intervene that arises from a knowledge of the world as it naturally is.

3. The Holism vs. Reduction Debate

Today all – or nearly all – philosophers of science would recognize each of these four points of the grand project of reduction as highly contentious and problematic. Scarcely a single philosopher would embrace this project in its classical form, and much of current philosophy traces the demise of the “Received View” of science, which was an attempt to formulate the grand reduction in rigorous terms (Klemke *et al.* 1988, Curd & Cover 1998). Despite this, however, many – perhaps even most – scientists still work with such assumptions about the nature of science (Wilson 1998). When scientists attempt to formulate in general terms the character of the scientific enterprise, they highlight exactly the core features of the grand reduction outlined above, and they contrast this with “vitalist”, “metaphysical”, or “religious” views that are taken as non-scientific.

It is worthwhile to explore these differences between philosophers of science and scientists, since the differences reflect a broader gulf between the sciences and humanities more generally. The isolation between the “science studies” of humanists (such as historians, sociologists and philosophers) and the activity of scientists themselves can thus be taken as an instance of this broader problem of fragmentation, providing an interesting lens on how diverse goals and methods of investigation lead to barriers in communication.

The divide between science and the humanities is more than just an academic dispute. Behind it lies a broader dispute about the role of science within the world. This is especially apparent in larger ethical and social disputes about certain areas of science and technology; for example, regarding genetically modified foods or nuclear power (Pool 1997). Generally, we address such ethical issues in the language of the humanities; namely, in the language of our cultural, literary, philosophical, and religious perspectives, all of which are holist in import. Because scientists (and much of the public) view science in reductionist terms, there is a bifurcation between the world of science and the world of ethics, as if “doing science” is completely different from “doing ethics”. (This bifurcation reflects the reductionist distinctions between facts and values, and between pure and applied science.) Social and ethical reflection is thus seen as coming from outside science, and it often focuses upon

constraints or regulation of the activity of science. This can further reinforce an antagonistic relation between the two domains, since scientists generally do not want to be thus constrained. However, at the same time, it is through science that we increasingly understand ourselves and our role within the world. The reductionist vs. holist controversy thus reflects a broader schizophrenia in our understanding of ourselves and our own activity.

When the leaders of NBIC convergence suggest that we need a new view of science, this can be taken as a challenge not just to the sciences, calling for a more sustained reflection on the nature of science, but also as a challenge to the humanities, and, more specifically, to the traditional gulf between the humanities and the sciences. In fact, NBIC leaders point in this direction when they suggest that there is a “trend towards unifying knowledge by combining natural sciences, social sciences, and humanities” (Roco & Bainbridge 2002, p. 11). If the scientists themselves come to appreciate the limits of reduction and explore alternative conceptualizations of the activity of science – something that is required by the very nature of the developing sciences – then this provides opportunities for convergence with notions of science found among philosophers, historians, and sociologists of science. This provides a unique opportunity for bridging the two cultures divide!

Claims to move beyond reduction should, however, be formulated in a careful way. A challenge to the grand project of reduction does not mean that one has to go to the opposite extreme. Older affirmations of holism were just as fragmenting as affirmations of reduction, since holists claimed a radical segregation of the disciplines, such that they are isolated by their logics from convergence/consilience. Put simply, it is time to move beyond the traditional opposition between the task of reduction and the interest in holism, emergence, and whole-part/top-down reasoning. Rather than either/or we now need a both/and approach. (I will elaborate more on this later.)

4. Modern Science Reframes the Debate: the Nano-revolution

Even though the project of the grand reduction did not and does not reflect the realities of scientific investigation (here I speak as a philosopher of science, and reveal my own bias), it has nevertheless provided a helpful model for structuring scientific investigation and for reporting the results of research. In other words, the grand reduction has historically served as a valuable heuristic, providing useful guidance to scientists who have been engaged in research. (Here the analogy is to a frictionless surface – useful as a heuristic, and providing a first approximation.) However, this model, which has for so long provided helpful guidance, is no longer helpful. Assumptions associated with the project of reduction now inhibit needed developments in science, engineering, and the humanities. In order to appreciate why a new account of the science and engineering is needed, I now consider the features of nanoscale science and technology (representing recent developments in science), showing why the older account of science no longer is helpful.

Many aspects of modern science have already challenged the grand project of reduction (Gibbons *et al.* 1994). One does not need to go to the nano-revolution to find these. To give just two prominent examples, 20th century developments in physics (esp. associated with quantum theory) already challenged older notions of causality and determinism, and with these, assumptions about method, the objectivity/subjectivity divide, and many other aspects of the grand reduction (Herbert 1985). Similarly, more recent work on chaos and complexity challenged the capacity to explain the world in terms of linear, causal interactions and to carry out the broader project of reduction (Waldrop 1992). Higher levels are now regarded as irreducible, leading to problems of emergence that cannot be resolved in traditional terms. However, these challenges – and many similar ones – are often taken in isolation, separated from one another, and understood as configuring localizable areas of crisis, but not undermining the whole project of reduction. Thus, for example, one could

concede that quantum logics are strange, resisting standard accounts of the nature and activity of science, but such strangeness characterizes the world of the super small only. There is a different, more traditional logic for the classical domain, and, so the argument continues, it is within that domain that the project of reduction is still advancing (Wilson 1998).

What characterizes the nano-domain (and also some other emergent domains of modern science and technology; Gibbons *et al.* 1994) is that the various areas that are taken in isolation now converge, requiring a rethinking of the nature and activity of science. Within nanoscale science and technology this is seen in the following areas:

(1) Bridging quantum and classical domains

The process of analysis involves breaking wholes into their components. Synthesis entails building the wholes back up from their constituent parts. The grand project of reduction postulated that as one moves downward in scale, there is a general continuity in the logic of interaction between wholes and parts. However, as one approaches the bottom end of the nano-region, there is a shift to a quantum domain where the logic of explanation is radically altered. There is thus a floor to the classical domain; a discontinuity exists between it and the quantum level. What characterizes the nano-region is that one must bridge the quantum and classical. As Michael Roukes notes, “[m]atter at this mesoscale is often awkward to explore. It contains too many atoms to be easily understood by the straightforward application of quantum mechanics (although the fundamental laws still apply). Yet these systems are not so large as to be completely free of quantum effects; thus, they do not simply obey the classical physics governing the macroworld. It is precisely in this intermediate domain, the mesoworld, that unforeseen properties of collective systems emerge” (Roukes 2003, p. 93). The assumptions of the grand project of reduction do not help the nano-scientist come to terms with this strange middle world. Here the metaphor is one of “bridging” not “reduction”.

(2) Merging bottom-up and top-down approaches

Two general approaches to fabrication are found within the nano-world: top-down and bottom-up. The first attempts to further refine and miniaturize methods already used in the micro world – methods such as lithography. The second seeks to build complex items up from the basic components, eventually leading to complex forms of self-assembly which mimic what takes place in the natural world. Within the nano-arena, these methods converge, and there is no clear preference in method (Venneri *et al.* 2002). At present, top-down approaches seem to have the edge in practicality, while bottom-up approaches hold greater promise for eventually realizing the broader ideals of nano-tech. However, both approaches will require more than a simple extension from the higher (in top-down) or lower (in bottom-up) domains. New “laws” will emerge for the nano-region. Here the standard hierarchies of explanation that characterize the grand project of reduction no longer apply.

(3) The symmetrical integration of physics, chemistry, and biology

Within nano-science, physics, chemistry, and biology are no longer related in the hierarchical, asymmetrical relation of dependence that characterizes the grand reduction. And these disciplines are not neatly associated with various scales (in fact, they never were). Rather, cutting-edge work in each discipline leads them to converge, and each informs the other. Yes, biology looks to physics and chemistry. However, the physicist and chemist also look to the natural self-assembly found in biology to better understand bottom-up nano-science

(Ball 2002). This is not just in the more “practical” technological endeavors, but in fundamental science, as well.

(4) Blurring the lines between pure and applied domains

If one views Feynman’s famous lecture, “There’s Plenty of Room at the Bottom” (Feynman, 1959), as a defining moment of nano-science, identifying core ideals, then it is clear from the beginning that older divisions between “basic science” and “engineering” are no longer applicable. The field was, in fact, defined by an interest in miniaturizing technologies already available; *i.e.*, in terms of engineering goals. The capacity to accomplish this was linked to new imaging technologies, which would enable us to “see” into the nano-realm; *i.e.*, to the results of the engineers endeavor. However, it is also clear that fundamental science is needed, and that, in fact, this realm promises to open up core areas of physics, chemistry, and biology to new forms of investigation. Rather than a simple hierarchy between basic and applied science, the nano-realm points to an iterative relation between them, with a continual blurring of the boundaries. Rather than a clear line, there is a continuum.

This iterative relation between science and engineering has another, significant implication: the goals that characterize the activity of the engineer reach into the basic sciences themselves, linking the focus and core features of analysis to the values and interests of the scientists and the broader community that funds them. This, of course, does not mean that anything goes, as if laws of the nano-world are created by the scientists. They are, indeed, discovered – for example, laws of self-assembly, or the quantum character of electrical or thermal conductivity – but the discovery is framed by the scientist’s interest in micro-electronics or in designing nano-machines. Thus certain features of the nano-world come into view, and the “laws” are as much governed by the aims of the engineer as they are by the meso-nature of the nano-world.

Taken as a whole, these and other features of nano-scale science and technology are so alien to the project of reduction that a new account of science and engineering is needed. An account is needed that can (1) support discontinuities as well as continuities across scale, (2) involves both top-down/whole-part as well as bottom-up/part-whole logics, (3) bridges disciplines and opens symmetrical lines of communication between them, and (4) sustains the iterative relation and blurred boundaries between fundamental science and engineering. The nature and activity of science is itself complex, and we need a model that can come to terms with such complexity.

5. The Systems Theoretic Alternative

The systems concept has a long history, which we cannot explore here. There are also many, intertwined meanings to “system”. However, for our purposes it is enough to highlight one aspect of this history and one core meaning to the systems concept.

The “systems” concept arose as an alternative to the contrast between mechanism in biology, on one side, and the vitalist impulse, on the other (von Bertalanffy 1952, 1968). This is the historically important context. (Another important historical origin is associated with attempts to formulate in logical/mathematical terms an idealized, abstract language for understanding logical operations. This work provided some of the logical and mathematical tools that are now used by systems theorists and applied to many domains in the empirical sciences (Henkin 1967). Here I highlight the biological debate, and I cite figures like von Bertalanffy and Weiss, because of the value of their ideas in understanding human enhancement, the stated goal of NBIC convergence. A fuller discussion of systems theory would necessarily involve a discussion of the formal tools of analysis, as well.)

Systems theory involves an attempt to transcend and encompass the two sides in the reduction vs. holism debate (this is central to its meaning, see Weiss 1977). On the side of the mechanist, the systems theorist affirms that many aspects of biological systems are subject to part-to-whole explanatory accounts, and that research should not postulate an isolated biological domain, insulated from the advances in physics and chemistry. Such isolation, advocated in the name of unique biological laws, only inhibits research in all domains. However, on the side of the holist, systems theorists claim that the whole often involves an irreducible priority in explanation, and that there are aspects of the system that could not be accounted for in terms of the sum of the components that make up that system (a variant of the many-body problem in physics.) Today, this holist argument is also closely wed to discussions of “complexity”, with the recognition that alternative forms of analysis are required for complex systems.

The core systems concept is well summarized by the noted developmental biologist, Paul Weiss:

First, what is it [a system] not? It is not a haphazard compilation of items nor, at the other extreme, a complex of rigidly linked pieces or events ... for in either of those cases, the complexion of the total unit could still be predicted unequivocally from the information about its constituent parts, pieced together. In a system, we are faced with the opposite property, that is to say, the state of a whole must be known in order to understand the coordination of the collective behavior of its parts; or if one prefers to objectivize this proposition, one can express it in terms of ‘control’ of the components by their collective state. (Weiss 1971, p. 13)

Once this basic idea is accepted, additional lines of investigation are opened up and legitimized in science, which cannot be sustained under reductionist assumptions.

First, complementing part-to-whole explanations, there are also whole-to-part explanations necessitated by the complexity of higher levels, and by the way higher level syntheses (the wholes) function in regulating the parts. In certain areas, such whole-to-part reasoning is well recognized; for example, in ecology or meteorology. By extending this systems concept more generally, however, one has a basis for integrating traditional part-to-whole explanatory accounts with higher level explanations. Some domains of investigation (such as an ecosystem ... or, perhaps, a cell ... or perhaps even certain properties of the mesorealm like quantum conductivity) need to be analyzed in their own terms, without a view to radical reduction. While reduction plays a role in broader analysis, there are also emergent problems – such as the equilibrium of an ecosystem – which cannot be accounted for in terms of the sum of lower level parts and processes.

Second, with the notion of a system comes the development of new, often iterative methods, which structure knowledge in terms of converging (or diverging) lines of investigation, and which transcend purely deductive or inductive approaches. Often there are iterative relations between experimentation and theory, or between pure and applied considerations, and one might never be able to completely account for one side of the iteration in terms of the other; for example, one might never be able to derive all results of experiment from background theoretical considerations. Scientific method is now seen as more complex than any formal accounts of the tools of analysis would imply.

Third, systems theorists are generally more self-aware regarding their role as scientists in the investigation, and the degree to which the “parts” and “causal line of influence” explored in science reflect the interests and choices of the investigators involved. Since interests and values play a role in even the most fundamental science, there is only a relative (but still valuable) distinction between pure and applied domains. Scientists need to see themselves as part of a broader natural system, and their knowledge arises from, and leads to, interactions with the systems that they study. This can be taken as a higher level gener-

alization of the entanglement already recognized within quantum theory when one attempts to measure, and thus take stock of, the smallest objects of investigation. The very attempt to know involves a perturbation of the system known, and this effect needs to be accounted for by the scientist.

These features, integral to systems theory and implied by the basic system concept, support the features of science that are integral to nanoscience, which we identified in the previous section. Systems theory provides a framework that can account for the insights of the grand reduction, while augmenting these insights with additional forms of analysis that are necessary for the higher level, interdisciplinary investigation that is necessary. Even more than this, such a theory enables us to incorporate ethical considerations – such as an interest in the appropriate end of an intervention – in such a way that these considerations are continuous with the broader framework of scientific analysis. There is thus a convergence between the meta-models of the scientist, the meta-model of the philosopher of science, and the self-understanding of those involved in reflection on the human condition generally. Such a convergence of science and the humanities is valuable in itself, and it is vital if we are to appropriately guide NBIC convergence for human enhancement.

Notes

- * Much of the material in this essay is drawn from the first main section of “Systems Theory and the Ethics of Human Enhancement: A Framework for NBIC Convergence”, *Annals of the New York Academy of Sciences*, 1013 (2004), 124-149.

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Unbounded Technologies: Working Through the Technological Reductionism of Nanotechnology

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Abstract. It will be shown that the umbrella term “nanotechnology” reveals the endeavor of recent engineering sciences and science-based technologies to find a fundamental technology, in other words: a root or core technology. This is linked to the leading and exciting vision of a specific kind of reductionism, namely *technological reductionism*, which has not yet been perceived by the philosophy of science. Further, it will be illustrated that the quest for a fundamental technology resembles the scientific research program of physics in its goal to find a grand unified theory of everything. Physicists have become pace-setters in research and development of nanotechnology.

1. Introduction

Hitherto, engineering sciences appear to be largely a diverse patchwork consisting of very different areas like civil, electrical, mechanical, material, informational, medical engineering. Classical technologies are bounded technologies which are applied in specific contexts, e.g. biomedical technologies in the field of medicine or information technologies in the context of information processing, management and storage. Today, specialization has splintered engineering sciences, and none of the disciplines can master more than a tiny isolated fragment of all problems. During the last 60 years, efforts have been made to bring together the various parts of science-based technologies (e.g. the earlier attempts of cybernetics in the 1940's, general systems theory, information theory, solid-state physics; micro systems technology). But an overall progress has not been reached until now. In a pragmatic sense, engineering sciences are sometimes labeled “inter- and transdisciplinary”, although this just remains a catchword without a distinctive feature. Further work has to be done in order to establish a “theory of interdisciplinarity” (Schmidt 2003).

The recent development of nanotechnology is an excellent highlight in bridging various engineering sciences (and natural sciences as well). This development is due to the progress in physics, chemistry, and molecular biology as well as in computer sciences and computer technologies. Disciplinary boundaries are being torn down, as “nanotechnology” seems to indicate. In between the disciplines, scientific knowledge “circulates” with high acceleration; an “interference”, merging and mixing of disciplines takes place, as Michel Serres stresses (Serres 1992). Today, nanotechnology is just an umbrella term for a wide range of technologies (see Metha 2002). At first glance nothing seems to be new, exciting, or problematic. But the umbrella term does not indicate merely a rhetorical shift or a renaming of well-known technologies without any content or visions of new R&D strategies. In addition, the umbrella term “nanotechnology” reveals the endeavor of recent engineering sciences and science-based technologies to find *a fundamental technology*, in other words: a root or core technology. This is linked to the leading and exciting vision of a specific kind

of reductionism, a *technological reductionism* that has not yet been perceived by the philosophy of science. That is my main diagnosis in respect of the development of nanotechnology, as I will go on to explain. In addition, I will show that the quest for a fundamental technology resembles the scientific research program of physics in its goal to find a grand unified theory of everything.

2. Driven by the Frontiers of Natural Sciences and by Application

The “no man’s land in between the disciplines” is neglected by the modern sciences, as Norbert Wiener stressed 50 years ago (Wiener 1968, p. 21). So he developed *cybernetics* to fill the gaps between the disciplines, but he did not succeed with his vision to radically change the sciences. Today, something similar is taking place. Although nanotechnology is in its infancy, it has become a popular umbrella term used to describe many types of research or knowledge production where the typical dimensions of the materials used are supposed to be below the microscale, *i.e.*, less than 1000 nanometers. This is, of course, not a definition, but an indication, where we should discuss the question: What is nanotechnology?

Before addressing this crucial question, let us concentrate for a while on the way in which nanotechnology is introduced in public discussion. In fact the core of this new technology is indicated by the dimensions of a particular “universe” and a specific scale of the world, the “nanocosm”, accompanied by space- and room-related metaphors. Whereas classical types of technologies are named with reference to specific objects, properties and processes, to definite functions or to areas of application, nanotechnology just refers to the scale of abstract objects. Although engineering sciences are also involved in developing traffic, infrastructural and building technologies, space- and room-related metaphors were not used until today. Key technologies especially were understood solely in a functional way without referring to space. This space-invariance reflects the functional universality and the seeming context-independence of application. By neglecting spatial aspects, the visionaries and lobbyists of high technologies could easily overlook ambivalent social impacts of development, application, and diffusion: social impacts are located in space and time, in other words, within specific contexts.

Though the space-relatedness of nanotechnology and the metaphors of the nanolobbyists might suggest otherwise, nanotechnology represents only a new and more rigorous construction of space-independent technology. The abstract micro- or “nanocosm” of nanotechnology on the one hand and the mesocosm of our day-to-day *Lebenswelt* on the other hand are entirely different. Phenomenologically we do not have access to the “nanocosm” with our senses; technological apparatus and experimental setups are necessary. In this respect, the spatial scale of nanotechnology shows us our spatial limitations and our endeavor to overcome them. Hence, nanotechnology has an implicit anthropological relevance (see Nordmann 2003): the position of humans in the scales of the cosmos is a mere point in between the nano- and macrocosm. But we do not have to remain isolated and epistemological limited in our own mesocosmic world; we may access the “nanocosm”, which might be the best cosmos to “live” in. The abstract reality of the “nanocosm” – this is suggested by the visionaries of nanotechnology – seems to be similar to (but better than) our day-to-day-reality in our mesocosms. The cramped conditions of the mesocosms (energy, entropy, information storage, time,...) will be altered and defeated. If the nanocosms will take over and fulfill several functions that today are restricted by the mesocosm, we will get more space and more freedom of action (see Schwarz 2004, this volume).

The reference to an abstract space is intermingled with the lack of semantic specification; the size of objects is a weak basis to define a new type of science or to integrate different disciplines. Similar to its predecessor in the 1990s, microsystems technology,

“nanotechnology” (still) lacks content and a core. Like an empty room or a new flat, everyone is invited to furnish, move into, paint or attribute to it whatever he or she wants. The main semantic character of nanotechnology is vague, uncertain, indefinite and indeterminable (see Gamm 2000, p. 275ff). Facts and fiction are merged and cannot be distinguished. It is hard to find scientific disciplines which may not be subsumed under the category “nanotechnology”. In the struggle for financial support, the vagueness seems to be a successful strategy of science policy that is promoted by the visionaries and lobbyists of nanotechnology. At least we have to be aware of the fact that the umbrella term “nanotechnology” could be a mere ideology and a clever strategy of different *scientific communities* to obtain financial support. This was, indeed, the case when James Yorke coined the term “chaos” in 1975 for some deterministic, irregular mathematical properties. “Chaos” became the catchword of dynamical systems theory and nonlinear dynamics, which from then on were called “chaos theory”, accompanied by the interest of the public and the scientific communities. J. Yorke and his group financially survived. But clever umbrella terms and catchwords do not seem to be sufficient for new contents and a homogeneous scientific research program.

The space-related metaphors of nanotechnology turn into an ideology by suggesting that the nanocosm has to be conquered like a country or a white region on the map. The conquest visions and metaphors of nanotechnology have been around for many years. The physicist Richard Feynman was supposedly the first person to speak about the idea of nanotechnology in 1959. He drew a map with a white unexplored region: “There’s Plenty of Room at the Bottom” (Feynman 1959/2003). Hence, the room awaits scientific conquerors. In a speech to the American Physical Society, he proposed that tiny machines could be programmed to replicate themselves at one half their original sizes. He suggested that it would be possible to manipulate individual atoms and molecules to form exactly the products desired. Today, this vision is indirectly adopted by the NSF slogan “shaping the world atom by atom”. According to Feynman, “The principles of physics [...] do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big. [...] But it is interesting that it would be, in principle, possible for a physicist to synthesize any chemical substance that the chemist writes down [...]: put the atoms down [here] [...] and to do things on an atomic level. [...] [This is a] development which I think cannot be avoided” (Feynman 1959/2003). But Feynman’s vision was not only the *bottom-up* strategy of “shaping and maneuvering the world atom by atom” in order to create new chemical substances, but also the miniaturization of well-known mesocosmic entities and artefacts *top-down*. At the end of his speech, Feynman issued a challenge to everyone: “It is my intention to offer a prize of \$1,000 to the first guy who can take the information of the page of a book and put it on an area 1/25,000 smaller [...] in such manner that it can be read by an electron microscope. And I want to offer another prize to the first guy who makes an operational electric motor which is...only 1/64 inch cube. I do not expect that such prizes will have to wait long for claimants” (Feynman 1959/2003). The vision of Feynman combines “cross-disciplinary” chemical engineering, mechanical construction, information processing, data storage, electroengineering, electrooptics, and others. Equivalent names for nanotechnology include molecular manufacturing, molecular fabrication, mechanosynthesis or chemosynthesis.

The objects nanotechnology tries to handle are mainly concentrated on the interdisciplinary borders between physics, chemistry, molecular biology – and engineering sciences. The scientific ambition is to link and to unify quantum mechanics, solid-state physics, inorganic chemistry, and molecular biology. These issues are, however, not new, but more or less classical. They are unsolved until today, when even in physics a unified theory merging quantum mechanics with macroscopic phenomena and with a complex system is not estab-

lished. In statistical mechanics, important theoretical entities of phenomenological thermodynamics like entropy are not explained in a satisfactory way. These theoretical gaps seem to reflect that nature is ontologically multi-tiered and coarse-grained. But the visionaries of nanotechnology fail to notice the state of the art in physics. They just orient themselves toward the heuristic objective of physics, which is mainly the quest for a fundamental theory of everything.

The vision of an extremely tiny technology was first raised not by an engineer, but by a physicist, Richard Feynman, who founded quantum electrodynamics (QED) and worked on macroeffects like suprafluidity. This does not seem to be a pure coincidence. Particle, high energy and nuclear physicists are used to preparing “nature” on the nanoscale. Their day-to-day experimental (technological) preparation has certainly influenced Feynman to expect and to predict the global success of nanotechnology. Physicists in the 20th century have always engaged in “nanoscience” (without naming this “nanophysics” or “nanotechnology”) and they advanced the “nano-methodology” in particle physics as well as in solid-state physics. To a certain extent, these aspects are a line of arguments against the hypothesis that nanoscience and nanotechnology are (in fact) a radically new type of science and technology. They base on the advancements of physics: Indispensable physical instruments in the rise of nanotechnology are scanning tunneling microscopy (STM) and the atomic force microscope (AFM), which stem from developments in the early 1980s. Nanoscience and nanotechnology are highly dependent on the advancements of instruments in the realm of physics. They are mainly driven by methodological improvements in the horizon of physics.

We should be aware of the fact that it is not engineers, but natural scientists who proclaim an advancement of nanotechnology – and they are working as natural scientists on topics which are relevant for the future of technology and hence, as they themselves state, for the future of society. Today, technology is even more science-based than in the 19th century, whereas – conversely – natural science is based on technological apparatus. The diagnosis of a “hybrid” consisting of science, engineering, and technology – an intermingled “technoscience” as pointed out by Bruno Latour and Donna Haraway – seems to be plausible (Latour 1987; Haraway 1995). The question of whether this indicates a “new production of knowledge”, as some sociologists have stated (Gibbons *et al.* 1994), cannot be answered just by referring to societal aspects whilst inner-scientific aspects and the inner-scientific evolutionary processes (like the paradigm of physics in the quest for unification and the leading research program) are mainly excluded. It is not at all obvious that the facts in the advancements in science and technology justify the diagnosis that we are entering into a radically new era or a new paradigm, as the nanolobbyists proclaim. And Martin Carrier stressed that technology or policy-related scientific research (“Mode-II-Production of Knowledge”, Gibbons *et al.* 1994) is by no means historically novel (see Carrier 2001, p. 25f). Phenomenological thermodynamics and hydrodynamics in physics are developed in close relation to technological applications and industrial innovations. The discussion about “*finalizing* scientific research programs” shows that the merging of science, technology, society, and politics has always been around, especially in the 19th and 20th century (Böhme *et al.* 1974). Nanotechnology, of course, is a new summit and it accelerates this merging process. What seems to be a qualitatively new step are its visions, particularly its *technological reductionism*. Even if we may (and can) not argue that the recent facts justify the diagnosis of a radical new era, the visions are a sufficient indicator for this diagnosis which should be analyzed seriously. Often, visions (science-fiction and “Leitbilder”) turn to facts; visions may open road-maps to reality (see Nordmann 2003).

A pioneer (and a lobbyist) of nanotechnology in the early 1970’s was Eric Drexler, who was involved in genetic engineering (see, *e.g.*, Drexler 1990). Drexler was convinced that the same principles behind the manipulation of DNA molecules could be applied to

other molecules. Drexler was probably one of first people, besides N. Taniguchi, to use the phrase “nanotechnology” in order to describe the process of precise molecular placement one atom at a time. In his papers and books, Drexler stressed three concepts which are fundamental to his vision of nanotechnology: assemblers/disassemblers, replicators, and nanocomputers. Assemblers are macroscopic pumps to carry out mechanical actions, *i.e.* to put things together; disassemblers take things apart; replicators are copying mechanisms; nanocomputers give instructions to the other parts, *i.e.* to assemblers, disassemblers, and replicators (Drexler 1990). Although it was Drexler’s objective to shape the term “nanotechnology”, he merely described the functional frame of molecular fabrication without any hint to objects, methods, goals, implementations, and social diffusion.

So we can sum up that, in the large, nanoscience and nanotechnology have their roots in traditional disciplines like physics and chemistry. This comprises three aspects: Firstly, the visions (“shaping the world atom by atom”) and *Leitbilder* arise in the realm of physics and chemistry. Secondly, the theoretical scientific basis lies in the area of physics, chemistry and in between. Thirdly, the instruments and experimental methodology necessary for nanotechnology (like Scanning Tunneling Microscopy or the AFM), are based on frontier advancements in physics and chemistry. Hence, gaining an understanding of nanotechnology may be possible by concentrating on the visions and *Leitbilder*, theories and methods primarily established in physics and chemistry – of course without neglecting the increasing power and influence of a globalized economy and an accelerated capitalism.

One main objective of physics and chemistry is the unification project in the metaphysical, epistemological and methodological sense. My line of argument will show that this successful unification strategy and reductionist metaphysics are grasped and extended by the visionaries of nanotechnology.

3. Nanotechnological Unification Project: Convergence and Reductionism

Nanotechnology, this is my main thesis, aims to be a fundamental technology (“root technology”) with hegemonic tendencies: Nanotechnology presents itself as *the* basis for all other technologies. The objective of this new fundamental technology seems to be the general foundation of science-based technologies. Similar to classical-modern physics and the unifying attempt to converge the four main forces to obtain a “theory of everything”, nanotechnology follows a unification program – here a unification program of engineering sciences – in order to eliminate the patchwork of various bounded technologies which are restricted in application. So nanotechnology is not at all a scale-restricted technology; it is not just another step towards miniaturization. Probably, G. Stix is right in emphasizing that “nanotechnology is all the range” (Stix 2001, p. 32). Hence, “nanotechnology” is not only an umbrella term for a variety of technologies, but, in addition, a strategic vision for a science-based unification research and development program of engineering sciences itself. Nanotechnology indicates the attempts of unifying engineering sciences. Some details:

Essential criteria for a technology being a “fundamental technology” can be derived from the quest for a fundamental theory in theoretical physics where at least some theories are converging. A fundamental theory and the unity of physics are mainly synonyms (see Weizsäcker 1974). A necessary condition for the unity of physics in the epistemological sense is a convergence of the four main theories. However, the heuristic concept of the unity of physics may be extended to the unity of technologies. In the case of technologies and engineering sciences one has to show that a unity of technologies exists and that one “mother technology” enables all other “daughter technologies”, *i.e.* the mother technology incorporates all daughter technologies, as in physics, where quantum mechanics claims (misleadingly) to ground the predicates of classical mechanics.¹ This is what I will name “*technological reductionism*” or “*reductionism of technology*”.² This kind of reductionism

– and the inverse path, that of technological constructionism – has to be further specified. The technological reductionism of engineering sciences is the metaphysical core of the heterogeneous and diverse fields of the umbrella phrase “nanotechnology”, covering electron-beam and ion-beam fabrication, molecular-beam epitaxy, nanoimprint lithography, projection electron microscopy, atom-by-atom manipulation, quantum-effect electronics, semiconductor technology, spintronics and microelectromechanical systems.

Arguments for my thesis, that nanotechnology aims to be *the* fundamental technology with imperialistic tendencies, are given by the US National Science Foundation (NSF) itself (Roco & Bainbridge 2002). The NSF states that technologies like nanotechnology (also: biotechnology, information technology and cognitive sciences) are not only “key technologies” but also “converging”. The NSF speaks of “Converging Technologies for Improving Human Performance” explicitly in terms of “Unifying Science and Converging Technologies” (*ibid.*, p. x). This is based on the traditional metaphysical claim of the unity of nature, revealing an implicit Platonism and showing, beyond Plato, a strong naturalism in the field of nature and of technologies (*ibid.*, pp. ix, 32):³

In the early decades of the 21st century, concentrated efforts can unify science based on the unity of nature, thereby advancing the combination of nanotechnology, biotechnology, information technology, and new technologies based on cognitive sciences. [...] Converging technologies could achieve a tremendous improvement in human abilities, societal outcomes, the nation’s productivity, and the quality of life. [...] The phrase ‘convergent technologies’ refers to the synergistic combination of four major ‘NBIC’ (*nano-bio-info-cogno*) provinces of science and technology, each of which is currently progressing at a rapid rate. [...]

Convergence means more than simply coordination of projects and groups talking to one another along the way. It is imperative to integrate what is happening.

The unity and convergence metaphors are linked with catchwords like “holism” and “synergism”, as stated by the NSF: “Converging of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale” (*ibid.*, p. x). “A trend towards unifying knowledge by combining natural sciences, social sciences, and humanities using cause-and-effect explanation has already begun” (*ibid.*, p. 13). The traditional naturalistic view of a continuous causality and a causal nexus of nature is renewed by the NSF in order to highlight the epistemological and technological possibility and importance of unification: It is “possible to develop a predictive science of society”. (*ibid.*, p. 22) “The sciences [...] have reached a watershed at which they must unify if they are to continue to advance rapidly” (*ibid.*, p. x). To illustrate this, a strange (piece of) poetry is placed in the NSF report (*ibid.*, p. 13):

If the Cognitive Scientists can think it
the Nano people can build it
the Bio people can implement it, and
the IT people can monitor and control it

Obviously, this could and would imply a circle in argument, in the sense that the IT people would control what the cognitive scientists think. More radically: the IT people would control the cognitive scientist, and so on. So the naturalistic causal nexus seems to “operate” without any influence of any human agent, like the Laplacian Demon in the 19th century.

I will proceed one step further, beyond the symmetry of “NBIC (*nano-bio-info-cogno*)”, and concentrate on nanotechnology. Nanotechnology seems to be, more or less, *the* fundamental basis for the unity of technologies because the abstract nanoscale is where the convergence of the four technologies is supposed to take place: “Convergence of diverse technologies is *based on material unity at nanoscale* and on technological integration

from that scale. The building blocks of matter that are fundamental to all sciences originate at nanoscale” (*ibid.*, p. ix). The unity of science itself, the unification of engineering sciences and technologies, is said to take place on the nanoscale. In the very small and abstract world of the nanocosm, everything seems to converge. Convergence is *the* pacemaker to unity; unity is the final point. The final point is the point of total control – it is the point of Archimedes. So it is not only a metaphysical unity of the (given) nature (“ontology”), a unity of knowledge and explanation about nature and about technologies (“epistemology”) or a unity of methods (“methodology”), but a unity referring to preparation, manipulation, acting in nature; it is a unity of technology, a unity of *technoscience* itself (see Latour 1987).

A common paradigm is stressed by the nanolobbyists and nanovisionaries: In terms of traditional epistemology, this is a classical reductionist strategy. It is not only a reductionism of science, but a *reductionism of technology*, which links knowledge, action and application. It is not solely a reductionism in the scope of truth production, theories and propositions (representation), but of knowledge production in the horizon of application and intervening (see Hacking 1996). The philosophy of science has not yet developed an approach and access to this new type of reductionism. The NSF criticizes all positions which do not support an overall reductionism:

Some partisans for independence of biology, psychology, and the social sciences have argued against ‘reductionism’, asserting that their fields had discovered autonomous truths that should not be reduced to the laws of other sciences. But such a discipline-centric outlook is self-defeating, because as this report makes clear, through recognizing their connections with each other, all the sciences can progress more effectively. [Roco & Bainbridge 2002, p. 13]

Hence, fundamental technologies are conveyed by a technological reductionism based on the metaphysical unity paradigm of (the given and constructed) reality – and a linear optimism about scientific progress.

In reductionist approaches, explanation has been defined as the subsumption of new phenomena under well-known general laws (Rule 5 in Descartes 1979, p. 379). According to Hempel and Oppenheim, to Nagel, Popper and Scheibe this is called the deductive-nomological (DN-) scheme of explanation (see Hempel and Oppenheim 1948, Scheibe 1997) or the “covering law model”. It is implicit in the convergence and unification program of the theories of physics (reductionism of explanation). In physics, three of four fundamental theories converge to a new “theory of everything”; in engineering science, a convergence of the four “NBIC (*nano-bio-info-cogno*)” technologies is stated by the NSF.⁴ Now, the theoretical strategy of explanation is partly interlaced with experimental or methodological reductionism. Reality is experimentally torn to pieces and the pieces are isolated from each other in order to gain deeper insight into the structure of matter (reductionism of experimental setups, reductionist and analytical methodology, even in “holistic” quantum physics). Implicitly, most scientists assume the *smaller* the entities of nature are, the *deeper* is the synthetic understanding of nature in general and the *more fundamental* is the explanation. Hence, it is assumed that understanding the microcosm implies understanding in a synthetic way the whole cosmos, but not vice versa (viability of the *bottom-up* strategy of explanation). The (metaphysical) claim necessary to argue for this epistemological statement is ontological reductionism, linked with naturalism. Further details in the debate on reductionism will be skipped here; different other aspects of a metaphysical, an epistemological or a methodological reductionism could be analytically distinguished. This has been done by philosophers several times. But philosophy of science has not yet grasped the *technological reductionism* which is apparently present in (the program and metaphors of) nanotechnology.⁵

What is *technological reductionism* in detail? Let us specify some aspects. *First*, in general, technological reductionists assume the possibility and effectiveness of shaping the world atom-by-atom. The world can be effectively shaped, manipulated and controlled by shaping atoms and molecules. This is an ontological claim and a perfect *bottom-up* methodology. Apparently, shaping the “bottom”, the nanocosm, will imply an intentional shaping of the meso-, macro- and megacosm. Hence technological reductionists debase other scales of acting in the world, like the micro-, meso-, macro- or megacosm. These scales are *not* relevant for general control of the world. The meso-, macro- or megacosm do *not* possess own strong supervenient properties which *cannot* be manipulated by the nanocosm (see Beckermann 2001, p. 203ff). This is, of course, a strong claim and reveals the straight naturalistic viewpoint which is based on the (classical) conviction of a continuous cause-and-effect nexus of the world, especially a naturalistic line from the nanocosm to the macrocosm. The phrase “shaping the world atom-by-atom” neglects classical engineering sciences (research and development) on scales of the micro-, meso-, macro- or megacosmos and just focuses on the nanocosm. Technological reductionism is anti-pluralistic, and is not based in a structural science (“Strukturwissenschaft”: Weizsäcker 1974, p. 22f). The NSF states: “The traditional tool kit of engineering methods will be of limited utility in some of the most important areas of technological convergence” (Roco & Bainbridge 2002, p. 11). This indicates that engineering sciences are in (a state of) transition, from bounded to fundamental nano-engineering sciences.

Second, to give some more formal details, nanoengineering sciences suggest a monocausal (epistemological) dependence structure of knowledge, action, and manipulation in the scope of technological reductionism, without emergent properties which cannot be controlled from the nanocosm. Technology t_1 is said to be reduced to technology t_2 if, and only if, the advancement of t_2 is fundamental to the advancement of t_1 . In other words: The development of t_2 is the bottleneck (and the necessary condition) for the development of t_1 . Technological reductionism does not only claim a reductionism of explanation, but (also) a reductionism of research and development activities, of technical handling, control, and intervention.⁶ In order to promote the daughter technology t_1 , one mainly has to enhance research in the field of technology t_2 . It does not mean that technology t_1 and t_2 are identical, but that a monocausal dependence exists. Progress of technology t_1 monocausally depends on technology t_2 . This new kind of reductionism is a way to give substance to catchwords like “key technology”, “enabling technology”, and “nanotechnology”, which I have renamed “fundamental technology” in order to highlight the parallelism to the ambitions of (classical-modern) physics.

Third, there is also a more societal understanding of “fundamental technology”. The *more fundamental* a type of technology is, the *more dominant* it obviously is in our day-to-day life, the *more* it becomes an implicit circular of our society, the *more* traditional distinctions (nature vs. technology, technology vs. culture, politics, ethics) are dissolved. Fundamental technologies are those technologies which constitute, like other mass media, a “medium of society” (Gamm 2000, p. 275ff); they are the nexus of knowledge circulation (Serres 1992). They cannot be defined solely as artifacts, instruments or processes. An external position of mere observation cannot be captured. Fundamental technologies are wherever we are, like the blood in our body.

Fourth, furthermore, technological reductionism merges and mixes scientific realism and constructivism of the very small, insofar as representation and intervening are both the core of technological reductionism. Technological reductionism does not only have its root in scientific realism, but merges and mixes realism and constructivism: it is a “pragmatic constructo-realism”.⁷

To sum up: Although, at first glance, “nanotechnology” just seems to be heterogeneous, diverse and pluralistic, *i.e.*, only loosely connected by the umbrella term, technological

reductionism is anti-pluralistic in its core. “Nanotechnology” may be interpreted as an overall research and development program of the *technosciences* which is based on a strong technological reductionism. For understanding nanotechnology, philosophy of science should address the core of nanotechnology, *i.e.*, its technological reductionism.

4. Epistemological Limits of the Technological Reductionism

Is the overall reductionism of the nanotechnological research program justified? – It is hard to see how the research program could succeed as stated by the nanolobbyists. By looking closer at reductionist strategies one has to be aware that even in recent physics we do not have a nice hierarchically ordered theoretical frame or a final unified theory of everything (TOE). The unification strategy is successful to a certain extent but has not reached its goal of a theory of everything until now. This, of course, is just an argument derived by referring to the status quo of physics. It is not a general argument which shows that the unification strategy of physics and of nanotechnology will fail in the future. Let us strengthen our argument that nanotechnology overestimates the possibilities of technological reductionism and present some principal and major limits.

The reductionist *bottom-up* methodology is and will be successful for the development of specific materials, instruments, properties, processes such as superconductivity or some quantum computing, but not in general. Many doubt the thesis of nanotechnological visionaries that nature can be constructed atom-by-atom. The constraints of physics and chemistry are too severe. In particular, I would advance here the following line of argument: If nanotechnological visionaries recognize as one of their fundamental theories dynamical systems theory, including nonlinear dynamics, chaos theory, and theories of self organization – and sometimes they claim that they do – they would be aware of the limits of all reductionist strategies and hence of the epistemological limits of technological manipulation.⁸ I am therefore inviting nanovisionaries to identify and to learn from the limits of physics.

First, we have to consider the instabilities in nature and in the objects of engineering sciences. The origin of nonlinear physics and chaos theory is an impartial criticism of classical modern physics and its leading paradigms of ontological and epistemological reductionism (see Schmidt 2001). One important lesson of the new physics for all mathematical and engineering sciences known today is the fundamental role of nonlinearity and instability in nature and in technical apparatuses. If nature and technological objects are governed by nonlinearity, they can be structurally and dynamically unstable; flipping points, bifurcations, and chaos can occur – with small changes in initial conditions producing large effects in the overall dynamics (sensitivity, “butterfly effect”). According to M.L. Roukes, a physicist working on nanosystems, instability of nature challenges the nanotechnological *bottom-up* strategy and limits technological control of the tiny objects and the (seemingly continuous) path from the nanocosm to the macrocosm: the smaller the objects are, the more unstable they can behave, the more the nanoeffects may be amplified into the mesocosm without control. Perturbations on the nanoscale cannot be handled and controlled in all details. “The instability may pose a real disadvantage for various types of futuristic electro-mechanical signal-processing application” (Roukes 2001, p. 37). A second limitation is given by the laws of physics, namely the fundamental threshold for the minimum operating power: the random thermal vibrations and fluctuations of a device impose a “noise floor” below which real signals become hard to discern. – Briefly stated, nonlinear physics and chaos theory question (a) the classical modern understanding of experimental repeatability and hence the methodology of experimental and technological preparation in general, (b) the computability and predictability of the future and therefore access to its, (c) mathematical modeling and in consequence the empirical testability of models in experiments. Such

severe methodological criticism challenges the common understanding of science (see Schmidt 2001, p. 276f) and restricts the ways of preparation and construction of certain aspects of reality. Hence technological interventions are restricted.

Second, the focus of interest: One main difference between classical-modern reductionist physics and new nonlinear physics lies in their respective methodologies, *i.e.*, in the approach to their objects. Classical-modern physics assumes relevant epistemic aspects for understanding nature to be located primarily in the nano- or microcosm; on the other hand, new nonlinear physics and chaos theory focus on objects of medium scale, the mesocosm, with their own properties. The scope of interest and inquiry is broadened towards mesocosmic objects, the phenomena and appearances therein, – contrary to the nanotechnological vision. For instance, fractal geometry, a daughter theory of nonlinear dynamics, investigates nonlinear processes, pattern formation and structure building of plants and animals, as well as of fluids, gases, and solid states. Fractal geometry does not aim to understand the “genetics” of a plant but to describe the morphologic structure and the pattern formation process. Contextualized modeling and simulation become the core of the scientific methodology of new physics. The perspective of a moderate epistemological functionalism, but not a fundamentalism or a foundationalism of engineering sciences seems to be evident. – In contrast to the nanotechnological paradigm, “there is plenty of room in *medium scale*”: the dimension of the mesocosm is not neglected by nonlinear physics. Yet, we do not understand processes on the mesoscale like tool processing machines, railway dynamics, mechanical production processes, or building construction. We do not know how to handle these processes in detail. Further work has to be done on this scale of the classical engineering sciences. Of course, they are linked with computer science to a certain extent, but they will not be dissolved in or reduced to computer science. Technological reductionism seems to be the wrong answer to a strange question: Which kind of engineering science is of major importance and has to be financially supported? Nonlinear physics advances a pluralistic image of natural and engineering sciences.

Third, methodological and “manipulological” issues: Two intermingled problems and limits have to be taken into account within the nanotechnological *bottom-up* strategy, as Richard Smalley points out (Smalley 2001). Smalley calls one the “fat finger problem” and the other the “sticky finger problem”. Because the “fingers” of a manipulator arm and technical apparatus must themselves be made of atoms, they have a certain irreducible size. In many applications the fingers of manipulation are far too “fat”. Furthermore, the atoms which should be shaped by nanotechnology will also be too sticky: the atoms of the manipulator arm will adhere to the atom that is being moved. It will often be impossible to release this nanostructure in precisely the right spot. – So there is no isolation and no definite border between the surroundings on the one hand and the object to be shaped on the other hand. Thus emerges in the nanocosm a kind of holism, based on instabilities, classical and quantum effects.

Fourth, limits of explanation and prediction: Complex nonlinear phenomena resist reductionist strategies of explanation: an a priori subsumption of phenomena under well-known unified laws is not possible, which can be concluded from the criticism mentioned above. Understanding reality requires a phenomenological process and the occurrence of pattern formation. Fractal geometry describes these processes in a phenomenological-morphological way but does not explain it based on “genetic” aspects, according to the reductionist scheme of nomological explanation. In consequence, the meanings of scientific “truth” and knowledge change. Since understanding is required for shaping and manipulation, this limit to explanation challenges nanotechnological strategies of understanding what it wants to construct. As weaker types of explanations are coming up, these imply limitations of prediction, and hence of acting and of shaping the world.

Fifth, the world is a constructo-realistic patchwork: Given and designed nature is not to be described as an invariant material block (see Cartwright 1999) but rather as a dynamically unstable, open process. New patterns and structures emerge from lower levels of complexity in unpredictable ways. Unpredictability on the one hand and technological construction on the other hand, contradict each other. Nature and technology, as N. Cartwright puts it, is “a patchwork, not a pyramid” (Cartwright 1999, p. 1f). If reality is indeed a “patchwork”, the technological reductionism that is based on the classical metaphysical assumption of a naturalistic, continuous cause-and-effect nexus of the world is a prejudice that cannot be justified reference to the natural sciences.

These arguments challenge and question the visions of the nanolobbyists, *i.e.*, their technological reductionism. A necessary condition for the scientific foundation of the nanotechnological research program is the success of reductionism in the realm of physics. But this remains a visionary dream (Weinberg 1996). Thus nanotechnology may be successful to a certain extent, in specific contexts of application. A global technological reductionism and fundamentalism, however, remains a utopia. This utopia is not a very new one, it traces back to F. Bacon and the founders of modern sciences in the 17th century.

5. Tracing Back the Roots of Technological Reductionism: Renewing and Extending the Baconian Project

F. Bacon is probably the founder of the technological reductionism. He proclaimed that science is an instrument to extend the power of man as far as possible (see Bacon 1959; Bacon 1990). Knowledge is power! Nature should be hunted by sciences like an animal in order to unveil her secrets; nature was for man to milk. Indeed, this view of nature had become dominant in the concept of modern science and put into practice within its experimental and technological framework. Nature was thought to be an enemy which has to be tamed and brought under control. In contrast to the Aristotelian understanding of nature, nothing was simply given, everything seemed to be subject to technological manipulation. *Homo Sapiens* became *Homo Faber*, and further aspires to become *Techno S@piens* today. An institutionalization of science in scientific communities, like the Royal Society, London, was supposed to establish and guarantee a program of scientific discoveries, technological inventions and innovations. Science-based technological progress became identified with social and human progress (see Böhme 1993). This identification was doubted from the 1960's until the middle of the 1990's, but evidently just for this short era. In the late 1990's technological optimism was back in science and politics: the Baconian Project seems to provide the underlying ethos of scientists and engineers working in the fields of nanotechnology.

The visions of a science-based technological shaping and manipulation of the world are not very new ones. They are rooted in the history of our culture. In the empiricist tradition David Hume confirms the Baconian Project. “The only immediate utility of all science is to teach us how to control and regulate further events [in nature]” (Hume 1990, p. 76). Immanuel Kant linked the manipulation and construction of nature on the one hand with understanding on the other hand: We understand nature only as far as we can constitute and construct her (Kant 1989, p. 25f). So the phrase “shaping the world atom by atom” is an extrapolation and a new summit of the Baconian Project since the 17th century. Representing and intervening are, as stated by Ian Hacking, twin sisters (Hacking 1996). Science and modern technology have always been merged as *technosciences* (see Latour 1987). The *more* one knows about nature in the scope of a science-based reductionist methodology, the *more effectively* one can act, intervene, and manipulate. Although in the 19th century technology became science-based in general, the 21st century will probably be the century of the emergence of fundamental engineering sciences and an overall technological reductionism.

In line with a general technological optimism the physicist Michio Kaku states today: “For most of human history, we could only watch, like bystanders, the beautiful dance of Nature. But today, we are on the cusp of an epoch-making transition, from being passive observers of Nature to being active choreographers of Nature. The Age of Discovery in science is coming to a close, opening up an Age of Mastery” (Kaku 1998, p. 17). Nanotechnology is the tip of the Baconian iceberg which is not yet recognized in the ocean of scientific propositions and scientific practice by most philosophers of science.

Until today, Bacon’s Project has not been realized and put into practice to its full extent. Bacon speaks in favor of a science-based reductionist “technological foundation”, a foundation for acting in and manipulating the world. The NSF’s phrases resemble Bacon’s words: “If we make the correct decisions and investments today, many of these visions could be addressed within 20 years’ time. Moving forward simultaneously along many of these paths could achieve an age of innovation and prosperity that would be a turning point in the evolution of human society” (Roco & Bainbridge 2002, p. x). The emergence of the new nanoscience-based innovations has renewed the convictions of “Nova Atlantis” to support not only scientific explorations and “truth” production but also discoveries, inventions, and innovations (see Bacon 1959, 1990).

Bacon was convinced that only an institutionalized research and development strategy could guarantee inventions and innovations. Nanoscience and the developments in nanotechnology are expensive R&D. They require cooperation between universities, governments, and industry, for example “private public partnerships”. These projects are called “megascience” (Ahluwalia 1994). Megascience projects are defined as those undertaken primarily for the production of knowledge in the horizon of application, where a classical distinction between fundamental and applied science is no longer plausible. They require formal management structures and resources that cannot be provided by a single agency, university, firm, or country. Other examples are the Human Genome Project or ITER’s tokamak fusion reactor. In order to get support from the public and to legitimate expensive R&D investments, Eric Drexler founded in the 1980’s the “Foresight Institute”, which is dedicated to the education of the public to help prepare society for the anticipated “technological advances” that the implementation of nanotechnology is thought to bring.

In the course of these institutional developments, the understanding of “technologies” may change from artifacts and procedures to media (see Gamm 2000, p. 275f). Technology is everywhere, it has become the “blood of society”. The distinction between nature and technology, between man and machinery, which is still present in our day-to-day life, seems to be dissolving steadily. The dissolution of the traditional culturally leading differences reveals a paradigm of a total and fundamental technology: Everything will be shaped, designed and controlled within the limits of the laws of nature. This is pure Baconianism. But, it remains a question of politics and subpolitics whether we will accept this dissolution of our cultural distinctions. Normative and ethical aspects are arising within new types of politics like nature-politics, bio-politics or of “nano-politics”, which may become established and should be reflected upon philosophically.

For the philosophy of science it remains a challenge to critically show that the vision of a totally shaped world overestimates the power of science and the power of men. Technology may be everywhere (Gamm 2000, p. 275ff) and the Aristotelian understanding of nature may be dissolved in a fundamental technology with its technological reductionism. But technology cannot be shaped and controlled everywhere. The boomerang effects of technology within society have been perceived and reflected upon since the beginning of the ecological crisis in the early 1960s. So it is surprising that the Baconian Project and its linear technological optimism are renewed by nanotechnology. The cultural and political progress of the last 40 years with its perception and recognition of the societal ambivalence of science and technology seems evidently to be retracted.

6. Technology Assessment as Vision Assessment

How to cope with nanotechnology and the technological reductionism within society? Technology assessment (TA) provides fruitful and, to a certain extent, successful tools for the societal shaping of technologies (Grunwald 2000). Procedures of perception, assessment, decision-making, management, and controlling have been developed during the last 35 years. But often TA comes too late to gain influence on the processes of technological advancement and societal diffusion; the speed of technological innovation grows rapidly; often concepts of co-evolution of TA and technological innovation have not been applied. Although nanotechnology as a technology is in its infancy, the leading goals, visions, *Leitbilder*, and metaphors are well known and fully established. Even if burdened with religious aspects and dreams of Baconian prosperity, visions are pathways to reality. They often turn from mere thoughts and abstract ideals to road maps for constructing and shaping reality. A leading magnet and a powerful *Leitbild* (“vision”) is technological reductionism, linked with the nanotechnological shaping metaphor, the “shaping of the world atom-by-atom”.

For the megascience “nanotechnology” a prospective Technology Assessment (TA) should not be restricted solely to assessing the technological artifacts and procedures and, in the end, the diffusion into society. A co-evolution should take place. Technology Assessment may include *Vision Assessment* (VA), in other words: an assessment of *Leitbilder* (Dierkes *et al.* 1992). An extended understanding of shaping technology covers a shaping of visions as well as a shaping of technical apparatus, technical procedures and societal diffusion: the way one thinks and talks, the way one might act and behave. The methodological philosophy of science and the science-related constructivism of the school of *Erlangen* (Lorenzen, Mittelstrass, Janich, and others) have shown the crucial role of terms, languages, and prototheories in the advancements of science. This could be transferred to the development and societal shaping of technologies, insofar as technologies are science-based. This extension of TA to Vision Assessment is controversial. Sometimes it is doubted that visions play any relevant role in the process of technological invention and innovation. Other critics may raise the objection that visions are too vague to be a fundament for rationally assessing prospective technological advancements; this is the position of those representing “Rational Technology Assessment” (see Grunwald 1998). Some critics believe that in the period in which *Leitbilder* still play a leading role it is far too early to say anything about a new technology, its chances and limits. And some natural scientists and engineers suspect a renewing of the *Two Culture* dichotomy: they fear that social sciences and humanities will dominate the shaping of technology, but without any inner knowledge about natural and engineering sciences and technologies.

But all of this would be a misunderstanding of the framing concept of Vision Assessment. By introducing Vision Assessment to the scope of Technology Assessment, the technological core of new technologies in the TA concept are not neglected or excluded. Vision Assessment stresses the relevance of soft aspects for the development, the diffusion and the use of new technologies, in the sense of Ernst Cassirer when he spoke about “symbolics and symbolism of technology” (Cassirer 1985). So two aspects may be distinguished within the framework of an extended TA: (a) Science and technology promote not only successful, but ambivalent knowledge about modifying, manipulating and designing nature. (b) Science and technology are interlaced with ideas, interpretations and thoughts. They create (and demolish) *Weltanschauungen*, cultural symbols and ideals by obtaining fascinating insight into structures, forces, and evolutionary processes of nature and technology. Scientific methodology is often thought to be culturally leading, as are its implicit norms and guiding values, its experimental setups and laboratory practice, its way of thinking and asking, its criteria for testing – and its pre-definitions and assumptions about nature, and hence the constitution of nature and technology in the scientific process.

TA of nanotechnology may be aware of the fact that nanotechnology has material and process, as well as social, symbolic, and anthropological components – and that its visions and *Leitbilder* may constitute the reality of the present and the future. So the core of nanotechnology, its technological reductionism, should be assessed. This extended approach opens the TA (of nanotechnology) to plural perspectives about the central questions: What are the central struggles and issues we have to resolve in society? What do we want to know? What can we realize? And: How do we want to live? Technological advancement, controlled and managed by an extended TA, would then become more problem- and purpose-centered than in the past. And corridors of (rational) decision-making about visions may be (re-)opened by a public debate on the future of our societies.

7. Conclusion

Let me summarize some of the fragments presented here: *First*, the driving forces, meta-physical backgrounds, leading metaphors and visions of nanotechnology have been developed in the horizon of physics (and chemistry). *Second*, the vision of nanotechnology is based on a convergence and unification program, revealing a new type of reductionism, *i.e.*, technological reductionism, which has not yet been recognized by the philosophy of science. *Third*, technological reductionism can be illustrated by the visions of the NSF, the metaphor of shaping atom-by-atom. *Fourth*, this reductionism is based on the naturalistic viewpoint of a closed causal reality and a cause-and-effect nexus of the world. *Fifth*, technological reductionism and the reductionism of the unification project of physics are somewhat similar. *Sixth*, I have sketched some arguments against technological reductionism by referring to recent physics of complex systems, nonlinear dynamics and chaos theory. *Seventh*, I added some remarks on the Baconian program which comes to a new summit in the context of nanotechnology, although it might fail. Conceptions of technology may shift from artifacts and procedures to media. *Eighth*, Technology Assessment of nanotechnology should encompass, as I have normatively stressed, concepts of Vision Assessment, especially to assess technological reductionism, and also the driving forces, the visions and desired states of a society of the future. *Technological reductionism* should be assessed in the horizon of our knowledge society. Further work needs to be done by the philosophy of science and cultural studies of technology to analyze it.

Notes

- ¹ To a certain extent this standard conviction of the “covering law model” is misleading because many parts of the theories are incommensurable, as Thomas Kuhn and others have already shown.
- ² Contrary to the rhetoric of the nanobbyists, not a holistic (or system theoretical) but a reductionist metaphysics about reality is heuristically leading.
- ³ The founder of the modern philosophy of technology, E. Kapp, advanced a naturalistic understanding of technologies. Similar aspects can be found in the anthropology of A. Gehlen.
- ⁴ This suggests that the number “four” is the magic number of unification projects in physics as well as in technology.
- ⁵ I do not ask here whether technological reductionism is justified.
- ⁶ Action theoretical specifications are necessary.
- ⁷ The concept of constructo-realism has not been worked out yet.
- ⁸ So the NBIC-report lacks of two related inconsistencies, one concerning holism and reductionism, a second one between referring to “complex systems” and shaping the world from the bottom up.

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Molecular Disjunctions: Staking Claims at the Nanoscale

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Abstract. Nanoscience may be surrounded by controversy but is characterized by its absence. Evidence for this comes from the reconstruction of a peculiarly muted scientific “debate” regarding the claim that a single organic molecule may serve as a wire in electronic circuitry. Even though there are fundamentally different theoretical approaches, the debate remains entirely implicit. This is because the research in question is motivated by interest neither in a true representation of nature, nor simply in the invention of devices or production of new substances. As a place-oriented enterprise NanoTechnoScience consists mostly in the settlement and staking of claims on the nanoscale.

1. NanoTechnoScience

The main thesis of this paper was motivated and explicated elsewhere (Nordmann 2002, 2004a, 2004b). What follows is an attempt to substantiate it with the help of a particular case study. To be sure, this is nothing like testing a hypothesis; at best, it will render the thesis more plausible and concrete.

Nanoscience is not an issue-driven but a place-oriented enterprise. It is neither interested in representations of nature nor in devices that work or substances with novel properties. Truth/falsity and confirmation/refutation do not serve as its epistemic standards, but epistemic success is also not measured in terms of functionality of devices or usefulness of substances. Instead, nanoscience is an exploratory attempt to claim foreign territory and to inhabit a new world or a hitherto unexplored region of the world. Epistemic success is therefore a kind of technical achievement, namely the ability to act on the nanoscale, that is, to see, to move around, move things around, carve your name into a molecule, perhaps initiate productive processes, in other words, to inhabit inner space somewhat as we have begun to inhabit outer space and certainly has we have conquered the wilderness.¹

This passage speaks of nanoscience as opposed to nanotechnology. Roughly speaking, *nanoscale research* concerns molecular architecture, *nanotechnology* aims for the control of this architecture, and *nanoscience* investigates the physical properties that depend on it.² However, if the thesis is correct, it turns out that even nanoscience isn’t “science” properly or traditionally speaking, and that even for nanoscience there is no distinction between theoretical representation and technical intervention, between understanding nature and transforming it. More properly one should therefore speak of NanoTechnoScience.³

First, some *prima facie* evidence will be presented for the thesis. It comes from the general area of molecular electronics. The initial impressions obtained from this will then be traced to two culturally distinct research groups that appear to be working on the same problem. Trying to identify in their writings the core commitments of both groups, one finds that one of them seeks to identify and solve “fundamental problems” and that this

orientation marks a rather fundamental disagreement between the two research groups. However, this disagreement remains entirely implicit and does not become subject of debate. Like the lack of scientific discussion on such basic issues as the physical possibility of “molecular assemblers”, this lack of debate can be taken as evidence for the thesis of a non-traditional NanoTechnoScience that is not driven by theoretical issues but consists mostly in the settlement and staking of claims on the nanoscale.⁴ Nanoscience may be surrounded by controversy but here it proves to be characterized by its absence.

2. Pressing Problems

In a September 2002 presentation Stan Williams identified a problem that “must be solved”: How are electrons going through molecules? This is a question for molecular electronics. It is accompanied by another question: Why is this such a pressing problem, what makes it so interesting?

There are two kinds of answers to this latter question. One of these belongs to an issue-driven enterprise, the other characterizes the place-orientation of NanoTechnoScience. According to the thesis, one wouldn’t expect the first of these or one like it offered at all. As we will see, it may not be quite that simple.

This first kind of answer requires for a foil the history of physics at least since the time of Faraday and Maxwell. As Jed Buchwald, in particular, has pointed out, they effected a transformation of physical thinking that prepared the ground also for quantum mechanics (Buchwald 1985). Physical effects were not to be attributed to spatio-temporally localized causes but to space itself which is no longer a mere medium for the transmission of effects as they traverse from their point of origin to a detector, but, in a sense, the space itself can get excited and the change of its state communicated. The propagation of effects therefore does not require particles on which they ride or by which they are transported – all this most famously exemplified in electrodynamics by the propagation of radio waves.

Against this background, the question of how electrons travel through molecules takes on a particular significance. In physical, though not perhaps in chemical terms, it presupposes a curiously old fashioned picture, one according to which a molecule is a discrete kind of body which first is penetrated by and from which then exits another body, namely an electron. Since this electron carries a charge, the passage of the electron through the molecule is associated with a flow of a current and the question by Stan Williams amounts to: Is a molecule qua molecule something like a channel through which current is propagated differently than it is through space on the one hand, through bulk material on the other? If yes, the shape and structure of molecules is physically significant (Woolley 1978). Furthermore, if molecules are conductors of electricity and, so to speak, channel the flow of electrons, do the same laws apply to them as to bulk material? In particular, do they offer a resistance to this flow that serves as a constraint on the amount of current such that too high a voltage would generate so much heat that the molecule ought to melt like a wire that is too thin (compare Di Ventra *et al.* 2002, p. 195)?

All this is terribly crude and simple-minded. It certainly does not even begin to reflect the availability of theoretical models that propose answers to Stan Williams’s question. But then Williams was not asking for a theoretical model but for an empirical determination. How *do* electrons move through molecules? Experimental answers to this question can be traced to Mark Reed and Jim Tour’s 1997 paper in *Science* on the “Conductance of a Molecular Junction” (Reed *et al.* 1997). Reed and Tour provide experimental evidence combined with statistical argumentation to distinguish current flow through a single organic molecule from the current that may or may not be propagated in its immediate environment. They use bulk material to create a so-called break junction where two coated gold electrodes are slowly moved together until conductance is achieved (Figure 1).

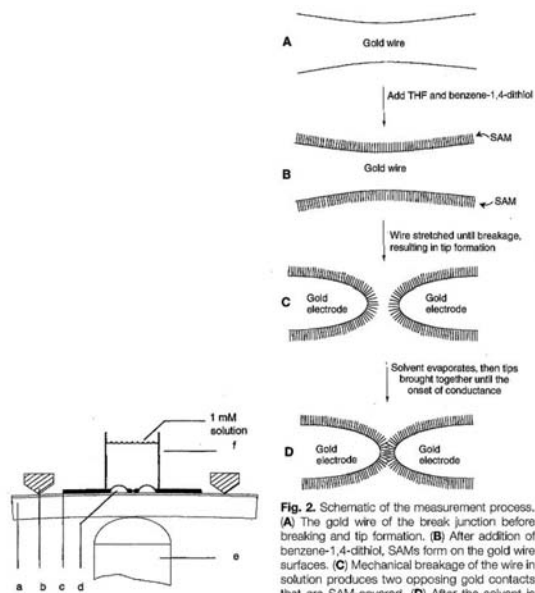


Fig. 1. A schematic of the MCB junction with (a) the binding beam, (b) the counter supports, (c) the notched gold wire, (d) the glue contacts, (e) the piezo element, and (f) the glass tube containing the solution.

Fig. 2. Schematic of the measurement process. (A) The gold wire of the break junction before breaking and tip formation. (B) After addition of benzene-1,4-dithiol, SAMs form on the gold wire surfaces. (C) Mechanical breakage of the wire in solution produces two opposing gold contacts that are SAM-covered. (D) After the solvent is evaporated, the gold contacts are slowly moved together until the onset of conductance is achieved. Steps (C) and (D) (without solution) can be repeated numerous times to test for reproducibility.

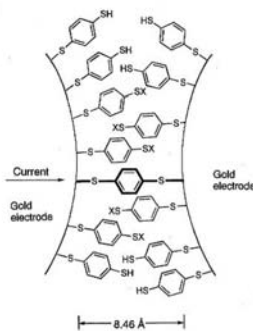


Fig. 3. A schematic of a benzene-1,4-dithiolate SAM between proximal gold electrodes formed in an MCB. The thiolate is normally H-terminated after deposition; end groups denoted as X can be either H or Au, with the Au potentially arising from a previous contact/retraction event. These molecules remain nearly perpendicular to the Au surface, making other molecular orientations unlikely (27).

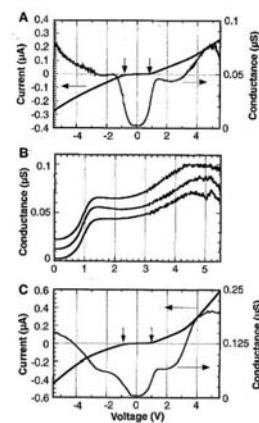


Fig. 4. (A) Typical I/V characteristics, which illustrate a gap of 0.7 V; and the first derivative $G(V)$, which shows a step-like structure. (B) Three independent $G(V)$ measurements, offset for clarity, illustrating the reproducibility of the conductance values. The measurements were made with the same MCB but for different retractions/contacts and thus different contact configurations. Offsets of 0.01 μS for the middle curve and 0.02 μS for the top curve are used for clarity. The first step for these three measurements gives values of 22.2, 22.2, and 22.7 megohm (top to bottom); the next step gives values of 12.5, 13.3, and 14.3 megohm. The middle curve is the same data as in (A). (C) An $I(V)$ and $G(V)$ measurement illustrating conductance values approximately twice the observed minimum conductance values. Resistances of ~ 14 megohm for the first step and 7.1 megohm (negative bias) and 5 megohm (positive bias) for the second step were measured.

Figures 1 through 4 from Reed *et al.* 1997.

Presumably, this happens exactly when atoms in the coating self-assemble into a first molecular bridge between the parabolically shaped electrodes. Figure 3 illustrates just how precarious a process this is: There is a lot going on in the space between the electrodes, and the experiment is to determine that the measured current is flowing through the single molecule and nowhere else. A first indication of the experiment's success was the fact that the distance of the electrodes when conductance is achieved agreed fairly closely with the calculated length of the single molecule that formed the bridge, namely roughly 8 angstrom. While the authors do not dwell on the amount of current and whether or not it exceeds or agrees with theoretical expectations, they wish to establish that the observed current flows through a single molecule even though they have no direct means of observing the number of molecules that bridge the electrodes. Their paper is based on four measurements, three of which showing very similar values for maximal resistance or minimal conductance (Fig. 4B and A), while the fourth shows approximately half of the resistance and twice the current flow (Fig. 4C). The first three measurements are taken to establish the high reproducibility of the minimum conductance level which, according to Reed and Tour "implies that the number of active molecules could be as few as one". While this is, so to speak, the carefully worded official conclusion of their paper, their statistical interpretation of the fourth measurement suggests a stronger claim.

Figure 4C shows [...] measurements of one singular observation that gave resistances that were approximately half (that is, 0.5) the value of the maximum resistances (using averages, 0.63 and 0.45, respectively). This suggests a configuration of two non-interacting self-assembled molecules in parallel, substantiating the idea that the threshold resistance of a single molecule is ~ 22 megaohm [...]. (Reed *et al.* 1997, p. 253)

In other words, if one consistently observes a certain amount of current flow and occasionally double that amount, this would seem to confirm the presence of normally one and occasionally two active molecules. In contrast, if there were always anywhere between 5 and 15 active molecules, one would get less consistent results and more smoothly distributed measurements.

What Reed and Tour do not state in this paper becomes apparent in their June 2000 *Scientific American* article. Here, the caption of an image of a single benzenedithiol molecule acting as a conductor mentions the “relatively large current flow” (Reed & Tour 2000, p. 90). They elaborate as follows in the body of the text (p. 91):

It turned out that the resistance of the molecule was in the range of tens of millions of ohms. The Yale researchers also found that the molecule could sustain a current of about 0.2 microampere at 5 volts – which meant that the molecule could channel through itself roughly a million million (10^{12}) electrons per second. The number is impressive – all the more so in light of the fact that the electrons can pass through the molecule only in single file (one at a time). The magnitude of the current was far larger than would be expected from simple calculations of the power dissipated in a molecule [...]

What Reed and Tour call an “impressive” finding has generated incredulity among some of their skeptical peers. To them, the magnitude of the current would indicate that it is not passing through a single molecule. Such a large current, they might argue, would destroy the molecule just as too large a current will melt a wire. This holds especially for the place of contact where the current is supposed to leave the bulk material and enter a single atom. Reed and Tour recognize this and indicate that their finding is consistent only with a particular account of this process:

The magnitude of the current was far larger than would be expected from simple calculations of the power dissipated in a molecule, leading to the conclusion that the electrons traveled through the molecule without generating heat by interacting or colliding.

We are thus confronted with a classical dilemma – indeed, a text-book dilemma for philosophers of science – where one has to either impeach the integrity of an experimental result or revise one’s theory, for example by adopting Reed and Tour’s somewhat off-handed conjecture.⁵ A dilemma like this may well prompt an urgent call for clarification such as Stan Williams’s insistence that we must solve the problem of how electrons go through molecules.

All of this adds up to a more or less plausible story about the theoretical interest of Reed and Tour’s researches and their perhaps startling conclusion. Indeed, this story would lead one to expect that their papers in *Science* or *Scientific American* might have appeared under the heading “New finding establishes that electrons travel through molecules without interacting or colliding”. However, this is not how their researches were presented, received, or discussed by the scientific community.

Stan Williams is a senior researcher for Hewlett Packard. He does not distinguish between molecular electronics and molecular computing but confronts major problems in the pursuit of Moore’s law and ever faster, ever smaller computers. He emphasizes that the size-regime of smaller computer chips gives rise to quantum tunneling effects and power leakage, which makes it harder to scale down, leading, for example, to silicon melting. In particular, electron/photon coupling may be responsible for anomalies that need to be understood before he can build the next generation of computers. It is in this context and in view of drastic current changes at low voltages that he calls for an account of how electrons go through molecules (Williams 2002). And this provides the second kind of answer to the question about the nature of Williams’s problem, this one belonging to NanoTechnoScience

as a place-oriented rather than issue-driven enterprise. Along the same lines, when electrical engineer Mark Reed and chemist Jim Tour call “impressive” the number of electrons that pass through their single organic molecule, this is not because of its more or less profound impact on our understanding of nature but because it underwrites their conviction that single molecules can serve as wires in nanoelectronic circuitry. Accordingly, their *Scientific American* article is entitled “Computing with Molecules”, their conclusion that electrons pass through molecules without generating heat appears almost as an afterthought or a mere aside, and the previously quoted caption reads in full:

The relatively large current flow bodes well for the ability of molecular devices to work with more conventional electronics. (Reed & Tour 2000, p. 90)⁶

3. Fundamental Questions

While there has been much work on in recent years on molecular conductance and electron transport (Friend & Reed 2004), it does not consist in a debate of theoretically significant claims. It furthers a common project in piecemeal fashion rather than explicitly evaluate a particular position or hypothesis. Prominent candidates for such evaluation would be Reed and Tour’s claim that they measured current passing through a single molecule or their theoretical conclusion that electrons pass through molecules without interacting or colliding. However, skepticism does not issue in a controversy about the Reed-Tour hypothesis with an aim towards its acceptance or rejection by the scientific community at large. Instead, it is deeply embedded or hidden in investigations that actually build upon their researches as, for example, in statements like these:

Pioneering single-molecule experiments were performed by Reed *et al.* and later by Kergueris *et al.* The nonlinear current-voltage characteristics (*IV*s) found by these groups were attributed to the electronic molecular levels. However, several fundamental questions remain unsolved: Are the *IV*s really arising from transport through single molecules? Is the electronic flow rather wave-like (coherent transport picture), or is a one-by-one electron transport scenario more suitable (hopping picture)? (Weber *et al.* 2002, p. 114)

This statement is taken from the 2002 paper “Electronic Transport through Single Conjugated Molecules” by a research group at the Institute for Nanotechnology of the Forschungszentrum Karlsruhe. The group around physicist Heiko Weber and chemist Marcel Mayor distinguishes itself from its counterparts in the United States by insisting on the fundamental character of these questions, that is, by pursuing molecular electronics as basic research. Their paper therefore begins by duly noting the technological significance of this research as secondary to theoretical considerations.

How does current flow through single organic molecules? This question plays an all-important role in the field of molecular electronics, a field which is not only a fascinating topic of basic research, but may have great potential for future data processing technologies. (Weber *et al.* 2002, p. 113)

Clearly, the thesis about NanoTechnoScience as a place-oriented rather than issue-driven enterprise seems to be contradicted by this statement.⁷ This paper therefore warrants a more detailed analysis. In particular, one might ask just how it represents basic research in the field of molecular electronics. Closer analysis will show that the Karlsruhe group conceptualizes its research in theoretical terms. It also indicates, however, that this self-understanding remains largely implicit and that the paper constitutes an explicit nanoscientific advance in that the research group is demonstrating the considerable facility it has

achieved at handling molecular break junctions experimentally as well as conceptually. Accordingly, their paper offers two versions of its conclusion: the first establishes the conclusion explicitly as a technoscientific contribution to nanoscale research, another flags it implicitly for its possible significance for open-ended theoretical discussion.

A first indication of this balancing act appears immediately after the just quoted opening. While the oldest paper cited by Reed and Tour in 1997 was one of Reed's first experimental papers on the topic from 1988, Weber *et al.* follow a 2000 review article in *Nature* and cite "first theoretical considerations" from 1974. However, the considerations in that 1974 article are "theoretical" only in the sense that the authors provided calculations where measurements were not yet available (Aviram and Ratner 1974).⁸ Just like the review article from 2000, its horizon of interest does not reach beyond electronic circuitry. Indeed, the review article casts the history of these researches in terms of manipulative access to the nanoscale and to the dictates of Moore's laws:

The first proposals for molecular electronics appeared in the 1970s, but it is only the appearance of a number of scientific and economic developments that has allowed the recent resurgence of activity in this field. Crucial are advances in nanoscale science and technology, such as new fabrication methods and probes, which enable individual molecules or small numbers of molecules to be connected in a controlled manner into actual test devices. The driving force behind this research is clearly the need for suitable alternative technologies to Si-based CMOS, which is expected to reach its limitations in 10-20 years. (Joachim *et al.* 2000, p. 547)

Just like the Karlsruhe group, this review article adopts a rather diffident view of Reed and Tour's findings, a view that neither criticizes nor endorses them.

Break junctions involve the gentle fracture of a microfabricated electrode in its centre by mechanical deformation while measuring the resistance of the metallic wire junction. Its application to single molecules is difficult because a liquid evaporation step is required after formation of the junction, and the conformation and the exact number of interconnected molecules remain essentially inaccessible. Nevertheless, measurements have provided estimates of $R = 22\text{M}\Omega$ ($T = 5.9 \times 10^{-4}$) for a junction containing molecule **9** shown in Fig. 1a. (Joachim *et al.* 2000, pp. 542-543)⁹

Weber *et al.* do not cite any discussion, principled considerations, or empirical evidence to explain why Reed and Tour's "pioneering single-molecule experiments" leave them unpersuaded as to whether they really involved single molecules. Their critique of Reed and Tour is only implicit in their own proposal to "unambiguously identify the *I*'s as current through our sample molecule" (Weber *et al.* 2002, p. 114). It serves as further testimony to the ambivalence of the Karlsruhe approach that its theoretical interests are contained in this largely implicit critique, while their own solution to the problem adopts a similar, albeit more persuasive strategy as did their counterparts in the United States.

Weber *et al.*'s implicit critique of Reed and Tour is that they were guided by the mental model of classical electronic circuitry.¹⁰ Instead of asking a question about nature, Reed and Tour appear to already be designing a molecular computer. They seem less interested in understanding molecules than in forging the smallest possible wire out of a molecule. They were satisfied as soon as they observed an onset of conductance that they could plausibly attribute to the formation of a molecular connection between the electrodes. Accordingly, they didn't consider it necessary to carefully differentiate their observed current flow from the surrounding and initial conditions, for example by investigating bonding configurations and contact geometry¹¹ or by assessing the contribution of the electric field's bias voltage (Weber *et al.* 2002, pp. 120-123). Moreover, after they satisfied themselves experimentally that they had obtained a molecular wire, Reed and Tour offer an apparently *ad hoc* theoretical model for electron transport.

This implicit critique of Reed and Tour by the Karlsruhe group is contained in its adoption of a more principled theoretical stance. Weber and Mayor set out to remedy these deficiencies and thus to improve and amend Reed and Tour's work. They do so experimentally and by modeling the experimental set up. Both parts of their argument advance the same implicit conclusion: While Reed and Tour were interested to show that current was flowing through an individual, *i.e.*, a single molecule, Weber *et al.* establish that the individuality of the molecule, *i.e.*, the molecule qua molecule with a particular shape and structure makes a difference to current flow. In effect, they work towards the non-trivial conclusion that "the chemical [rather than physical] nature of the junction is crucial and predominant for the conductance properties of a metal-molecule-metal junction" (Weber *et al.* 2002, p. 124).

Experimentally, the Karlsruhe group advances this conclusion by offering an improved variant of Reed and Tour's experiment. The rather limited statistical interpretation of that original experiment did not exclude the possibility that in all the observations, more than one molecule was active,¹² nor did it offer effective statistical controls (but see Reed and Tour 1997, 253). The paper of the Karlsruhe group is based on a greater number of experimental observations involving two molecules that differ mainly in their spatial symmetries. The symmetric molecules produced symmetric current-voltage curves, the asymmetric molecules asymmetric ones, their peak sometimes offset in a positive and sometimes in a negative direction. This affords a more sophisticated version of Reed and Tour's statistical argument. Weber *et al.* offer 5 observations that, taken together, still "do not give an unequivocal proof, but strongly indicate that we are indeed sensitive to single molecules". In other words, Weber *et al.* do not claim that their and, by implication, Reed and Tour's molecular junctions do consist of single molecules. They merely argue that their data is statistically sensitive to the individuality of molecules. This is best exemplified by the fourth of their five observations:

For the asymmetric molecule, the spectrum appears either with a peak at $U \approx -(0.35 \pm 0.1)$ V or a similar peak at positive bias. This discrete asymmetric behaviour indicates that a discrete set of molecules, which is randomly oriented, most probably a single one contributes. A larger set of randomly oriented asymmetric molecules would average out the asymmetry, a fact that has never been observed. (Weber *et al.* 2002, p. 118)¹³

The experimental part of the Karlsruhe paper thus appears on the one hand as a mere extension of Reed and Tour's approach. Five years later, one might say, the production and experimental control of molecular junctions has improved. What was once considered a precarious procedure has now been routinized. A greater facility to vary the experiment also provides a regime of improved assessment and control of the experimental observations. This similarity between the two research groups in terms of argument and approach tends to disguise the difference in their orientations. This difference is exemplified firstly by the apparent diffidence of the Karlsruhe researchers as to whether or not they are looking at a wire consisting of a single molecule and secondly by their pronounced interest in the chemical nature of the observed conductance patterns.

An analogous account can be provided for the theoretical part of the Karlsruhe paper. It overtly continues where others leave off. At the same time it questions Reed and Tour's approach by conceptually reframing the issue. Reed and Tour referred to transport models only to show that their findings are physically consistent with physical and chemical background knowledge. In contrast, the Karlsruhe researchers model the onset of conductance in purely quantum chemical terms. Without reference to "elaborate", physically derived "theoretical transport models" (Weber *et al.* 2002, pp. 124, 123), Weber *et al.* exhibit the chemical sensitivities of the entire experimental set-up. They model it as a single super-molecule

that includes the electrodes as clusters of gold atoms. The sensitivities of interest are the architectural features of that super-molecule – spatial symmetry, in particular – and the onset of conductivity which moves the molecule from an insulating to a conducting regime.¹⁴

This difference in approach is underwritten by entirely different, indeed incommensurable ways of using of the term ‘molecule.’ According to chemical usage, a compound of an organic molecule and metal atoms involves complex bonding. Depending on whether ionogenic or covalent bonds prevail, these compounds are referred to as complexes or as molecules (in the case of purely ionogenic bonds one does not customarily speak of molecules at all). In the case of the gold atoms and the organic molecule that serves as the wire, the transfer of charge produces an overlapping of their orbitals. By definition, therefore, covalent bonds prevail in this case and these bonds create a new molecule that includes the gold atoms together with the inserted organic molecule. In these chemical terms, then, one can no longer refer to the (organic) molecule by itself when that molecule shares orbitals with the gold atoms in the transfer of charge. Accordingly, that organic molecule no longer exists as a discrete entity or as a wire that connects the gold atoms of supposedly separate electrodes. By treating the entire experimental set-up as a “supermolecule”, Weber and Mayor follow chemical usage as opposed to Reed and Tour.¹⁵

No theoretical difference could be greater than that between incommensurable approaches. And yet, the significance of this difference is not reflected at all in the paper by the Karlsruhe group. It implicitly claims, throughout, that the diversity of perspectives advances a common project. It therefore remains unclear even whether the choice of a different conceptualization constitutes a critique of Reed and Tour’s approach. Similarly, the paper by Weber *et al.* leaves open whether and how their qualitative use of pure quantum chemistry constrains the physical transport models which are, perhaps, too obviously shaped in the image of electronic circuitry.

For now, the only explicit conclusion that can be drawn from that single publication of the Karlsruhe group is that they are adding to the conceptual tool-box of molecular electronics (see also Tian *et al.* 1998, Di Ventra *et al.* 2002, etc.). Five years after Reed and Tour, researchers have expanded not only their experimental control of the phenomena but also their conceptual grasp. More and more abstract models are becoming available first to represent the phenomena and then to indicate where the phenomenological observations may yet be too crude (Di Ventra *et al.* 2002, pp. 192-194; Weber *et al.* 2002, p.122).

4. Revisiting the Thesis

Two distinct attitudes have now been identified, two approaches, perhaps styles of research in molecular electronics. Since one of them implicitly refers to a theoretical conception of basic science, is it really defensible to claim both for the thesis that nanoscale research is a place-oriented technoscience rather than issue-driven science? In conclusion, four considerations are offered in support of this claim.

The endeavor of contrasting the two research groups is caught up in a fundamental difficulty concerning the very notion of “technoscience”. This notion was introduced by Bruno Latour (1987) and Donna Haraway (1997) to mark a new stage in the development of science, namely the technological constitution of the objects of scientific research such as transgenic mice that are hybrids of nature and technology. However, as soon as this new era of technoscience was proclaimed, it became possible to consider all of experimental science as technoscience. Even a vacuum-pump or certain observational protocols, one might say, constitute the supposedly natural objects of scientific research technologically. While this appears to dissolve the novelty claimed for technoscience, this claim can be maintained on another level, namely at that of the self-understanding of science (Nordmann 2004b). Perhaps, all science has always been technoscience, but traditionally trained scien-

tists are only abandoning their traditional self-understanding in the contexts of nanoscience, the biomedical sciences and genetics, artificial intelligence research and robotics. Instead of seeking to humbly understand and explain a given nature, they now openly embrace the project of overhauling or transforming nature, of “Shaping the World Atom by Atom” (NSTC 1999, Nordmann 2004a). Thus, the difference between Reed and Tour on the one hand, and the Karlsruhe group on the other hand is not that one has a technoscientific orientation while the other adopts a theoretical stance. Both contribute to NanoTechnoScience. Reed and Tour do so openly while the Karlsruhe group still represents itself in terms of the traditional opposition between fundamental versus applied science and technology.¹⁶

Secondly, this paper has shown that the fundamental problem investigated by the Karlsruhe group presented itself not in the development of a quantum-chemical research program, but in the technoscientific pursuit of electronic circuitry made up of organic molecules. Similarly, their explicit contribution consists in the enhancement of experimental and conceptual control of molecular break junctions. In contrast, their ultimate interest in the specifically chemical nature of this junction appears as an oblique gesture towards an ongoing and open-ended discussion of a fundamental question that stands in the tradition of natural philosophy. Indeed, if their focus had been on theoretical understanding, they could not sustain their implicit claim that incommensurable perspectives can advance a common project. The incommensurability of concepts does not matter precisely because the various perspectives are oriented toward the acknowledged significance of molecular electronics and the interest to achieve electron transport in some kind of circuitry.

Thirdly, this disjunction between the implicit and explicit dimensions of the argument by Weber *et al.* exposes the missing middle ground. It is significant, I believe, that between the finite demonstration of achievement and an obliquely philosophical gesture there is no overt critical engagement of a hypothesis or theory. Reed and Tour did not place the ball in the court of public opinion. Instead, the ball remained in their court and the scientific community adopted a wait-and-see attitude: “If they think they have mono-molecular-wires, let’s see where this gets them; they can win us over by demonstrating a more targeted conceptual, experimental, technical control of the phenomenon. They can present better and better arguments in the form of better and better molecular wires and, ultimately, devices.” To be sure, as in any age of exploration and the claiming of new territory, many will not wait and see what Reed and Tour might achieve. Instead, they will themselves attempt to get there first. While such efforts build upon Reed and Tour’s experiments, they can do so without buying into or bothering to contradict any particulars of their account. The technoscientific occupation and appropriation of the nanoscale thus differs from standard conceptions of theoretical science not only in the orientation towards its subject-matter but also in the interaction among scientists: The critical aspect or “organized skepticism” of public science takes the backseat to the staking-out and entrenchment of private claims.¹⁷

Finally, Joachim Schummer has pointed out that the reasons why experiments are done in chemistry differ from those in physics. They do not serve to test theories or confirm hypotheses. Instead, chemical experiments serve the purposes of “(1) performing chemical reactions in order to form new products [...] (2) investigating various properties of the new products” (Schummer 2004a, p. 400). While it may appear at first that Reed and Tour’s approach fits this description, the insistence by the Karlsruhe group on an element of basic science points to a middle ground here, too. Research that aims for conceptual as well as physical mastery of a certain territory, domain, or size regime, is interested neither in theory nor merely in novel devices and substances. It is exploratory research, literally speaking, where settlement follows upon exploration and new practices, perhaps a new culture is founded.

Notes

- ¹ The metaphor of inner and outer space was introduced by Sean Howard (2002) in the context of his discussion of military applications of nanotechnology and the need for an “inner space treaty”.
- ² This definition was adapted from a presentation by Cathy Murphy at the “Reading Nanoscience” workshop, University of South Carolina, August 2002.
- ³ An “issue-driven” scientific research programme is oriented towards “problems” in the sense discussed by Kuhn (where a paradigm defines the problems of research and where science progresses by solving the outstanding problems or puzzles). It might also be oriented towards a problem like the cure of cancer or the creation of artificial intelligence. As a whole, neither of this holds for Nanoscience. Instead, the “place-orientation” refers to the claiming and inhabiting of a space. Learning to move around, to act and be productive in this space is no easy task but does not involve “problems” in the previously mentioned senses.
- ⁴ The recent exchange of letters between Richard Smalley and Eric Drexler serves only to highlight this absence of a sustained scientific debate (Baum 2003).
- ⁵ It is possible, of course, that the dilemma evaporates in light of adequate background knowledge. Mark Reed suggests that “those who seemed surprised by the magnitude had not thought critically about comparing this to the quantum of conductance, $2e^{2/h}$ ” (personal communication, compare note 10 below). Compare also Di Ventra *et al.* 2002, 195: “This suggests that molecular wires can operate at very large fields without current-induced breakdown. Also, the molecular device at hand [the one from Reed and Tour’s 1997 paper] can carry current densities larger than 10^9 A/cm², *i.e.*, much larger than those allowed in conventional interconnects.” To be sure, the relevant question of electron transport does not concern simply the current carrying capacity of the molecule but what happens at the place of contact.
- ⁶ Compare note 10 below. – Jim Tour emphasizes that the high rate of publication recommends the motto “interpretations change while facts remain”. Accordingly, this reconstruction of their work attributes too much deliberate interpretive work to their experimental researches. Tour recounts that a suggestion on the mechanism was requested as a condition of publication by the editors of *Science* for a related paper (personal communication). In this paper, Tour and his collaborators introduced the potential mechanism in a highly qualified manner as “a candidate mechanism”. While they call for further theoretical work, this is justified in strongly application-oriented terms: “Theory to explain the temperature dependencies and future experimental work to examine frequency and optical response should elucidate the transport mechanisms that would further permit engineering of device performance for room-temperature operation.” They add a footnote to this which appears to render this theoretical work redundant: “Since submission of the manuscript, room-temperature [performance] has been observed in a similar molecule” (Chen *et al.* 1999, 1551).
- ⁷ Indeed, the Karlsruhe group’s emphasis on basic research might also suggest that the thesis of this paper is not about nanoscience at all, but rather about a cultural difference between the pragmatic orientation of nanoscale research in the United States as opposed to the traditional orientation of publicly funded research in Germany. Similarly, it could also be a thesis about interdisciplinary collaborations between physics and chemistry in contrast to those between electrical engineering and chemistry. A single case study cannot decide among these various theses. In the end, the notion of place-oriented NanoTech-noScience requires evidence from a variety of sources.
- ⁸ It calculates I - V characteristics “of a molecular rectifier including direct electrode to electrode tunneling” which agree rather well with those obtained by Reed and Tour 1997 and by Weber *et al.* 2002, 118, though it does not anticipate voltages nearly as high. This agreement is communicated visually through the likeness of their diagrams. See Aviram and Ratner 1974, 282, Weber *et al.* 2002, 116 (Figs. 2 and 3), Reed and Tour 1997, 253, also Di Ventra *et al.* 2002, 193. This likeness of diagrams may have been the downfall of Jan Henrik Schön who may have taken these diagrams for icons signifying current flow rather than records of particular experimental measurements.
- ⁹ Here is another example of an elliptic critique of Reed and Tour: “Due to the lack of any specific experimental information, we assume that a single molecule makes contact to both right and left leads as shown in Fig. 1, even though this configuration might not be the actual experimental one” (Di Ventra *et al.* 2002, 192). This article goes on to establish a closer fit between (improved) experimental observations and theoretical models.
- ¹⁰ Compare Michael Gorman’s discussion of mental models as a means of structuring nanoscale research (Gorman 2002). Indeed, it is intriguing to ask what mental model is operative in Jim Tour’s reminiscence: “Current/voltage responses were recorded for a single molecule bridging the gap. Remarkably, 0.1 microamps current could be recorded through a single molecule. However, few or none of those 10^{12} electrons per second were colliding with the nuclei of the molecule, hence all the heat was dissipated in the contact. Note that the mean free path of an electron in a metal is hundreds of angstroms; hence, it is not surprising that collisions did not take place within the small molecule. Most importantly, since most computing in-

- struments operate on microamps of current, the viability of molecular electronics became all the more tangible” (Tour 2003, 238).
- ¹¹ “... it becomes evident that the type of bridging as well as the proximity of gold atoms to the molecular π -system has significant influence on the electronic structure and on electron transport” (Weber *et al.* 2002, 122).
- ¹² In particular, it is hardly credible that their results were based on exactly and no more than four measurements.
- ¹³ According to Weber (in conversation), the required discrete set of molecules should be no more than a handful, certainly less than ten.
- ¹⁴ This transition is marked by the breakdown of the theoretical model that was adopted for an analysis of the insulating regime. “In the insulating regime, no current is flowing and the method [an equilibrium method for investigating the electric field in terms of external electric potentials for the two clusters of gold atoms] is justified to a good approximation. In the conducting regime, different things happen in the experiment and in our model: whereas in the experiment a current is flowing, within our computation the molecule will screen the external potential by a static charge transfer from one gold cluster to the opposite. However, both effects are obviously closely related to conductivity” (Weber *et al.* 2002, 123).
- ¹⁵ I owe this analysis to Joachim Schummer (in conversation). This case study resonates with Schummer’s contention that any discipline constitutes its objects through its theoretical perspective, its questions, problems and issues. Schummer’s observation raises a skeptical doubt regarding the possibility of a truly interdisciplinary nanoscience. If interdisciplinarity consists primarily in the abandonment, loosening, or black-boxing of the theoretical frameworks of the contributing disciplines, how then is an interdisciplinary nanoscience to arrive at “common objects” (Schummer 2004b, this volume)? Only the development of a specifically nanoscientific theoretical perspective would provide a solution. While George Khushf (2004, this volume) envisions such a new disciplinary perspective, there appears to be little pressure or movement toward its development.
- ¹⁶ This is not to say, of course, that such self-ascriptions are inconsequential for the development of research. To acknowledge this is easy for Kantian, Peircean, or Wittgensteinian philosophers of science, for Weberian or Mertonian sociologists of scientific knowledge. It is far more difficult to acknowledge for all those who are interested in the material culture of (techno)science and therefore tend to deny the historical influence or material efficacy of concepts, ideas, theories, and beliefs.
- ¹⁷ To be sure, Popper’s and Merton’s view of science as organized skepticism may have become obsolete even before nanoscience came along. The suppression of theoretical disagreement in the advancement of an application oriented research agenda may characterize many scientific publications (compare Carrier 2004). In this case, one might say that nanoscience helps foreground this technoscientific development.

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Societal Dimensions of Nanotechnology as a Trading Zone: Results from a Pilot Project

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Abstract: If nanotechnology is to represent social as well as technological progress, societal dimensions need to be incorporated from the outset. The best way to do this is to create interdisciplinary trading zones among scientists, engineers, ethicists and social scientists. This chapter describes a collaboration between a materials scientist and a psychologist, who jointly supervised a graduate student as she did cutting-edge scientific research directed towards a socially beneficial outcome.

Productive work on societal implications needs to be engaged with the research from the start. Ethicists need to go into the lab to understand what's possible. Scientists and engineers need to engage with humanists to start thinking about this aspect of their work. Only thus, working together in dialog, will we make genuine progress on the societal and ethical issues that nanotechnology poses.
(Davis Baird, in testimony before the Senate Committee on Commerce, Science and Transportation, May 1, 2003)

1. Models of Technology Development

There are probably as many models of technological development as there are authors that have tackled the topic (Hughes 1987, Pacey 1993), but for purposes of our discussion, three will illustrate the range of possibilities (see Figure 1).

The Technological Determinism model, or Chicago World's Fair motto, embodies the classic 'throw it over the wall to society' approach to engineering, immortalized in the Tom Lehrer song about Werner von Braun: "Once rockets are up, who cares where they come down? That's not my department, says Werner von Braun". During the GMO debate, the so-called Terminator trait was seen by the Rural Agricultural Foundation International as an example of this sort of technological determinism. Farmers would be forced to buy seeds that would be viable for only one generation; many, especially in the developing world, considered this a violation of their fundamental right to re-use seed they had purchased (Gorman *et al.* 2001).

The second model, Social Goals Drive Research, was suggested, but not necessarily endorsed, by Henry Etzkowitz as an alternative to Technological Determinism (Etzkowitz 2001). Here society dictates the direction of research. Advocates of GMOs thought they were following this strategy. What could be wrong with a suite of products that promised to feed the world's growing population while reducing the need for pesticides and herbicides (Magretta 1997)?

Although technological determinism and social goals appear to be very different approaches to directing scientific discovery, they share a common problem. In each model, one group or community is seeking to dictate to others, *e.g.* the engineers and scientists imposing their view of nanotechnology on the rest of society or a non-governmental or-

ganization like ETC (Erosion, Technology, Concentration) imposing a moratorium on scientists and engineers (Mnyusiwalla *et al.* 2003). The idea of forcing people to conform to any technology is clearly wrong; indeed, that is one of the problems experienced by companies like Monsanto that try to make a profit from GMOs. Studies have shown this to be a common trait – socio-technical networks dominated by a single group are better for control than innovation, and they are certainly not democratic (Gorman & Mehalik 2002, Gorman 2002, Scott 1998).

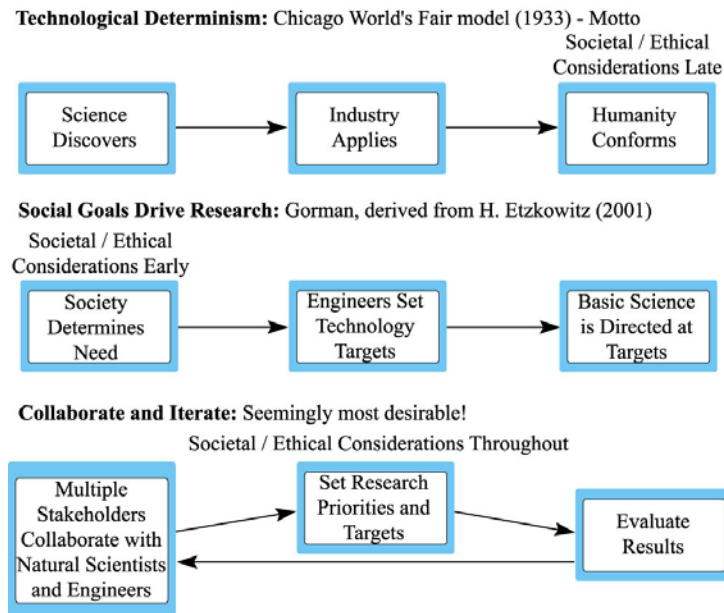


Figure 1: Three models for the development of new technologies.

In contrast, the pilot project described in this paper follows the ‘collaborate and iterate’ approach in which a social psychologist (Gorman) collaborates with a materials scientist (Groves), sharing a graduate student. This project is consistent with Davis Baird’s advice that a genuine dialog between scientists and humanists includes ‘ethicists going into the lab’, as Gorman is also on the board of the University of Virginia’s Institute for Practical Ethics.

Thomas Kuhn argued that normal science is conducted within paradigms, and that deep, meaningful communication across paradigms is nearly impossible – participants in these different research cultures literally talk past one another (Kuhn 1962). This problem of ‘incommensurability’, to use Kuhn’s terms, occurs *within* disciplines like physics.¹ Imagine how much larger it is *across* disciplines as diverse as psychology, ethics and materials science!

Peter Galison noted that physicists and engineers have collaborated on the creation of technological systems like radar and particle detectors (Galison 1997). To explain how they got around the problem of incommensurability, Galison invoked the metaphor of a *trading zone*. Cultures with radically different epistemologies can still trade by developing creoles, or reduced common languages.

Trading zones are not a mere metaphor. Jet Propulsion Laboratory (JPL) engineers have used the term “trade” to refer to negotiations over design options (Lambert & Shaw 2002). Because these trades involved exchanges of information and perspectives, they are not the same as trade-offs. For example, on the Mars Rover, engineers and scientists had to conduct a series of trades to arrive at a landing site that was both satisfactory from a scientific standpoint and feasible from an engineering one.

In order for developments in nanotechnology to represent social and scientific progress, engineers, natural scientists, social scientists, and ethicists will have to develop their own dialect, a kind of ‘nanocajun’², that allows them to communicate effectively. Nanotechnology trading zones such as these can be multidisciplinary – in which there is a division of labor between the ethicists and scientists and the groups develop a specialized dialect, a creole, to coordinate activity, or they can be genuinely interdisciplinary – with all participants engaging in discussions of all aspects of the research and development activity.

The goal of trading zones is the sharing of expertise. Collins and Evans distinguish between three *levels of shared expertise* (Collins & Evans 2002):

1. *None* – This level is akin to Kuhn’s incommensurability. Those in the old paradigm supposedly cannot communicate effectively with those in the new, even though they are working in the same field – because the world-views are incommensurable. The same kind of incommensurability could potentially occur between different disciplinary specialties and cultures.
2. *Interactional* – This level involves knowing less than an expert in another area, but enough to communicate. A good example is a problem that emerged early on in the application of magnetic resonant imaging (MRI). Between 1987 and 1990 “it became fashionable for physicians to reduce the rather long MR (magnetic resonance) imaging times by using anisotropically shaped (*i.e.*, non-square) imaging pixels in studies of the spine. As it turned out, this resulted in a prominent dark line appearing within the spinal cord. The dark line was a Gibbs ringing artifact. Unfortunately, clinicians, not aware of this kind of artifact – for not being conversant with the mathematics used to transform the instrument signal into an image – at times interpreted this artifact as a disease process: a fluid filled lesion known as a ‘syrinx’ requiring aggressive medical treatment” (Baird & Cohen 1999, p. 238). An interactional expert who bridged medicine and physics detected the problem and solved it.
3. *Contributing* – This level involves experts jointly contributing to an area of inquiry. An example is the way in which Walter Alvarez, a geologist, brought in his father Luis a physicist, and the two jointly made a significant contribution to paleontology: the asteroid explanation for the extinction of the dinosaurs (Alvarez 1997).

These three kinds of sharing potentially create three kinds of trading zones.

1. There is no sharing of expertise, so experts do not really trade; they just throw disciplinary solutions ‘over the wall’ to other participants across an incommensurable gulf.
2. Interactional expertise and the use of a creole partially circumvent incommensurability, leading to the kind of trading noted by Galison on radar, Lambert on the Mars rover, and Baird & Cohen on MRI.
3. Contributing expertise creates the possibility of a new paradigm, like the asteroid theory of dinosaur extinction. This kind of sharing indicates that incommensurability is partly an attitude. Experts who are working on a cutting-edge problem can share conceptual frameworks, if they are willing to see that their paradigm is a useful comprehensive framework that can be transcended, not a reality.

Every emerging technological system raises questions about values. What kind of future are we building with GMOs? Europeans, at least, have rejected a future in which they will have no choice – they will have to eat genetically-modified organisms. What kind of future are we building with nanotechnology? One in which a few countries – like the U.S. – will create a new generation of supersoldiers that will keep them ahead of the rest of the world? Or one in which nanotechnology will help solve enduring problems like the absence of clean water, safe food and security for much of the world?

If trading zones around nanotechnology are going to expand to include societal dimensions at a deep level, then social scientists, ethicists, scientists and engineers will have to jointly contribute to new research paradigms. This kind of interdisciplinary collaboration

will require *moral imagination* (Werhane 1999). Kuhn discusses how paradigms are learned from textbook stories about how science is done. Similarly, moral imagination assumes our most important lessons come from stories which we turn into mental models for conduct (Johnson 1993). To practice moral imagination, each member of a truly interdisciplinary trading zone involving societal dimensions of nanotechnology will have to:

1. Become aware of her or his own mental models of the potential societal impacts of nanotechnology.
2. Learn about mental models of other members of the trading zone.
3. Imagine alternate directions for nanotechnology development, in light of these different views – evolving new mental models
4. Establish criteria and methods that can be used to evaluate the impact of these new alternatives.

Moral imagination creates the possibility of going from a multidisciplinary trading zone to a true interdisciplinary collaboration, in which relevant experts from ethics, social sciences, engineering and natural science understand enough of each others' disciplinary cultures to ensure that an emerging technology makes genuine social and technical progress (Gorman & Mehalik 2002). Other stakeholders need to be added to the trading zone as well. For example, Monsanto discovered that NGOs like Greenpeace and RAFI did not share the company's vision for GMOs, nor did European consumers. Could these stakeholders have been drawn into the trading zone, or are their views incommensurable with those of Monsanto? An attempt at mutual moral imagination might have failed, but would have been worth trying.

2. Pilot Research Activity

To see if these observations concerning trading zones, levels of expertise and moral imagination could be turned into reality, the authors obtained a grant from the National Science Foundation to set up a small trading zone, involving a social scientist (Gorman), a materials scientist (Groves), and a graduate student. Gorman and Groves co-advised the graduate student, and all members of the team were supposed to send reflective e-mails to an offsite cognitive scientist, Shrager, following a methodology he created for recording his own cognitive processes as he entered a new field (Shrager 2004). Shrager was not a part of the trading zone – he did not attend meetings nor contribute to the content of the discussion – but acted as an “unbiased” observer and recorder.

Team members tried to exercise moral imagination from the start, articulating and sharing their mental models. Figure 2 shows the process team members followed to find a specific research topic that would incorporate societal dimensions and allow the student to complete a degree in materials science. The funnel shape indicates the way the project starts with broad social concerns and ends up with a focused research project a Masters student could carry out. The line to the left of the funnel indicates continuous development of a creole. The line on the right indicates that the whole process is iterative – that work at a lower level could send the team back up to the top, re-opening discussion of project goals and motives.

The graduate student began by attempting to create a matrix that combined global problems with possible nano-engineered devices that could mitigate such ills. While mitigation of certain problems could involve development of a newly engineered sensor system (*e.g.* to detect a chemical, biological, or radiation hazard), other research might seek to develop systems for purification (*e.g.* of ground water for drinking, of manufacturing plant effluent, or of fluids used in medical treatments). Still other research might investigate newly engineered medications and delivery systems for improved human and biosphere health. In certain instances, it was unclear how nanotechnology might make a direct impact

upon a recognized problem – for example, gender disparity in science. Here indirect impacts were considered, *e.g.*, making certain that nanotechnology education made a special effort to reach out to groups traditionally under-represented in science and engineering. It was our hope that linking nanotechnology to societal benefits might provoke students' concerned with society to consider careers in science and engineering.

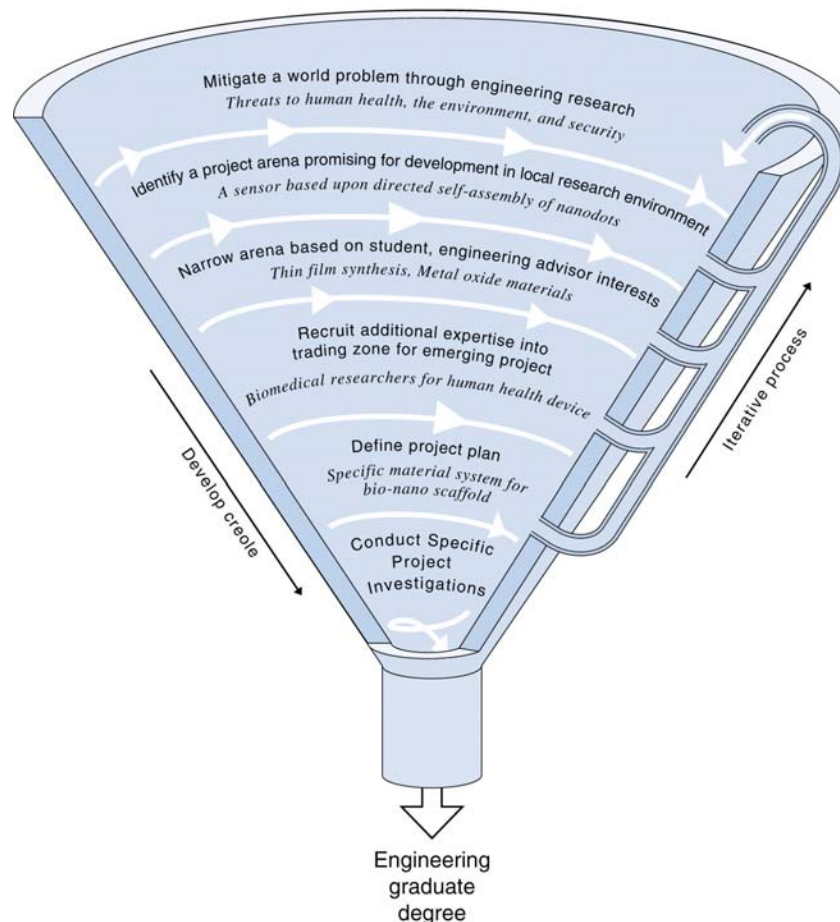


Figure 2: A process for developing graduate student thesis projects that incorporate societal and ethical considerations from the outset. The actual steps followed during the pilot project are included in italics beneath each step.

The student recognized that this matrix of global problems and possible links to nanotechnology could turn into a never-ending task. To constrain the task, the team considered expertise and resources available in the local research environment through the Center for Nanoscopic Materials Design, a National Science Foundation Materials Research Science and Engineering Center (MRSEC) established in 2000 to investigate the directed self-assembly of materials onto patterned surfaces. The members of this societal dimensions of nanotechnology project were already affiliated with the Center, and the Center's research, which focused faculty investigations on related aspects of the same scientific challenge, presented a naturally collaborative environment.

The Center for Nanoscopic Material Design studies directed self-assembly of nanodots, primarily in the silicon-germanium material system. Researchers have reported the formation of nanodots in semiconductor material systems in which a single crystal growth surface (*e.g.* a silicon substrate) and a depositing thin film (*e.g.* pure germanium) have the same crystal structure and a small lattice mismatch (Eaglesham & Cerullo 1990; Floro *et al.* 1990). The crystal structures of silicon and germanium (*i.e.* the arrangement of

their atoms) are both diamond cubic, and pure Ge has a lattice constant (*i.e.* interatomic spacing) 4.1% greater than that of pure Si. Under carefully selected growth conditions, germanium will form small dots of material on the silicon surface, *i.e.* nanodots. However, if nature is left to perform the process on its own, the dots generally appear at random locations across the substrate, *e.g.* like water droplets on the hood of a car. The Center is performing fundamental studies of how the growth location of dots can be specified to enable applications that demand dot placement in specific areas (Kammler *et al.* 2003, Du *et al.* in press). Applications under consideration by faculty affiliated with the Center range from next-generation computer architectures to biological scaffolds built upon arrays of nanodots.

Having chosen to couple the materials science aspects of this project to mitigation of one or more global problems, and having chosen to couple the work to the Center, the team found it necessary to introduce a third constraint to the research problem space. They agreed to allow the particular physical science research expertise of the materials science faculty team member (Groves) and the interests of the graduate student to narrow the field of focus. The team agreed to guide the research towards consideration of how the self-assembly of metal oxide nanodots might be directed (or guided) in a manner similar to the Center's work in the silicon-germanium system (Kammler *et al.*, 2003). Recent reports in the literature suggest that a number of metal oxide material systems demonstrate a nanodot self-assembly process similar to that observed in semiconductor systems (Y. Liang *et al.* 2001, Markworth *et al.* 2001). Export of the Kammler *et al.* results in Si-Ge to metal oxide systems through the efforts of this societal impact project could enable the creation of one or more engineered devices that can address global problems.

The student set a goal of identifying at least five global problems that could be linked to these metal oxide nanodots, then select one or two that could potentially be reduced to proof-of-concept. The literature suggested that metal oxides might be useful as a foundation for a bio-nano scaffold (Michel *et al.* 2001), that could be used to mitigate global problems like terrorism, disease, and pollution.

The team took advantage of the fact that a biomedical engineer associated with the Center was interested in how endothelial cells lining the artery wall at the blood tissue interface adapt to fluid mechanical forces that vary with time and place (Helmke & Davies 2002). The mechanisms by which these cells translate mechanical stimuli into biochemical signals are not well understood. Breakthroughs in this area could lead to increased understanding of progression of arteriosclerosis in arteries, tumor cell invasion and potentially contribute to wound healing.

We added the bio-medical engineer to our trading zone, discussing what kind of bio-nano scaffold would be most useful in this research. The student and advisors decided to focus on finding a combination of metal oxides that could bind a single endothelial cell in several places, allowing its response to fluid forces to be studied at the nano level. Such a binding process could be useful in a wide range of other bio-medical applications.

This pilot project demonstrated that it was possible for a social scientist and a material scientist to share a graduate student who would explicitly consider societal dimensions as part of her research project. She had to present her project to the other graduate students, and they were both interested and puzzled by the emphasis on social impacts – her presentation generated a lot of questions, some of which occurred in one-on-one follow up conversations. Members of the Center's advisory board noted that this student was the only one who had an understanding of societal and ethical issues, and recommended that other students be given more exposure.

As a result, the nanotechnology graduate students organized an internal workshop on societal and ethical implications of nanotechnology. Clearly, this project had positive ripple effects on the Center of which it was a part.

3. Developing a Metaphorical Language

In order to trade, members of this small zone had to develop a creole. At one level, this creole was simply agreeing on shared meanings for common terms. Gorman had to learn what ‘directed self-assembly’ meant, and why isoelectric points and lattice structures were important. Groves had to learn what trading zones and moral imagination meant. Shared understanding of these terms evolved through frequent explanations, collaborative poster sessions, and publications.

Gorman’s understanding of a term like ‘directed self-assembly’ was never as deep, as replete with examples, as Groves’, and vice-versa with respect to the concept of a trading zone. The student was learning both of these concepts for the first time, so she benefited from her advisors’ efforts to explain concepts to each other.

The team also had to develop a metaphoric language to talk about its goals (see Figure 3).

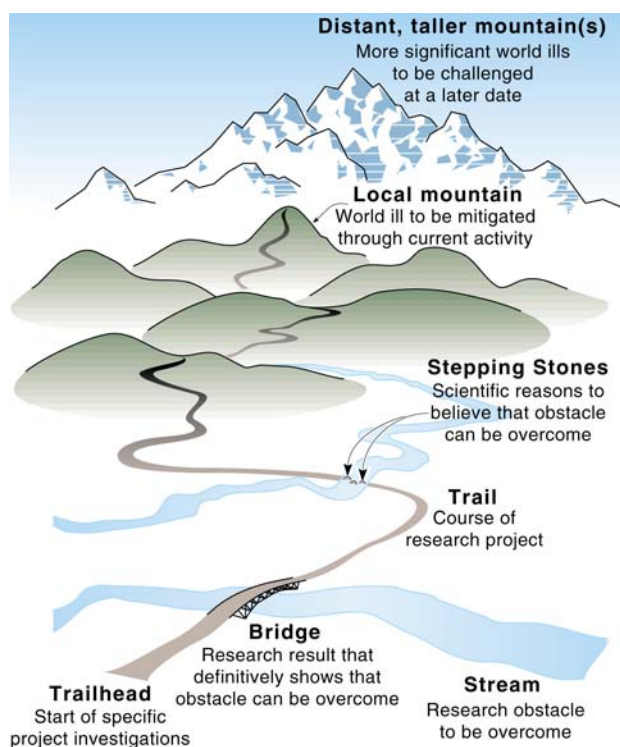


Figure 3: Metaphoric language used to relate societal dimensions to project goals

All three participants in the trading zone liked hiking, which is why this seemed a natural set of metaphors. Groves took the lead in creating the language. Distant mountains are major global problems and opportunities, like human health, climate change, the prevalence of warfare, and so on. Surfaces patterned at the micro- and nano-scale with biomaterials could be useful for a host of new applications ranging from the field of medicine (*e.g.*, fundamental research into protein-surface and cell-surface adhesion; optimized cell-culture substrates for biotechnology applications in tissue engineering; cell-based compact diagnostic systems; functional biochip surfaces for high sensitivity, high-throughput DNA/RNA and protein detection; and nanoarrays of single molecules for the study of molecular interactions) to homeland security (*e.g.*, detection of biological, chemical, and radiological terror agents) and environmental assessment (*e.g.* detection of pollutants in air and liquids).

Closer foothills represented specific aspects of these problems, like providing more data on toxins introduced into the environment either as a form of biological warfare or as

pollution. The graduate student needed to build a bridge that could be used by us or others to reach a range of local mountains, or foothills. This bridge would be part of a trail, but could also give access to other trails.

The bridge, in this case, corresponded to directing the deposition of one metal oxide on another in a way that would create positive or negative surface charge (determined by the oxide's inherent isoelectric point). When a biomolecule of opposite charge came into contact with the charged metal oxide surface, that biomolecule would adhere to the surface. Therefore, the foothills we were targeting involved gaining better understanding and control of cellular mechanisms – specifically, in our case, the flow of blood cells through an artery.

The existing methods for linking metal oxide surfaces with biomaterials require the use of slow and expensive methods to produce the biomaterial patterns. Photolithography and self-assembling monolayer (SAM) techniques require the creation of expensive masks and could be limited by the resolution of the photolithography equipment. These photolithographic and SAM techniques are also known, in some instances, to denature or degrade the previous biomaterial deposit. Microcontact printing requires the creation of stamps prior to pattern generation. Once created, these stamps can generally not be reconfigured. They are often difficult to align for large area printing, and they are known to transfer contaminants to the biosurface.

The students' bridge, therefore, provided an alternative to existing methods that might allow a bio-medical researcher to hold a single cell at several places, in order to study its function. This path could lead towards treatments for arteriosclerosis and other medical conditions.

4. Stages in the Acquisition of Shared Expertise

In order to participate in this trading zone, Gorman and Groves both found that they had to go through the three stages described by Collins and Evans (2002).

- None: Gorman began the project with a little general knowledge about nanotechnology, and no specific knowledge about the metal oxide domain. Similarly Groves did not recognize how to consider the project's activities within a trading zone that used a creole for effective communication.
- Interactional: After repeated conversations about research direction, and exchanges of e-mails, Gorman acquired a working knowledge of a few terms like directed self-assembly and a shakier knowledge of terms like isoelectric point and lattice mismatch. There was no hands-on experiential component to this knowledge; although Gorman observed the graduate student and others use equipment, he never actually used it himself. Groves soon became comfortable with the trading zone concept and the common reduced language of the group. Understanding of additional concepts like moral imagination continued to be somewhat superficial.
- Contributing: Gorman's goal was to acquire enough knowledge to participate in intelligent conversations about what experiment should be done next, and what results meant. Gorman's background in studies of scientific and technological thinking was helpful, here (Gorman 1992, Gorman *et al.* 2004). The other participants in the trading zone convinced Gorman to share in a patent application on the grounds that the project had taken a different direction because of his input. Groves sought to restructure his typical research process by including societal considerations at every step of the project. These considerations led to deep reflection upon issues such as patenting of the technology. If the goal of the technology development is societal benefit, how can this group best ensure that the technology developments of the project are put to

“good” use? The group finally decided that patenting provided them with greater control over the eventual end use of their discoveries.

5. Lessons Learned from this Experience

This pilot study indicated that a trading zone including a social scientist, a materials scientist and a materials science graduate student could be formed around nanotechnology and negotiate a scientific project that was explicitly aimed at what they thought of as a social goal: facilitating breakthroughs in the understanding and management of arteriosclerosis and related conditions. One problem with this pilot project is that there was no control group. It was impossible to run Groves and the student through a Masters project both with and without input from Gorman and see if there was a difference in terms of research approach and results. But it was obvious to Groves that there was a difference. No other project involved the explicit consideration of global problems, the metaphoric language and the persistent focus on the major research theme.

Additionally, the direction taken by the project was distinctly different because of the societal considerations. This unique direction led the group to confront scientific challenges and questions that otherwise would have remained unexplored. As Campbell notes, graduate research in the sciences is frequently opportunistic, with students pursuing multiple problems to see which ones will pan out (Campbell 2003). In this project, disappointing results were not used as excuses to abandon the project, because the bridge was so important we wanted to be certain that it could not be built before switching to another approach. The graduate student was never asked to achieve a positive result – that would constitute confirmation bias (Gorman 1992) – but was instead offered every opportunity and given every encouragement to thoroughly test whether specific metal oxides could be deposited in a way that produced the key differences in charge across the surface as needed for the bio-nano scaffold application.

In the end, the materials scientist felt that the result was better science. The social scientist learned more about the kinds of negotiations that go into achieving a Masters degree on the cutting edge of a new science, and also gained specific knowledge about a promising area of nanoscience. The graduate student at the very least caught a glimpse of how her thesis looked from social sciences and ethics perspectives, and this kind of perspective is important for any science student (Campbell 2003). But the student was necessarily focused more on the difficulties encountered in coursework and empirical work, and could only spend a limited amount of time doing research on global problems. Furthermore, she was immersed in a graduate science culture where no one else discussed these issues unless she brought them up.

A logical follow-up to this pilot study is one in which science students are paired with a social sciences or ethics student working with them on the same topic. If nothing else, such research and training experiences would help eliminate the problem of compartmentalization, in which scientists view their research activities, and engineers their design processes, as value-free (Gorman *et al.* 2000). Not every scientist and engineer needs to engage in a collaboration of this sort, but it is recommended for those working on the cutting edge in areas where society has provided significant funding in anticipation of social benefits.

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Notes

- ¹ Kuhn's work is controversial, and not everyone agrees on the extent of the problem of incommensurability, or on the nature of a paradigm. See Giere 1992, for a good overview of the issues, and examples from controversies like plate tectonics.
- ² The term nanocajun was suggested by an unknown member of the audience at a paper Gorman gave on converging technologies and trading zones at UCLA on February 6, 2003.

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Nanoscale Technology: A Two-Sided Challenge for Interpretations of Quantum Mechanics

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Abstract. In this contribution I consider the consequences of using quantum mechanics in nanoscale technology. I argue that this use leads to a problem that poses a two-sided challenge for interpretations of quantum mechanics. Firstly I present the problem: engineers typically ascribe technical functions to artifacts; function ascriptions imply particular physical descriptions of artifacts, and quantum mechanics sometimes fails to reproduce these descriptions. This problem may be solved by adopting an interpretation of quantum mechanics. An interpretation turns quantum mechanics into a theory that gives richer physical descriptions and that may reproduce the physical descriptions implied by function ascriptions. It can be shown, however, that not all interpretations fulfill this promise. Secondly I argue that these results amount to a two-sided challenge. It challenges philosophers of physics to provide an interpretation that gives nano-engineers rich enough quantum-mechanical descriptions to ascribe functions to artifacts. And it challenges engineers to help philosophers of physics with selecting tenable interpretations. Philosophers of physics are in need of tests for judging the different existing interpretations, and nano-engineers can provide such tests by requiring that interpretations should reproduce the function ascriptions to the artifacts they design. A nanoscale technology example I consider is quantum teleportation.

Introduction

Quantum mechanics has found its way to technology. Nuclear technology and laser technology are well-established examples, quantum cryptography and quantum computer technology are emerging ones. Nanoscale technology, when realized, will increase the use of quantum mechanics in technology. Quantum mechanics is the theory that describes matter on the atomic level. So, if nano-engineers are to build their universal assemblers that “will let us place atoms in almost any reasonable arrangement”,¹ then quantum mechanics is the theory they apply.

Already in his seminal work Drexler reviewed the consequences of this use of quantum mechanics in nanoscale technology. His message appears to be that these consequences can be brushed aside. Drexler considered, for instance, the question of whether the uncertainty principle of quantum mechanics “makes molecular machines unworkable”, and concluded that one “needn’t study quantum mechanics” to come up with a negative answer: the biological cell “demonstrates that molecular machines work”. Drexler also mentioned the perceived strangeness of quantum mechanics and the revolution it caused in our knowledge about matter. But again he reassured us that our knowledge about “the world of living things and the machines we build” will not be upended any further: future quantum-mechanical oddities and novelties will only occur under extreme circumstances engineers are never faced with.²

In this contribution I also consider the consequences of using quantum mechanics in nanoscale technology. In contrast to Drexler, I argue that this use leads to a problem that should not be brushed aside. This problem is that quantum mechanics cannot always accommodate a rather essential element in engineering descriptions of technical artifacts, namely, that these artifacts have technical functions. This problem should be solved since it seems obvious that engineers also will ascribe technical functions to the nanoscale artifacts they are to design. Moreover – and more positively – this problem poses a two-sided challenge for the philosophy of quantum mechanics that, when taken up, may lead to progress in this field.

More specifically I consider the quantum-mechanical description of nanoscale artifacts and argue that this description can fail to accommodate function ascriptions to those artifacts. I show that this omission is due to a general problem of quantum mechanics, namely, that it provides a rather sparse description of the world: quantum mechanics can easily temporarily deny an atom a familiar physical property such as position, velocity or energy. Then I argue that quantum-mechanical descriptions of artifacts may accommodate function ascriptions if one adopts an *interpretation* of quantum mechanics. Such interpretations have been developed in the philosophy of physics and are meant as solutions to the just-mentioned general problem by turning quantum mechanics into a theory that gives a richer description of the world. It can be shown, however, that not all interpretations fulfill this promise of accommodating functions. This is the first side of the challenge that is posed by the use of quantum mechanics in nanoscale technology. It challenges philosophers of physics to provide an interpretation of quantum mechanics that gives nano-engineers the means to ascribe functions to artifacts. Finally, I argue that in response, nano-engineers may also help philosophers of physics. Nowadays there exist many competing interpretations of quantum mechanics, and philosophers of physics are in need of clear tests for judging them. I propose that nano-engineers can provide such tests by requiring that interpretations of quantum mechanics should accommodate the functions they ascribe to the nanoscale artifacts they will design. And this is the second side of the challenge. It challenges nano-engineers to come up with functional descriptions of artifacts that enable philosophers of physics to decide which of the existing interpretations are tenable.

The plan for this contribution is as follows. In section 1, I consider functional descriptions of artifacts and state how a physical theory can accommodate them. Quantum mechanics and its interpretations are introduced in a colloquial way in section 2. In section 3, I show how quantum mechanics is capable of accommodating the ascription of technical functions to a specific class of artifacts, namely, measurement devices. The argument that quantum mechanics can also fail to accommodate function ascriptions, is given in sections 4 and 5. For this argument I consider other artifacts, namely, decoders that are part of a scheme called ‘quantum teleportation’. In section 6, I discuss how nano-engineers and philosophers of physics meet in attempts to overcome this problem.

Although I am happy with arguing that nano-engineers and philosophers of physics may benefit from one another’s work, it also confronts me with the problem of addressing two audiences. This contribution is therefore part of a pair that also includes a more quantum-mechanical paper. Here I introduce the reader to quantum mechanics in a colloquial fashion and stripped of mathematical niceties. The discussion of measurement devices and teleportation decoders is likewise rather informal. In the complementary paper the quantum-mechanical details are given by means of the usual theoretical language (Vermaas 2004). That paper contains the proofs of the different claims which are only presented here.

1. Technical Functions

If a material object is taken not only as a physical object but also as a technical artifact,³ its description becomes substantially richer. The description of a material object ‘qua’ physical object makes use of physical and chemical concepts such as geometrical dimensions, configuration, mass, types of matter, and so on. But if that object is taken as an artifact as well, intentional concepts enter the description. The object was designed and made by specific persons, and the object is meant to be used by people for achieving goals. An artifact has a technical function and may consist of components that have subfunctions. Technical artifacts are thus described by both physicochemical *and* intentional concepts and can be said to have a ‘dual nature’⁴ in contrast to purely material objects that have merely one physical nature. These physical and intentional descriptions are not independent from one another. If a technical artifact is described intentionally as an object with the technical function of drilling holes, it clearly can’t be described physically as a lump of sugar. Hence, the intentional description of a technical artifact typically imposes constraints on its physical description.

In this contribution I focus on the description of nanoscale artifacts as material objects that are ascribed technical functions. I take the position that the constraints these function ascriptions impose on the physical descriptions of artifacts can be captured by conditional statements about physical states of affairs. For everyday artifacts, these constraints are met: everyday artifacts are described by classical physics and classical physics provides for physical descriptions of artifacts that are rich enough for reproducing the mentioned conditionals. But for nanoscale artifacts described by quantum mechanics, things are different. Quantum-mechanical descriptions of nanoscale artifacts need not reproduce the physical conditionals and in that way fail to accommodate function ascriptions. But before being able to argue for this, I firstly consider functional descriptions of artifacts in more detail, and then introduce quantum mechanics in the next section.

Technical artifacts can be ascribed technical functions. A light bulb has the function of emitting light and a lawn mower has the function of cutting grass. There is, however, no consensus about what such function ascriptions mean. Philosophers have defended a number of positions. Some authors relate functions mainly to the *intentions* of agents. Searle, for instance, analyses function ascriptions in terms of the purposes agents impose and the suppositions they make: if an agent ascribes a function f to an artifact x , this implies that (i) the agent takes x as part of a larger system on which s/he imposes certain goals, and that (ii) the agent supposes that x can cause or result in f -ing in virtue of its physical makeup (Searle 1995). So, if an agent ascribes to a bulb the function of emitting light, s/he imposes, say, the goal of illumination to a lamp of which the bulb is a part, and s/he supposes that the bulb can emit light by its physical structure. Neander takes the position that “the function of an artifact is the purpose or end for which it is designed, made, or (minimally) put in place or retained by an agent” (Neander 1991, p. 462). Hence, ascribing to a lawn mower the function of cutting grass means that it was designed by engineers for cutting grass, or that a gardener kept it in a shed for this end. Other philosophers relate functions of artifacts not to the intentions of agents but to the *physical roles* of those artifacts in larger systems. Cummins, for instance, takes the ascription of a function f to an artifact x part of a larger system as implying that (i) in that larger system x actually has the capacity of f -ing, and that (ii) this capacity of x explains in part that the larger system has some other capacity (Cummins 1975). So, ascribing to the bulb in a lamp the function of emitting light means now that the bulb has the physical capacity to emit light and that this explains in part why the lamp has the physical capacity to illuminate. A third group of philosophers sees an analogy between technical functions and mathematical functions. They take function ascriptions to artifacts

as ascriptions of *input-output relations*: saying that the lawn mower has the function of cutting grass means that it transforms non-cut grass into cut grass.⁵

This is not the place to settle the debate between the different positions on what it means to ascribe functions. I therefore adopt a particular position that was argued for by Houkes and Vermaas (2004). Firstly, I assume that the ascription of a technical function f to an artifact x implies that x has a corresponding physical capacity (categorical or dispositional).⁶ The light bulb has the capacity to emit light when an appropriate electrical current is running through it, and the mower can cut grass when it is brought in an appropriate state. Secondly, I assume that the ascription of a physical capacity to an artifact x implies, in turn, the ascription of conditional physical relations to x : if certain physical circumstances C pertain, then the artifact will exhibit certain physical results R .⁷ These two suppositions lead to the following position. If the function f is ascribed to an artifact x , then a conditional relation is ascribed to x that is given by:

$$f: C \Rightarrow R,$$

where C and R refer to physical states of affairs. The descriptions of C and R need not necessarily be in terms of physical properties of the artifact x itself. For the bulb C can be described as an electrical current flowing through the bulb, and R as the bulb emitting light. But for the mower R are cuts in blades of grass. This position coheres with the analyses that relate technical functions to physical roles and to input-output relations; it need not cohere with analyses that relate functions to intentions of agents.⁸

On this position a function ascription to an artifact puts constraints on the physical description of the artifact: this physical description should accommodate the physical conditional $C \Rightarrow R$ implied by the function ascriptions.

2. Quantum Mechanics and its Interpretations

Quantum mechanics is the theory developed in the beginning of the twentieth century by people such as Bohr, Heisenberg and Schrödinger to describe the physics of atoms and elementary particles. In that period classical physical theories – Newtonian mechanics, electrodynamics, and so on – were found not to adequately describe these particles and thus lost their status as universally applicable theories. For some time classical and quantum theories coexisted peacefully as two ‘partially universal’ theories. Bohr took quantum mechanics as the theory that describes the atomic realm and Newtonian physics as the one that covers the everyday realm of macroscopic objects. Nowadays, however, quantum mechanics and its successors have taken over and are the universal and fundamental theories that reveal the physics of elementary particles and of all objects – macroscopic or not – made up of these particles. Classical theories are consequently seen as merely useful tools: they provide descriptions of macroscopic objects that approximate the correct quantum-mechanical descriptions.

Despite this success, quantum mechanics is also a rather problematic theory. Quantum mechanics describes physical objects in a manner that substantially deviates in two ways from the descriptions provided by the more familiar classical theories. Firstly, it does not systematically ascribe properties such as ‘position’, ‘velocity’ and ‘energy’ to objects, whereas classical theories do; quantum mechanics systematically describes the properties only of measurement devices (and then only those properties that correspond to the outcomes these devices are supposed to display). Secondly, there is in quantum mechanics a fundamental distinction between the description of measurements and of processes that do not count as measurements, whereas this distinction is absent in classical theories. These differences had the effect that physicists and philosophers of physics have tried and are still trying to reformulate quantum mechanics in such a way that the gap between quantum me-

chanics and classical physics diminishes. These reformulations are called interpretations of quantum mechanics.

Before I illustrate this and in order to further prepare the ground for discussing the quantum-mechanical descriptions of nanoscale artifacts, I expand a bit on quantum mechanics in the formulation by von Neumann (1955).

Quantum mechanics describes the physics of a system x by assigning a state to that system. This state determines some physical properties of the system and, probabilistically, all outcomes of measurements performed on the system. The state may be represented by a ‘wave function’ ψ and generates a probability $p(\psi, A, a)$ for each physical magnitude A pertaining to x and each value a that this magnitude may take. Examples of magnitude are the position of x , the velocity of x , or its energy. The meaning of the probability $p(\psi, A, a)$ is given by two rules:

Property Rule:

If and only if $p(\psi, A, a) = 1$, then x has the property that magnitude A has value a .

Measurement Outcome Rule:

If magnitude A is measured on x , then the outcome is a with probability $p(\psi, A, a)$.

Consider now a system with a specific state ψ . If one calculates the probabilities $p(\psi, A, a)$ for this system, one obtains the following. For some magnitudes A of the system the probabilities $p(\psi, A, a)$ are equal to 1 or 0. That is, for each of these magnitudes there exists one value a' for which $p(\psi, A, a')$ is equal to 1, and for all other values the probabilities $p(\psi, A, a)$ are equal to 0. But there are also magnitudes A of the system for which it holds that the probabilities $p(\psi, A, a)$ are smaller than 1 for all the possible values a . This fact does not constrain the effectiveness of quantum mechanics to generate predictions about measurements: the Measurement Outcome Rule produces such predictions regardless of whether one measures magnitudes A for which the probabilities $p(\psi, A, a)$ are equal to 1 or 0, or all smaller than 1. But this fact does constrain the effectiveness to ascribe properties to systems: the Property Rule only ascribes properties associated with magnitudes A for which the probabilities $p(\psi, A, a)$ are equal to 1 or 0 – this rule then ascribes the property ‘ A has value a ’ – but it does not ascribe properties associated with magnitudes A for which the probabilities $p(\psi, A, a)$ are all smaller than 1 – in this case the properties ‘ A has value a ’ are for all values a not ascribed. If such a magnitude is position or energy, and that may very well be the case, then the system has (temporarily) not a definite location in space, or no specific energy. This amounts to the first difference between quantum mechanics and classical physics. According to classical physics, systems usually have properties such as ‘the position has value p ’ and ‘the energy is e ’.

The state ψ of a system x evolves in time, and quantum mechanics gives again two rules for this evolution. The first rule is deterministic and applies when no measurements are performed on x : in this case the state ψ of x evolves with certainty to a later state ψ^* . The second is the notorious ‘collapse of the wave function’-rule. This rule is a probabilistic one and holds when measurements are performed. Assume that x has the state ψ and that the magnitude A is measured. The outcome is then value a with probability $p(\psi, A, a)$. The collapse rule now states that if the outcome is indeed value a , then the state of x becomes a new state ϕ for which holds that $p(\phi, A, a)$ is equal to 1.⁹ Hence, the original state ψ changed with probability $p(\psi, A, a)$ to this new state ϕ . The rules for state evolution, given more compactly:

Deterministic Evolution Rule:

If no measurement is performed on x , then the state ψ of x evolves deterministically to a later state ψ^* .

Collapse Evolution Rule:

If magnitude A is measured on x and the outcome is a , then the state ψ of x changes with probability $p(\psi, A, a)$ to a state ϕ for which holds that $p(\phi, A, a) = 1$.

The fact that there are in quantum mechanics distinct rules for the evolution of the states of systems during measurement amounts to the second difference with classical physics. Classical theories treat measurements and non-measurement processes alike; they usually give one uniform rule for the evolution of states.

Among philosophers of physics there have been extensive debates about whether or not quantum mechanics is an acceptable physical theory. May a theory be silent about whether systems possess key properties such as ‘the position has value p ’ and ‘the energy is e ’? And may a theory distinguish between the description of the evolution of the states of systems during measurements and during non-measurement processes? This second question is even more complicated since quantum mechanics does not give a criterion for distinguishing measurements from other processes. The concept of a measurement is a primitive one in quantum mechanics, meaning that the characterization of measurements has to come from outside quantum mechanics. A number of options are available. A first well-known one is that conscious observers make the difference: whenever agents consciously observe the properties of systems, a measurement takes place. A second option is that large macroscopic systems count as measurement devices and that interactions with those devices are measurements. And thirdly, one can take the position that in practice experimenters just know when measurements take place. All these options have their disadvantages. The first makes ‘consciousness’ a central notion in the formulation of quantum mechanics – a conclusion that makes quantum mechanics even more odd compared to other physical theories. The second is less than strict. The distinction between atomic and macroscopic systems is a gradual one. And throughout the years it has been shown that larger and larger systems can evolve by means of the Deterministic Evolution Rule proving that (more) macroscopically sized systems need not always be measurement devices. It was recently shown, for instance, that the states of molecules with a mass equal to approximately 1632 times the mass of a single hydrogen atom can evolve by the Deterministic Evolution Rule.¹⁰ Also, nanoscale artifacts are nice examples of this development: the quantum dots that are currently constructed and studied are not single atoms but are described by the Deterministic Evolution Rule. Finally, the practical way out seems to imply that experimenters have a criterion but are unable to articulate it.

An *interpretation* of quantum mechanics is now meant to turn quantum mechanics into a more acceptable theory. For instance, an interpretation provides rules that ascribe more properties to systems than does the Property Rule. This may seem a simple task: just take a rule that assigns values to all the magnitudes A pertaining to a system. However, rules that ascribe more properties to systems than does the Property Rule can lead to inconsistencies, as was proved by Kochen and Specker (1967). An interpretation thus has to find a balance: it has to ascribe enough additional properties to systems for turning quantum-mechanical descriptions into sufficiently informative ones, but avoid ascribing too many properties in order to prevent inconsistencies. An interpretation, moreover, provides a single rule for the evolution of states in order to prevent a fundamental distinction between measurements and other processes.

Physicists and philosophers of physics have developed in the last century a number of such interpretations. Well-known examples are ‘Bohmian mechanics’ and Everett’s ‘relative state interpretation’ (Bohm 1952, Everett 1957); more recent ones are modal interpretations.¹¹ There are thus many ways in which quantum mechanics can be made more acceptable.

3. Measurement Devices

Let us now consider artifacts that are described by quantum mechanics. Can quantum mechanics itself reproduce the physical conditionals $C \Rightarrow R$ implied by the functions ascribed to these artifacts? Quantum mechanics itself already provides a class of such artifacts: the measurement devices to which it grants such an important status. The conditional relations implied by function ascriptions to measurement devices can indeed be reproduced by quantum mechanics itself. But a more detailed analysis reveals problems.

By the Measurement Outcome Rule the function f_m of a measurement device m is to measure a magnitude A on a system x with state ψ_x , and to reveal an outcome a with probability $p(\psi_x, A, a)$. The outcome is to be displayed by the device as a pointer pointing to the value a on some scale, or as a digit on a screen. Usually an ‘outcome magnitude’ R is associated with these outcomes; the measurement device then displays the outcome a if and only if it possesses the property ‘ R has value a ’. The physical conditional implied by this function ascription can thus be stated as:

$$f_m: \text{state } \psi_x \text{ of } x \Rightarrow \text{device property ‘} R \text{ has value } a \text{’ with probability } p(\psi_x, A, a).$$

This conditional can be reproduced if measurements are described in more detail (a reader less interested in details may skip the remainder of this section). The standard toy-model of a measurement of a magnitude A of a system x by means of a measurement device m is as follows. The system x has its state ψ_x and the device has a particular initial state ψ_m . Together these two systems have a joint state Ψ_{xm} . The measurement interaction takes place and by the Deterministic Evolution Rule the joint state becomes Ψ_{xm}^* . If this would be the whole story, then there is a problem. If one calculates the probability $p(\Psi_{xm}^*, R, a)$ for the outcome magnitude R , then one obtains that this is equal to $p(\psi_x, A, a)$. This result makes sense because the measurement device is required to have the property ‘ R has value a ’ with probability $p(\psi_x, A, a)$. But the consequence is that the device in general does not have the property ‘ R has value a ’; $p(\psi_x, A, a)$ need not be equal to 1. It thus appears that the device does not display this property ‘ R has value a ’ as an outcome. Fortunately this is not the end of the story. Since we are dealing with a measurement, the state of the system x has to change by the Collapse Evolution Rule. The state of x has to become ϕ_x with probability $p(\psi_x, A, a)$ and for this new state holds that $p(\phi_x, A, a)$ is equal to 1. Through this change the joint state of x and the device changes as well: it changes with probability $p(\psi_x, A, a)$ to a state Φ_{xm} for which holds that $p(\Phi_{xm}, R, a)$ is equal to 1. Hence, by the Property Rule, the measurement device does have the property ‘ R has value a ’ and thus possesses the outcome after all. The above conditional implied by the function ascription to the measurement device is thus reproduced.

In models for measurements that are slightly more realistic than the one described, it may, however, become difficult to reproduce this physical conditional for measurement devices. Consider, for instance, a model in which the measurement device is described as consisting of components rather than of one monolithic object. Say, the device m consists of a pointer p and a mechanism q . The measurement interaction can then be split into firstly an interaction between the system x and the mechanism q , and secondly an interaction between the mechanism q and the pointer p . Let the first interaction be similar to a measurement interaction but assume that the ‘outcome’ magnitude R_q of the mechanism cannot be observed by humans (say, the properties ‘ R_q has value a ’ are too small to be detected). Let the second interaction also be similar to a measurement interaction and assume that it magnifies the values of R_q to values of a magnitude R_p of the pointer that can be observed. A measurement by means of a Geiger counter is one that satisfies this scheme: if the counter interacts with an incoming particle, this particle first produces a small electrical current and

this current is then transformed into audible beeps. The function ascriptions to p and q imply the conditionals:

f_q : state ψ_x of $x \Rightarrow$ mechanism property ‘ R_q has value a ’ with probability $p(\psi_x, A, a)$,

f_p : mechanism property ‘ R_q has value a ’ \Rightarrow pointer property ‘ R_p has value a ’.

The measurement interaction between the system x and the measurement device $p+q$ consists now of the sequence of interactions between x and q and between q and p . And on the basis of this one can argue that the collapse of the state of x takes place only after q and p have interacted. Hence, during the period in which the interaction between x and q has ended but the interaction between q and p has not ended yet, the joint state of x and q is a state Ψ_{xq}^* for which holds that $p(\Psi_{xq}^*, R_q, a)$ is equal to $p(\psi_x, A, a)$. And because $p(\psi_x, A, a)$ need not be equal to 1, it follows that during that period the mechanism q does not have the property ‘ R_q has value a ’. Hence, during that period the conditional implied by the function ascribed to q is not reproduced by quantum mechanics. Only once the interaction between q and p has also ended and the states have changed by the Collapse Evolution Rule, q will obtain the property ‘ R_q has value a ’. And only then one can conclude that the conditional implied by q ’s function is reproduced.

The upshot of all this is that the conditionals implied by function ascriptions to measurement devices can be reproduced by quantum mechanics because the states of systems collapse in quantum mechanics. But if this collapse is postponed a bit, then those conditionals may (temporarily) not be reproduced by quantum mechanics. In the next two sections I consider other artifacts described by quantum mechanics. I argue that in the quantum-mechanical descriptions of these artifacts, collapses of states need not occur, and that quantum mechanics then cannot reproduce the conditionals implied by function ascriptions.

4. Decoders in Quantum Teleportation

Other artifacts that are described quantum-mechanically are the systems realized or envisaged as part of the emerging fields of quantum cryptography, quantum teleportation and quantum computation.¹² Examples are quantum dots in quantum computers and the various components – decoders, encoders, channels, and so on, that is, part of schemes for sending and encrypting information. In this section I consider one of these artifacts, namely, the decoder that is part of *quantum teleportation*, a scheme for transferring the quantum-mechanical state ψ of one particle via an ordinary digital channel to another (distant) particle. In the scheme proposed by Bennett and collaborators, a decoder interacts with the first particle and produces the digital signal that is sent to the other particle (Bennett *et al.* 1993). I here focus on the function that is ascribed to this decoder.

The quantum teleportation scheme works as follows (see figure 1).¹³ Particle 1 initially has the quantum state ψ . This particle hits a decoder d at position A where a girl called Alice is located. At the same time a second particle 2 also arrives at the decoder, and this second particle originates from a source K . This source has emitted a pair of particles, of which particle 2 is one. The other particle – particle 3 – is sent to a second position B , where Bob is located. This pair of particles 2 and 3 is emitted in a special state, called an ‘Einstein, Podolsky, Rosen (EPR)-state’. Moreover, Alice can send digital signals to Bob via a channel c and Bob has an ‘encoder’-device e that can transform the state of particle 3.

The procedure that is followed is that Alice performs a measurement with her decoder d on the joint system consisting of the particles 1 and 2. She measures a specific magnitude G and records the outcome. In the standard case this measurement has four possible outcomes g_1 to g_4 , and quantum mechanics predicts that all these outcomes occur with equal probability 0.25. Then she sends this outcome digitally to Bob via the channel c . Bob re-

ceives it and performs a quantum-mechanical transformation with his encoder e on the state of particle 3; for each outcome $g_1, g_2, g_3,$ and g_4 he has a different transformation. After this transformation particle 3 has exactly the state ψ that particle 1 originally had. This result may seem trivial. It may seem that Bob knows what state particle 1 initially had once he receives Alice's signal. It is then simple for Bob to transform the state of particle 3 into that same state. However, quantum teleportation is not trivial since Alice and Bob neither can reconstruct the precise state of particle 1, nor need to do so. Ignorant of ψ they simply follow the procedure and manage to transfer this state to particle 3. Moreover, they manage to do so with a finite number of digital bits (two bits in the standard case) whereas if Alice had known the state ψ and wanted to inform Bob about it, she had to send an infinite number of bits.

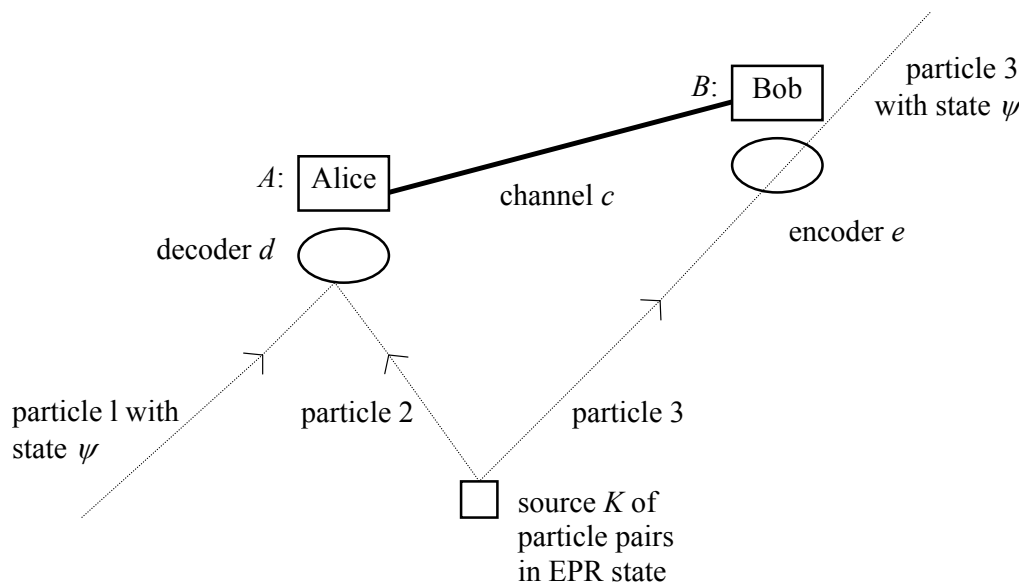


Figure 1. Quantum Teleportation

Let's now consider the decoder d in this scheme. It has the function f_d to decode the quantum-mechanical state ψ of particle 1 into a signal that Alice can send to Bob. This signal is the outcome of a measurement of magnitude G on the joint system consisting of the particles 1 and 2, and may take the values g_i , where i runs from 1 to 4. Let Ψ_{12} denote the state of the joint system 'particles 1+2'. The conditional $C \Rightarrow R$ implied by the function of this decoder d , can then be written as:

$$f_d: \text{state } \Psi_{12} \text{ of } 1+2 \Rightarrow \text{decoder property 'R has value } g_i \text{' with probability 0.25,}$$

where R is the observable outcome of the decoder.

The quantum-mechanical description of the decoder can reproduce this conditional without problems. Since the decoder is taken as a measurement device, it follows that its state collapses after its interaction with particles 1 and 2, and that the decoder then indeed acquires a property 'R has value g_i ' with probability 0.25.

5. Decoders in Nanoscale Quantum Teleportation

The teleportation scheme as presented above and discussed in the literature seems fine and is of technological significance. To be sure, it will be a challenge to design a system that allows particles 2 and 3 to arrive at the decoder and encoder without being disturbed by

outside interferences. But once that is achieved, quantum-mechanical states ψ can be sent via a finite number of digital signals – an impressive case of data-reduction. But the scheme can also be criticized. And if this criticism is taken seriously, one can argue that the conditional implied by the function ascription to the decoder may fail to be reproduced by quantum mechanics.

Let us start with the criticism which is prepared by two points. The first is an empirical one and concerns the incorporation of Alice and Bob in the scheme. Authors have proposed experimental set-ups to actually perform teleportation and have to some extent shown that teleportation is possible.¹⁴ But these set-ups do not always incorporate human agents who take the roles of Alice and Bob. In these there are, for instance, no ‘Alices’ included who determine the outcome that is displayed by the decoder and who feed this outcome into a channel. Instead the decoder is directly connected to this channel. It thus seems that Alice and Bob can be removed from the scheme, and it seems that the signaling between the decoder and the encoder via the channel can be modeled as successive physical interactions between the decoder, the channel, and the encoder. This scheme would have the further advantage that all systems involved in quantum teleportation can be described quantum-mechanically, which is consistent with the fact that quantum mechanics is a universally valid theory. (In the teleportation scheme discussed in the literature, Alice, Bob and the channel c are kept outside the quantum-mechanical description, which seems to bring us back to the times of Bohr).

The second point makes use, in part, of the prospects of nanoscale technology and challenges the assumption that the interaction between the decoder and particles 1 and 2 needs to be taken as a measurement. Quantum mechanics itself provides no criterion for distinguishing measurements from other interactions. It was shown in section 2 that such a distinction has to come from outside quantum mechanics and that a number of options are available.

On the basis of these two points, it can now be challenged whether on any of these options the decoder really has to be taken as a measurement device. The first option was that conscious observers make the difference: when a conscious agent observes a system it counts as a measurement. If one now accepts that quantum teleportation need not incorporate Alice and Bob, the decoder interaction with the particles is by this first criterion not a measurement implying that the decoder is not a measurement device. The second option was that large macroscopic systems count as measurement devices. The equipments used for the decoders in the mentioned experiments probably have macroscopic dimensions and thus are measurement devices by this second criterion. But this need not always be the case, especially from the perspective of nanoscale technology. Imagine that teleportation will become commercially available and that one can send one’s quantum-mechanical states from, say, Darmstadt in Germany, to Columbia in South Carolina. Initially it may be something special, instantiated in huge expensive machinery and operated by skillful staff that sends and receives the signals ‘manually’. The staff then takes the roles of Alice and Bob. But as nanoscale technology advances and competition for market share increases, teleport companies may make the staff redundant and miniaturize the machinery. One then has fully automated ‘on-line’ teleportation links: glass fibers with nanoscale decoders and encoders on their tips that automatically teleport incoming states. If such a scenario comes true, the decoder becomes a nanoscopic device and is thus not a measurement device on the ‘macroscopic dimensions’-criterion. Moreover, the decoder may also become a kind of device that experimenters typically do not use as measurement devices. Indeed, the decoder may no longer contain a pointer or a display, but can be a minuscule component attached to the glass fiber. Hence, also by the ‘determined by experimenters’-criterion the decoder now ceases to be a measurement device.

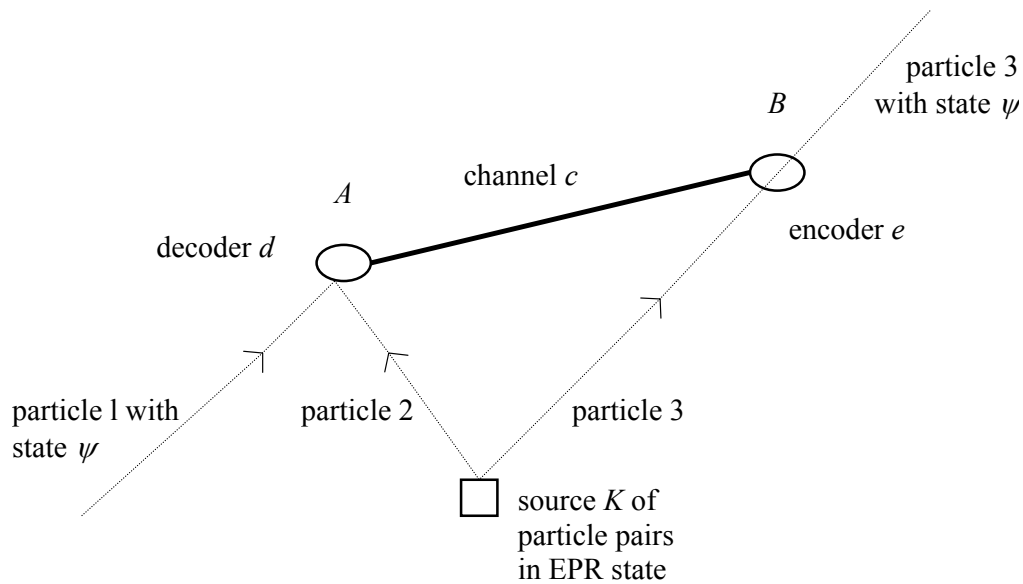


Figure 2. Nanoscale Quantum Teleportation

The upshot of this criticism is that quantum teleportation may become a nanoscale ‘de-gentized’ procedure in which the decoder is not a measurement device (see figure 2). All systems part of this scheme can then be described quantum-mechanically and the relevant states all evolve only with the Deterministic Evolution Rule. Since there are no measurements involved in the scheme, states do not change by the Collapse Evolution Rule. It can be proved that this new scheme still transfers the initial state ψ of particle 1 to particle 3 (Vermaas 2004), which supports the position that neither the presence of Alice and Bob, nor the assumption that the decoder is a measurement device are necessary ingredients of quantum teleportation.

But does the quantum-mechanical description of this nanoscale quantum teleportation scheme still reproduce the conditional $C \Rightarrow R$ implied by the function ascription to the decoder? The answer is negative. The decoder now has the function f_d to decode the state Ψ_{12} of particles 1 and 2 into a signal that is sent through channel c to the encoder. Let the signals correspond to the properties ‘ S has value g_i ’, $i = 1, 2, \dots$, where S is the ‘signal magnitude’ of the channel c . The conditional implied by this function can then be written as:

$$f_d: \text{state } \Psi_{12} \text{ of } 1+2 \Rightarrow \text{channel signal ‘} S \text{ has value } g_i \text{’ with probability 0.25.}$$

A quantum-mechanical description of the channel c reveals, however, that it never possesses one of the properties ‘ S has value g_i ’: the channel acquires a state ψ_c for which holds that $p(\psi_c, S, g_i)$ is not equal to 1 (the probability $p(\psi_c, S, g_i)$ is equal to $p(\Psi_{12}, G, g_i)$, which always has the value 0.25). Hence, by the Property Rule, the channel does not possess one of the channel signals ‘ S has value g_i ’. The above conditional is thus not reproduced by quantum mechanics. So, to conclude, descriptions of technical artifacts by quantum mechanics sometimes fail to accommodate the technical functions that (nano-)engineers ascribe to those artifacts.

6. A ‘Technical Descriptions’ Criterion for Interpretations

One may now try to correct this failure in the quantum-mechanical descriptions of artifacts by adopting an interpretation of quantum mechanics. An interpretation ascribes more properties to systems than quantum mechanics itself. So, possibly an interpretation does repro-

duce the conditionals $C \Rightarrow R$ implied by function ascriptions. This strategy may work in the case of the detector of our nanoscale quantum teleportation scheme: many interpretations do ascribe the signals ‘ S has value g_i ’ to the channel.¹⁵ By providing nano-engineers with rich enough interpretations philosophers of physics may thus help these engineers with the accommodation of function ascriptions to artifacts described by quantum mechanics.

However, this strategy confronts one with another problem, namely the problem of which interpretation to adopt. As was said at the end of section 2, there are currently a number of interpretations available and many of them ascribe the signal. The existence of all these interpretations has now transformed the problem of interpreting quantum mechanics partly into a *selection problem*: instead of just finding an interpretation for quantum mechanics, one now also has to judge which of the existing interpretations is the best or, more humbly, which are the tenable ones. I will show in this section that this selection is currently difficult because philosophers of physics lack clear, generally accepted, and discriminating criteria for judging interpretations (Vermaas 2003). Nano-engineers can, of course, take the easy way out of this second problem by assuming that it is sufficient to know that there exists an interpretation by which quantum mechanics can accommodate function ascriptions; the problem of selecting interpretations is then moved back to the philosophy of physics, where the problem was caused in the first place. I wish to argue that philosophers of physics can be helped in solving their problem if this strict division of labor is overcome.

Philosophers of physics have two clear and accepted criteria available for considering the selection problem: a tenable interpretation should be *consistent* and *empirically adequate*. The first criterion indeed succeeded to remove some interpretations: the mentioned proof by Kochen and Specker showed that interpretations that ascribe too many properties can be inconsistent. But this criterion has done its job and does not discriminate any further. One may assume that the main interpretations that are now available are all consistent. The second criterion appears stronger, but is in fact also not very effective in turning down interpretations. An interpretation of quantum mechanics ideally generates exactly the same empirical predictions as quantum mechanics itself. As stated above, interpretations are meant to turn quantum mechanics into a more acceptable theory; they are not meant to change the empirical content of quantum mechanics. A consequence of this is that empirical tests in principle cannot differentiate between tenable and untenable interpretation.

Philosophers of physics also apply more discriminating criteria to interpretations. But these criteria are not (yet) generally accepted. An extensively discussed criterion in physics is the requirement that interpretations of quantum mechanics should yield ‘*local*’ and ‘*Lorentz-covariant*’ descriptions of reality in order to maintain consistency with Einstein’s theory of relativity. This criterion, however, does not help selecting tenable interpretations either. It can be formulated in a strong and straightforward way, but then it seems that no interpretation satisfies it. Weaker formulations are possible and these allow some interpretations to survive and others not. But this moves the game of selecting interpretations towards a debate on the right way of weakening the criterion. This then reveals that the criterion doesn’t yet have a clear and generally accepted form. There are other more specific criteria proposed in the philosophy of physics literature. Clifton, for instance, lists five “desiderata” for modal interpretations (Clifton 1996). These range from an elusive desideratum that the set of ascribed properties should be ‘metaphysically’ tenable, to a more tangible one that modal interpretations should provide for a dynamics of these properties. Cushing and Bowman speak of possible conceptual advantages of Bohmian mechanics over quantum mechanics itself, since the former may provide better means to connect quantum mechanics to other theories such as chaos theory and classical mechanics (Cushing and Bowman 1999). These criteria are to some extent clear and may be discriminating. But their effectiveness is harmed by their lack of full acceptance. For instance, a verdict that an author’s pet interpretation is untenable because it does not

thor's pet interpretation is untenable because it does not provide for means to connect quantum mechanics to chaos theory, can still be countered easily by that author with a discussion about the value of this criterion itself: "my interpretation is metaphysically tenable and that is more important than providing the means to link up quantum mechanics with a silly little theory like chaos theory, isn't it?"

Thus philosophers of physics currently seem to lack the means for solving the selection problem as part of interpreting quantum mechanics. In order to make progress they need new acceptable and discriminating criteria for interpretations. They may arrive at such criteria by improving on the 'physics' criteria discussed in the previous paragraph. But philosophers of physics may also look for criteria in other fields. I now propose that engineering can provide for a new criterion: interpretations should accommodate the descriptions of artifacts employed by nano-engineers. The criterion demands minimally that interpretations should reproduce the conditionals $C \Rightarrow R$ implied by the functions ascribed to artifacts that are described by quantum mechanics (but it may demand more¹⁶). In this reading, the criterion is clear and can be accepted by philosophers of physics. Whether it is also discriminating is something to be determined by future research. Most interpretations of quantum mechanics can reproduce the conditional implied by the function ascribed to the teleportation decoder. But other examples of nanoscale artifacts may prove the proposed criterion to be more discriminating. The search for such examples is future research, and my guess is that nanoscale technology, when it takes off, will produce many of these examples. If the criterion is accepted, nano-engineers can thus help philosophers of physics select the tenable interpretations of quantum mechanics.

7. Conclusion

In my contribution I considered the consequence of describing technical artifacts by means of quantum mechanics. I gave an argument that this description can fail to accommodate the ascription of technical functions to those artifacts. This argument proceeded in five steps. Firstly I took the position that the ascription of a function to an artifact implies a conditional physical relation. A quantum-mechanical description of the artifact can then be said to accommodate the function ascription if it can reproduce this conditional. Secondly I presented the scheme of quantum teleportation and focused on the decoder that is part of the scheme. I showed that a quantum-mechanical description of teleportation can accommodate the function ascribed to this decoder. This positive result was conditioned upon the fact that the decoder is taken as a measurement device. Thirdly I argued that one can envisage a nanoscale version of quantum teleportation in which the decoder need not be a measurement device. The quantum-mechanical description of this nanoscale scheme cannot accommodate the function ascribed to the decoder.

I then showed that quantum-mechanical descriptions of artifacts can be turned into descriptions that do accommodate technical functions if nano-engineers adopt an interpretation of quantum mechanics: A conceptual gap that arises when artifacts are described quantum-mechanically can thus be closed by means provided by philosophers of physics. In this sense the use of quantum mechanics in nanoscale technology poses a challenge for the interpretations considered by philosophers of physics. Finally I reversed the order of assistance, and argued that nano-engineers can help philosophers of physics select tenable interpretations from the multitude of available interpretations of quantum mechanics. In philosophy of physics there already exist criteria that should be met by tenable interpretations, but these criteria are not sufficiently discriminating. I proposed a new criterion for tenable interpretations: interpretations of quantum mechanics should accommodate the descriptions of artifacts that are employed by engineers. This criterion demands minimally that interpretations should reproduce the conditionals implied by the function ascriptions to artifacts

that are described by quantum mechanics. Further research has to decide whether this criterion is discriminating; the use of quantum mechanics in nanoscale technology thus poses a challenge also to nano-engineers, namely to come up with examples of function ascriptions to artifacts such that only a few interpretations can reproduce the implied conditionals. If the proposed criterion is accepted, a fruitful co-operation between nano-engineers and philosophers of physics will emerge: development of new nanoscale artifacts becomes intimately connected to singling out tenable interpretations of quantum mechanics.

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Notes

- ¹ Drexler 1986, p. 14.
- ² Drexler 1986, pp. 15 and 151-154.
- ³ When I speak of (technical) artifacts in this contribution, I always refer to material objects that are made to be used for practical purposes. I thus do not consider artistic artifacts such as paintings, nor non-material artifacts such as software and organizations.
- ⁴ Kroes *et al.* 2002.
- ⁵ *E.g.*, Baird 2002.
- ⁶ This first assumption ignores the unfortunately well-known phenomenon that we sometimes ascribe functions to technical artifacts that actually cannot perform them: a mower can temporarily lack the capacity to cut grass because it is broken, although we still take it as an object with the function of cutting grass. A consequence of this phenomenon is that the ascription of a function to an artifact need not imply that the artifact actually has the associated capacity. Houkes and Vermaas (2004) incorporate this phenomenon by formulating the first assumption as follows: the ascription of a function to an artifact implies that it is believed and justified that the artifact has this physical capacity. In this contribution I ignore the phenomenon by restricting the discussion to artifacts that do perform their functions.
- ⁷ I have drawn here on Mumford’s (1995, Chapters 3 and 4) analysis of how ascriptions of categorical and dispositional properties entail (subjunctively) conditional relations. But I adopt this analysis only partly because Mumford characterizes these conditional relations as the ‘functional roles’ of the properties entailing them. I have to reject this characterization since it would make my position about what function ascriptions mean partly circular.
- ⁸ This analysis of technical functions relates function ascriptions to intentions of agents (Houkes and Vermaas 2004). The position I take thus coheres at least with some intentionalist accounts.
- ⁹ Because $p(\phi, A, a)$ is equal to 1, the Property Rule yields that after the measurement the system x indeed has the property ‘ A has value a ’ that corresponds to the outcome a of the measurement.
- ¹⁰ Hackermüller *et al.* 2003.
- ¹¹ *E.g.*, Vermaas 1999.
- ¹² *E.g.*, Bouwmeester *et al.* 2000 and Rieffel *et al.* 2000.
- ¹³ As announced in the introduction I ignore all quantum-mechanical details concerning the precise states of particles 1, 2 and 3, Alice’s measurement and Bob’s transformations. These details can be found in, for instance Rieffel *et al.* 2000 and Vermaas 2004.
- ¹⁴ *E.g.*, Bouwmeester *et al.* 1997, Boschi *et al.* 1998, and Nielsen *et al.* 1998.
- ¹⁵ For readers familiar with philosophy of physics terminology: when the signal is supposed to be sent from decoder to encoder, the (somewhat idealized) state of the channel is a degenerated improper mixture of eigenstates of the magnitude S . If the degeneracy is ignored, then many interpretations take this state as indicating that the channel has one of the properties ‘ S has value g_i ’ associated with the eigenstates.
- ¹⁶ For instance, engineers are known for their sketches of (envisaged) artifacts. One can take the criterion that interpretations accommodate technical descriptions as demanding also that they reproduce the properties represented in these sketches (Vermaas 2004).

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Nanoscience and the Janus-Faced Character of Simulations

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Abstract. In nanoscience, simulations (partly) take the place of “real” experiments. For example: in a simulation, well-known physical laws can produce surprising behaviors. It is argued that simulations are both part of experimental practice and form a theoretical instrument, inducing a methodological shift in scientific practice: if one desires a “quantitative understanding” of matter at the nanoscale, one must rest content with the ability of simulations to imitate systems and cannot ask for more direct means of validation.

1. Illustration: Simulation in Nanoscience

At the beginning, I would like to discuss two examples of simulations in nanoscience. There is, of course, a wide variety of simulations used in nanoscience as well as in other branches of science. The following examples are by no means exhaustive, rather they illustrate some typical properties of simulations and give a glimpse of some problems connected with them.

Both examples stem from Uzi Landman, director of Georgia Tech’s Center for Computational Materials Science. In a landmark 1990 *Science* paper, Landman and his co-workers employed large-scale molecular dynamics simulations. They showed that when a nickel tip was brought into close proximity to a sheet of gold, gold atoms would jump from the sheet to the probe (Landman 1990).

Figure 1 consists of six (simulated) snapshots. On the upper left, a nickel tip has crushed into a gold surface. On the following slides, the tip is removed slowly and a thin wire of gold atoms is generated. The coloring is added to make the visualization more convenient. The atomic layers in figure 1 are marked with different shades of gray, the original images used artificial coloring which is here adapted to black-and-white print. Hence, unfortunately, the images lose a great deal of what F. Rohrlach (1991) has called the character of simulations as “dynamically anschaulich”. Landman describes his situation as being very similar to that of an experimenter who is watching the outcome of a complicated experimental setup. I quote Landman from an interview:

To our amazement, we found the gold atoms jumping to contact the nickel probe at short distances. Then we did simulations in which we withdrew the tip after contact and found that a nanometer-sized wire made of gold was created. That gold would deform in this manner amazed us, because gold is not supposed to do this.

Their “amazement” is also theoretically amazing, because well-known physical laws at the atomic level served as the basis of the simulation that, in turn, showed unexpected behavior at the nanoscale. The formation of a nanowire was, at that time, a prediction. It was confirmed by experiment with AFM some years later.

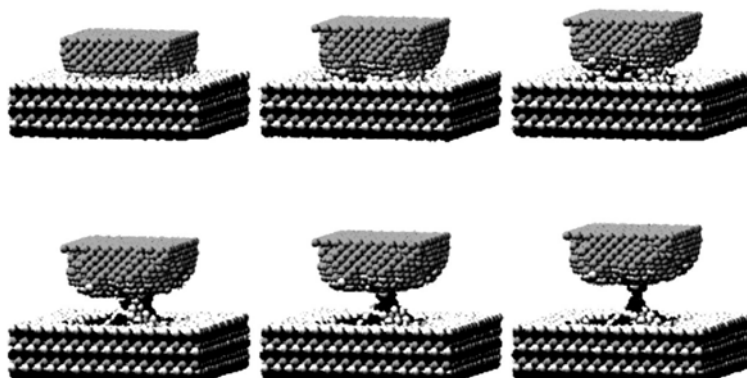


Figure 1. A nanowire of gold atoms emerges between a nickel tip and a sheet of gold (from Landman 1990).

The second example is concerned with lubrication and the properties of lubricants that are confined to very small, that is, nanoscaled spaces. When confined to tight spaces, long-chain lubricant molecules seem to act more like “soft solids” than like fluids.

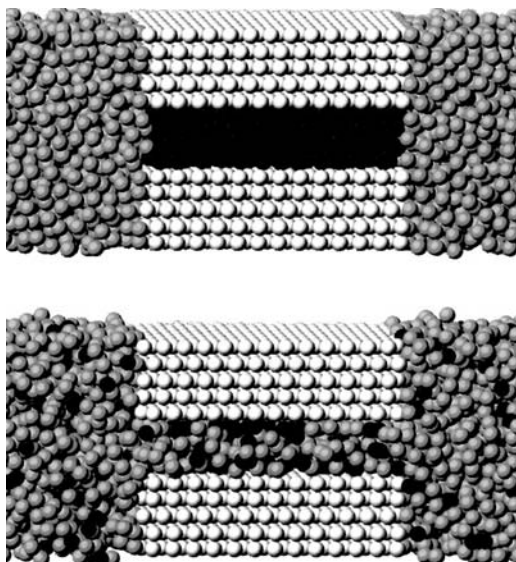


Figure 2. Ordered high friction state (upper image) and oscillation-induced disordered low friction state (from Landman 2001)

The result of a numerical experiment with two sliding surfaces is shown in figure 2. Two surfaces (light-colored, originally yellow) are sliding one against the other. Lubricant molecules are in the small, nanosized, gap between the surfaces, as well as in the bulk outside. The upper part of the picture again shows a simulated snapshot: the molecules of the lubricant are forming *ordered* layers that significantly influence the movement of sliding surfaces as friction increases. The molecules that are confined between the surfaces are colored dark. (The coloring of the original visualization on the computer screen is much more vivid.) Landman also tried to “overcome the problem” of high friction in a simulation

study. Carrying forward the molecular dynamics simulations, he manipulated the movement of the slides. The simulation shows how oscillating the gap between the two sliding surfaces reduces the order of thin-film lubricant molecules (thereby lowering the friction). In the lower part of the image, molecules that had been confined within the surface, and which were marked red after the first snapshot, have moved out into the bulk lubricant unconfined, and molecules from the bulk areas have moved into the gap. (Admittedly, that is hard to recognize without colors.) These “soft-solid”-properties are unexpected from the normal behavior of fluids. Again quoting Landman:

We are accumulating more and more evidence that such confined fluids behave in ways that are very different from bulk ones, and there is no way to extrapolate the behavior from the large scale to the very small. (Landman 2001)

Again one is confronted with really surprising behavior, even though the theoretical ingredients of the simulation are well-known. (To be sure, it is very demanding to implement a simulation model in a parallel computing environment.)

For his achievements, Landman has received several prizes, *e.g.* the Feynman prize in theoretical nanotechnology (2000), and the Materials Research Society Award (2002) for “the development and implementation of research methodologies that use molecular dynamics simulations to predict the often-surprising behavior that occurs at the nanoscale when surfaces of solid and liquid materials meet” (press statement, see Landman 2002).

The examples should illustrate that using simulations is an important part of nanoscience. Furthermore, the cases exhibited some intriguing properties that shape the practice of nanoscience. I will argue that this gives reason, in turn, to revise some central concepts in the philosophy of science.

2. The Epistemic Status of Simulations

2.1 Simulations as Models of Second Order

Recall the statement of Landman about accumulating evidence for unexpected behavior. By what means is this new evidence obtained? And in what sense is it unexpected? To tackle these questions, it is necessary to consider the epistemic status of simulations.

Traditionally, mathematical modeling is oriented to the paradigm of partial differential equations (PDE) that model the propagation of a system governed by natural laws. One can say that PDE and the analytical tools of the differential calculus fit like gloves. (And do so since the days of Leibniz, Newton, and the Bernouillis.)

But in complex systems this approach encounters severe difficulties. H. Poincaré was among the first to experience this when he was conducting equally ingenious and tedious calculations to solve the so-called three-body-problem. At last, he had to acknowledge the insolubility of this problem. Even seemingly simple questions about highly idealized systems with only a very limited number of particles can be very difficult to treat. The question whether our solar system is stable, is of that kind. This observation applies even more so to systems with many interacting particles, like the cases from nanoscience that were considered above. With mathematical-analytical means it is nearly hopeless to achieve interesting results. As Dirac, for instance, had observed, although the basic quantum laws governing large parts of physics and chemistry are known, progress will still be obstructed by the fact that the pertinent equations are too difficult to solve. In particular, this observation applies to the laws governing the nanoscale. You have a mathematical model, but it doesn't help you. In a certain sense, simulations help to circumvent this problem. They are a kind of imitation in the computer of mathematical models. In other words, simulations build a *model* of the mathematical model, namely of the system of equations.

One should be aware of the fact that simulations are not mere calculations in the sense that they would provide just a numerical solution of the original equations that are analytically unsolvable. Surely, there are important differences between an analytical solution and a numerical one. The former typically provides information about what will happen when some initial conditions are altered, while a numerical solution provides nothing of that kind. If anything is altered, everything has to be computed again. While this might not be a serious constraint, because computational time is cheap, it constitutes a fundamental difference between analytical and numerical solutions. I want to stress, however, that this difference does not concern the essential point here.

Often simulations do not intend to *solve* a system of continuous non-linear partial differential equations at all. Instead, such a system is replaced by a discrete model, that is, the mathematical model is modeled again. Simulations work with a discrete version of the mathematical equations and it is a rather difficult task to construct a simulation model that is at once computationally treatable and sufficiently similar to the original system. This, one could say, is the generic problem of modeling – to find a tractable and at the same time adequate analogue. P. Humphreys (1991) has remarked that the approach of computer simulations broadens the realm of tractable mathematics enormously. Much in the same way as PDE and the differential calculus fit to each other, simulation models and the computer fit. (I use simulation and computer simulation equivocally.) Mathematically intractable models become computationally tractable models. Thereby, the art of modeling changes.

I propose that simulations involve a specific kind of modeling that can be called ‘modeling of the 2nd order’. For example, the problem of finding an adequate discretization is typical for simulation modeling. At the same time this problem is an instance of a more general type of problem: the adequacy of a certain model always needs to be considered in scientific, or mathematical, modeling. Thus, firstly, there are specific problems connected with simulations, and secondly, these problems are of a type generally found in modeling. For this reason, I prefer to speak of *simulation modeling* to indicate that the core of simulation consists of a special kind of modeling. Another way of putting this: simulations are second order models (see Küppers & Lenhard 2003, 2004). Admittedly, in fields like mathematics or physics, models of models are common – as indicated by the verdict of the mathematician Stefan Banach that good mathematicians see analogies between models and theories, while the best see analogies between analogies. So, what is peculiar about simulations? It is how the modeling is carried out and which new possibilities open up. A decisive point is that simulation modeling borrows from experimental practices.

The concept of experiment is itself a much debated topic in philosophy and history of science (see, for example, Radder 2003), thus one would not be well advised to use this concept as a fixed basis of philosophical analysis. To me, it seems promising to argue along empirical case studies, so to say a methodologically mixed approach. A heuristic use of ‘experiment’ appears admissible, even if the concept is not well defined. Anyway, simulation experiments are part of scientific practice and I will argue that a philosophical account of what an experiment is can learn from that.

2.2 Experimental Practice with a New Theoretical Instrument

Having implemented such a simulation model, one is able to *observe* what happens when the system evolves in time and what surprises it may offer. Taking into account the enormous capacity for visualization that is provided by the computer, the use of the term “observation” appears well justified.

Admittedly, one can think of the behavior of such a system as guided by natural laws, for example by the Schrödinger-equation, and indeed this was the starting point of our ex-

amples. But this is, as Dirac had observed, only a consideration “in principle”. In fact one is simply not able to derive the observed properties from general theory.

Simulations of the kind performed by Landman therefore look like experiments in the computer. This experimental aspect of simulations has attracted some attention of philosophers and has occasioned a series of perspicacious investigations. However, there is no consensus on how the experimental aspects should be grasped conceptually (see Humphreys 1995/96, Hughes 1999, Fox Keller 2003, or Winsberg 2003.) I like to point to the stance of the scientists: The examples have highlighted how even a computer scientist’s behavior resembles that of an experimenter. One can be amazed or even surprised by unexpected observations. Simulations are thus part of the experimental practice of, for example, nanoscience.

The above statement is clearly a one-sided account of simulations since simulations are also theoretical instruments. Obviously, simulations are based on highly theoretical efforts of applied mathematics and computer science. Without recent progress in applied mathematics one would not be able to tackle most of the problems actually investigated by simulation methods. Again, Landman’s efforts provide a good example: what is implemented are models, guided by general laws of interaction between atoms (the Schrödinger equation).

2.3 *Simulation as a New Method?*

In philosophical literature, one can find claims about the hybrid status of simulations. For example, “their use requires a new conception of the relation between theoretical models and their applications” (Humphreys 1991, p. 497). And Peter Galison speaks of simulations as a “*Tertium Quid*” between experiments and theory (Galison 1996). I find it very attractive to think of simulations as crossing the boundaries of experiment and theory. As the last two concepts are not understood very consistently, the considered cases can provide reason to doubt the existence of a clear-cut boundary between experiment and theory in the first place.

The main line of philosophical debate is whether simulations present an entirely new method of science or not. I find the claim of novelty rather convincing. While the computational powers of the electronic computer are necessary, they by no means determine the whole picture. Simulation is faster than computation. The methodological ingredients, so to say, are standard – extensive experimentation and model building. But their combination seems to be very specific, constituting a new methodological approach.

I have argued for both points: Simulations are part of experimental practice and simulations are theoretical instruments – new instruments that bring with them a new practice that is still in flux in many scientific fields. It appears astonishing how components as divergent as experiment and theory can merge in such an effective way. What traditionally counts as a problem or even a painful insight in the philosophy of science, namely that observation is always theoretically “contaminated”, now seems to be part and parcel of the method itself. This may be seen as a change of the very conception of experimentation, one that transposes *explanans* and *explanandum*: Instead of explaining simulation as a hybrid, constituted from experiments (and other ingredients), one could take the practice of simulation as a starting point, contributing to the question of what is meant by “experiment”. As Alfred Nordmann has pointed out in discussion, the concept of experiment causes constantly philosophical troubles, so it could be fortunate not to take it as a basis.

3. Back to Nanoscience

In May 2002, a DOE-Workshop on “Theory and Modeling in Nanoscience” took place. The report formulates the *Central Challenge*: “Because of the rapid advance of experimental investigations in this area, the need for quantitative understanding of matter at the nano-scale is becoming more urgent, and its absence is increasingly a barrier to progress in the field quite generally” (DOE 2002, p. 5).

Let us assume that the report is right in stating that the missing quantitative understanding is one of the central problems of nanoscience. This raises the question whether simulations are part of the problem or part of the solution?

On the one hand, simulation is an experimental practice that requires theoretical understanding. In the case of the golden nanowire, created by withdrawing a nickel tip, the amazing behavior could be observed, and even validated independently, but the simulation does not offer an explanation in the usual sense. Clearly, the laws that are implemented in the simulation model produce the behavior – somehow. The simulation, mediating between the general Schrödinger-equation and a concrete wire, has rendered the phenomenon somewhat opaque. Despite being obviously theory-based, the simulation does not offer something like a theory-based insight! In this respect and emphasizing the term “understanding”, simulation does not provide “quantitative understanding of matter” and is therefore part of the problem.

On the other hand, simulations are quantitative and present an opportunity to explore the field where no general and accepted theoretical basis exists, or at least, where it is not applicable. Dirac’s verdict that the knowledge of the guiding laws does not lead to an understanding of behavior in complex situations, expresses a rather general fact. Mathematical insights into computational complexity indicate that this situation will persist: general laws are often useless in concrete situation of applied problems. One has to look after instruments that scientists can work with and that allow for a kind of understanding so that manipulation becomes possible. What is at stake is thus the potential for intervention. In *this* respect and emphasizing the term “quantitative” in “quantitative understanding of matter”, simulations seem to provide a solution. In the case of the moving slides, for instance, the manipulation of the movement, from a flat to a slightly oscillating one, restored the desired properties of the lubricant. Therefore, too, simulations can be seen to be part of the solution.

I do not intend to give an unequivocal answer to the question whether simulations are part of the problem or of the solution. The adequate court to address this question would be the future development of nanoscience.

While it seems to be adequate to conceive of simulations as a quantitative approach, the question is whether it can provide genuine understanding. I have argued that simulations involve a second order modeling and this causes serious problems of validation. Simply put, simulation results have to face the objection that they are “only imitating” the real system.

In the case of nanoscience, however, it seems to be questionable whether another approach that provides genuine understanding and thereby overcomes the barrier diagnosed in the DOE-workshop, is possible at all. In this field, there is perhaps simply no alternative to simulation.

Let me consider as a further case so-called density functional theory (DFT), a fundamental theory in computational chemistry. It is especially useful for dealing with the properties of larger molecules that have many interacting electrons. The situation is quite similar to Dirac’s problem, that is, the properties should in principle follow from the Schrödinger-equations, but the number of involved electrons makes a solution unachievable. The point of DFT is to replace the many interacting electrons by an electron density function.

The DFT was essentially developed by W. Kohn in the late 1960s. Since it offers a strict simplification, theoreticians question the justification of its use, but it turned out to be an effective approach in computational chemistry. However, the application of DFT is far from trivial. In fact, only with the availability of simulation programs has DFT become applicable in a wider range of quantum chemistry problems. Again, the mediating simulation models make the relation between theory and phenomena opaque. The DFT is used to obtain quantitative rules and its success is unquestioned. Consequently, in 1998 the Nobel Prize in chemistry went to W. Kohn and A. Pople to equal parts. The latter had written extensive simulation programs that ensured DFT's widespread use.



Figure 3: Electron density of nitroglycerine, The Coloring is altered to fit black-and-white print (from the Nobel e-Museum, <http://www.nobel.se/chemistry/laureates/1998/illpres/density.html>).

That simulations have become eligible for a Nobel Prize underlines their status as theoretical instruments. This leads us directly back to the report on “Theory and Modeling in Nanoscience” and its call for more quantitative understanding. The report mentions a paradigmatic example for the success of nanotechnology. It is the so-called Giant Magnetoresistance (GMR) that has led to miniaturized hard-disks only a few years after the discovery of this rather obscure effect. The key for this extraordinary quick development from an obscure effect to a reliable product of nanotechnology was just the “quantitative understanding” that could be provided by DFT. The report itself thus provides an instance for the desired kind of “quantitative understanding”, namely the DFT-account of the GMR which is essentially a simulation-based approach.

The goal is not theory-based insight as it is elaborated in the philosophical literature about scientific explanation. Rather, the goal is to find stable design-rules, rules that might even be sufficient to build a reliable nano-device.¹ Thus, clearly, simulation does not meet the high standards of theoretical explanation, nevertheless, it offers potential for intervention. This challenges the received criteria for what may count as adequate quantitative understanding.

We have observed that simulations have a Janus-faced character which reveals properties of both experiment and theory. Yet, the hybrid epistemological status of simulations is precisely what undermines the alternative assumed in the question. Thus, I conclude that simulations are both part of the problem *and* the solution. The judgment depends on how the problem is formulated and “understanding” is conceived. From the perspective of theory-based explanations, simulations are part of the problem. But they answer the needs of applied science to work with stable design-rules. From this perspective, therefore, simulations also offer the solution.

The simulation method is continuing its triumphal march through large parts of the sciences, observable particularly in nanoscience. The methodological shift connected with simulations seems to indicate that the role of design-rules becomes more important at the expense of theories. And this, in turn, has the potential to change the very conception of scientific understanding.

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Notes

- ¹ See Roukes 2001 for a consideration of rules versus laws. The claim that theory leaves centre stage is not uncommon in current science studies, see, for example, Hessenbruch 2003.

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Von Neumann, Self-Reproduction and the Constitution of Nanophenomena

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Abstract. As part of a larger study of the immediate antecedents of nanoscience and nanotechnology, I examine, in this paper, the role played by John von Neumann's work on self-reproduction in the constitution of these fields (see especially von Neumann 1951, 1956 and 1966). Von Neumann's proposals have always been characterized by an overall unified vision, in which, depending on the domain under consideration, a given logic, specific mathematical theories, probability and the relevant scientific theories were integrated in a clear and well-motivated way. I discuss how this overall vision prompted von Neumann to develop his work on self-reproduction, and how this vision was then transferred to nanoscience and nanotechnology. In particular, I examine the influence of von Neumann's proposals in the development of Eric Drexler's work in molecular manipulation and computation (Drexler 1992). By understanding the influence that von Neumann's work had in nanotechnology and nanoscience, a different – and perhaps slightly more unified – picture of these fields emerges.

Introduction

Despite being relatively new, nanoscale research already involves delicate historical and conceptual issues. Why was 'the' field (to the extent that there is such a well-defined field!) constituted in the way it was? Which criteria have been used to stabilize nanophenomena in their current shape?

In this work, I start to address these issues by discussing some forerunners and immediate antecedents of nanoscale research. In particular, I examine how the interaction between what is physically and mathematically possible, but also impossible, in this domain has shaped the constitution of nanophenomena. Two forerunners, in particular, should be considered: Richard Feynman and John von Neumann. In "There's Plenty of Room at the Bottom", Feynman outlined a vision for the development of nanoscience. He advanced, for the first time, the idea that it should be possible to build objects atom by atom (Feynman 1960). Feynman was concerned with exploring what was physically possible to do at the nanoscale, and he outlined the benefits that should be expected from such a research. Not surprisingly, the nanoscience community took the work as a founding document.

In a series of works on the theory of automata, John von Neumann provided a different picture. He explored what was mathematically and logically possible, but also impossible, to do in the process of building reliable organisms from unreliable components (von Neumann 1951, 1956, and 1966). Although there has been a considerable amount of reflection on Feynman's contribution, especially in the nanoscience community, von Neumann's work has received significantly less attention. By focusing on von Neumann's contribution, a better understanding of the emergence of the theories of automata and self-reproduction is provided. We also obtain a new perspective on the role played by these theories in the constitution of nanotechnology, nanoscience, and the relevant phenomena.

But there's an additional reason to focus on von Neumann's contribution. As will become clear, von Neumann articulated throughout his career a *unified* picture of various domains of science, exploring and establishing connections between apparently unrelated areas. For example, on his view, logic, geometry, and probability are context dependent and should emerge from the formalism of the relevant field to which they are applied (von Neumann 1954). It's not by chance, then, that von Neumann developed quantum logic in the context of quantum mechanics (Birkhoff and von Neumann 1936), and various probability models depending on the particular areas of physics one considers (von Neumann 1937). Furthermore, as we will see, von Neumann showed the need for continuous methods not only in the foundations of quantum mechanics – elaborating the theory of continuous geometry (von Neumann 1960, 1981) – but also in the theory of computation – generalizing the usual discrete approaches found in the area (von Neumann 1951). Von Neumann also searched for a *unified* way of introducing probability in quantum theory, which eventually led him to go beyond his own Hilbert space formalism for quantum mechanics (Rédei 1997). As we will see below, the situation is in no way different when von Neumann developed his theories of automata and self-reproduction. Several moves made by him resulted from the attempt to articulate a *unified* approach to these theories. It's my hope to indicate that, by examining the influence that von Neumann's work had on nanotechnology and nanoscience, it will be possible to see how a more unified picture of *these* fields can emerge.¹

I first sketch, in Section 1, a conceptual framework in terms of which the study of von Neumann's work will be articulated. The framework combines features of Peter Galison's work in *Image and Logic* (Galison 1997) with some additional aspects of an analysis of scientific practice. I then provide, in Section 2, some of the conceptual background for von Neumann's work on self-reproduction, examining key aspects of his work on large-scale computing machines and the theory of automata. In this way, in Section 3, all the elements to discuss von Neumann's theorem regarding self-reproduction will be on the table. I present the theorem and consider its significance. Finally, in Section 4, I examine the impact of von Neumann's work on self-reproduction to the constitution of nanophenomena, by exploring the role played by this work in Eric Drexler's conceptualization of nanotechnology (see Drexler 1986, 1992). A brief conclusion follows.

1. A Conceptual Framework

To examine von Neumann's contribution, it is useful to have a conceptual framework to guide and give some structure to the questions that will be raised. I'll adopt, in part, a framework Peter Galison developed to describe theoretical practice in microphysics (Galison 1997), but which turns out to be extremely helpful to the historical study of nanoscience. Just as the case of microphysics Galison examines, nanoscience – taken as a discipline – is a genuinely interdisciplinary field, with contributions emerging from a very special combination of chemistry, biology, engineering, and computer science (among other domains). The particular types of interaction among these areas are diverse and complex, just as are diverse and complex the interactions between microphysics and engineering (among other fields) that Galison describes. Although it is a substantive issue how to characterize the particular forms of interactions among fields in nanoscience, there is no question that *there are* such interactions. This becomes particularly clear, for example, in Drexler's work, where different areas of chemistry, biology and computer science are woven together to articulate an account of molecular manipulation and computation (see Drexler 1992). As I'll discuss, von Neumann's approach played a significant role in Drexler's work, providing part of the theoretical context in which the work emerged. To represent the com-

plexity and diversity of this trajectory in the history of nanoscience within a well-structured setting, Galison's approach seems to be perfectly suited.

As will become clear, Galison's framework has the advantage of highlighting important features of scientific practice, while still being plastic enough to be applicable to areas other than microphysics. The framework has four main components (see Galison 1997 for details):

(a) *Constraints and contexts*: Despite the plurality of approaches often found in science, scientific practice is *constrained* in various ways. *Theories* impose constraints on the acceptable solutions to problems. But these constraints also indicate how new problems can be solved. *Experiments*, in turn, constrain the way theories are formulated, entertained, tested, rejected or accepted. They also provide new parameters for theory construction. *Instruments* constrain the practice of discovery in laboratories, while they also produce new data for theoretical and experimental research. This is, of course, all done in a *social* context, where *political* considerations play a variety of roles.

In other words, there are several kinds of constraints: *theoretical*, *experimental*, *instrumental*, *political* and *social*. These constraints play both a negative role of limiting, say, the range of acceptable solutions to various problems, and a positive role of suggesting solutions to new problems.

Not only is scientific practice constrained in the above ways, but it is also something *local* and *contextual*. Different scientific communities have different languages, employ different standards and adopt different norms to conduct their research. It comes as no surprise then that different scientific communities pursue and assess their research according to different criteria. As a result, scientific practice becomes a contextual and local phenomenon. It seems appropriate to examine it in this way.

(b) *Trading zone*: A major challenge to any genuinely interdisciplinary work is to have a common language in which the different assumptions, theoretical commitments and proposals of the various scientific communities in question can be expressed and communicated. In order to develop a genuinely interdisciplinary research – that bridges very different communities (physicists, engineers, mathematicians etc.) – scientists develop a 'trading zone'. In this 'zone', through the development of a simplified language, scientists are able to communicate, despite the (often dramatic) differences in their backgrounds. Of course, the language in question, being extremely simplified, is unable to capture the full content of the theories and methods of the various communities. But the language typically has enough resources to make possible the communication between the members of these communities.

(c) *Image and logic*: In Galison's view, there are two different traditions of instrumentation in physics (Galison 1997). According to the *image tradition*, images of natural processes should be produced with such clarity that these images could serve as evidence for the existence of a new entity. This involves the use of cloud chambers, nuclear emulsions, and bubble chambers. According to the *logic tradition*, evidence is established in a different way. Through the use of electronic counters, coupled in electronic logic circuits, masses of data are aggregated. And through the application of statistical techniques to these data, arguments for the existence of the entities in question are produced. Of course, this whole approach depends on very different instruments than the image tradition, including counters, spark chambers, and wire chambers. These traditions clearly use different tools to achieve their goals, and have succeeded in their own different ways. There is no doubt about the importance of these traditions. In fact, as Galison argues, the history of 20th century microphysics is, in many ways, the history of the vicissitudes of these two traditions of instrumentation. As will become clear, these traditions also found their way into nanoscience and nanotechnology.

(d) *Three levels of analysis*: Throughout the discussion below, three levels of analysis will be explored. The first level examines *theoretical practice*,² and it engages the role played by various theories in the formulation of several approaches to nanotechnology. The second level concerns *experimental practice*, the practice of experimentation and its connection to theoretical practice. Finally, the third level addresses *instrumental practice*, exploring the role played by various types of instruments in the constitution of the relevant phenomena. There are, of course, important connections between these three levels of analysis, and the interconnection between them in the context of nanoscience and nanotechnology will be explored in the discussion that follows.

Having briefly indicated the overall framework to be used in this paper, I am now in a position to begin the analysis of von Neumann's work in light of the conceptual setting just presented.

2. Background to von Neumann's Approach

Von Neumann was always concerned with developing new strategies for problem solving, whether such problems involve novel ways of representing the state of a quantum system or the strategic interaction between economic agents. As we will see, it was ultimately this unfathomable interest in heuristics – particularly in the context of mathematics – that led von Neumann to be involved with large-scale, high speed computing. And it was in the context of his work on computing and automatic machines that von Neumann first articulated his approach to self-reproduction. So, I will start by providing some of the background to von Neumann's work on computing machines and the nature of the problems that led him to address the issue of self-reproduction.

In a paper written in 1946 with Herman Goldstine, "On the Principles of Large Scale Computing Machines", von Neumann points out:

In this article we attempt to discuss [large-scale, high speed, automatic] machines from the viewpoint not only of the mathematician but also of the engineer and the logician, *i.e.* of the more or less (we hope: 'less') hypothetical person or group of persons really fitted to plan scientific tools. We shall, in other words, *inquire into what phases of pure and applied mathematics can be furthered by the use of large-scale, automatic computing instruments* and into *what the characteristics of a computing device must be in order that it can be useful in the pertinent phases of mathematics.* (Goldstine & von Neumann 1946, p. 317; italics added.)

It is important to note that, given the way von Neumann conceptualizes the issue, it concerns people working across very different disciplines: from mathematics through engineering to logic. Clearly, the implementation of a project of this magnitude requires the development of strategies of communication between different fields, and what each participant has to contribute and can get from the project is very different. The concerns of mathematicians are not the same as those of the engineers, which in turn are different from the logicians'. Similarly for the expertise each of them will bring. In the end, the articulation of such an enterprise ultimately demands a 'trading zone'.

Note also the *constraints* on the problem. There is a two-way relation between the computing machines to be devised and their users (particularly if we consider mathematicians): First, mathematics should be developed further by the use of these machines. For example, the solution of some problems that were intractable at the time should be achieved through computing machines. Second, the machines themselves should have an architecture that supports such mathematical developments. In fact, as von Neumann emphasizes, analytical methods at the time were inadequate for the solution of a number of non-linear par-

tial differential equations. Large-scale computing machines were expected to be particularly useful in this context.

In other words, von Neumann's concern with heuristic devices for mathematics motivated him to be involved with high-speed computers. But, in von Neumann's view, the implementation of such computing machines required a theory of automata. And as will become clear in a moment, it was in the context of his theory of automata that von Neumann was led to examine self-reproduction. Now, according to von Neumann, what were the main features of a theory of automata?

In 1951, in an article on "General and Logical Theory of Automata", von Neumann answered this question by putting forward a program to elaborate a whole theory of automata. To develop the theory, von Neumann explicitly invoked two *constraints*: (a) to explore, within certain boundaries, the *analogy with living organisms*, and (b) to use *structures from (mathematical) logic*. I will elaborate on each of these constraints in turn.

(a) With regard to the *analogy with living organisms*, von Neumann tried to model the functioning of the automaton, in part, in analogy with the functioning of a neuron, and the way in which the latter transmits impulses. Given the remarkable ability that neurons have to transmit impulses and information, it certainly seems to be an appropriate starting point for a theory of automata. This is particularly the case if we first realize the important *differences* (or *disanalogies*) between automata and neurons. In fact, von Neumann stressed two important dissimilarities.

First, the extremely *small size* of the neuron compared to the vacuum tube (then used in computers). The neuron is not only *smaller*, but *much more efficient* than the vacuum tube. As von Neumann notes: "the basic fact is, in every respect, the small size of the neuron compared to the vacuum tube. [...] What is it due to?" (von Neumann 1951, p. 403) This was not a rhetorical question on von Neumann's part. He had a partial explanation for the greater efficiency of neurons in comparison to vacuum tubes, despite the smaller size of the former: it referred to the *materials* that constituted each of them. In the case of vacuum tubes, we have a combination of metals separated by vacuum; in the case of neurons, we have the cytoplasm and nucleus of human cells.

In fact, the different *materials* that characterize neurons and computers amount to a *second disanalogy* between the two. This also helps to explain the difficulties faced at the time in successfully developing computing machines. As von Neumann points out:

The weakness of this technology lies probably, in part at least, in the *materials employed*. Our present techniques involve the using of metals, with rather close spacings, and at certain critical points separated by vacuum only. This combination of media has a peculiar *mechanical instability* that is entirely alien to living nature. By this I mean the simple fact that, if a living organism is mechanically injured, it has a strong tendency to restore itself. If, on the other hand, we hit a man-made mechanism with a sledge hammer, no such restoring tendency is apparent. (von Neumann 1951, pp. 404-405; italics added.)

That is, the mechanical instability and lack of a self-restoration tendency in computing machines are significant differences between these machines and neurons, and these differences arise, at least in part, from the dissimilar materials used. Note however the strange slipperiness on von Neumann's part from mechanical instability to lack of self-restoration in the case of living organisms. The mechanical instability may lead a given object to suffer some sort of malfunction or to be somehow damaged. But clearly, even in the case of living organisms, this doesn't mean – nor does it entail – that the object in question will go through any self-restoration. The two notions (mechanical instability and lack of self-restoration) are not obviously equivalent.

But the mechanical instability also has a significant consequence for the size of the computing machines. In von Neumann's view, it is in virtue of that instability that the size of computers hasn't been reduced yet. And the instability, in turn, is the outcome of the materials that have been employed:

It is this mechanical instability of our materials which prevents us from reducing sizes further. [...] Thus it is the inferiority of our materials, compared with those used in nature, which prevents us from attaining the high degree of complication and the small dimensions which have been attained by natural organisms. (von Neumann 1951, p. 405)

In other words, von Neumann emphasizes the limitations due to the *materials* used to produce computers – this is a constraint at the *instrumental* level. Moreover, he also highlights the limitations due to the *scale* of the relevant objects (after all, the size of the neuron is an important factor in the successful transmission of the relevant bits of information). Issues about scale also provide a limitation at the instrumental level. By identifying these two instrumental differences between neurons and computers, von Neumann is clear about the areas in which further work still needs to be pursued: to identify new and better materials and, through them, to implement and construct computing machines at a smaller scale.

But, according to von Neumann, there is still an additional constraint to be met. This one arises at the *theoretical* level:

(b) The use of *structures from (mathematical) logic* is crucial for von Neumann's project. After all, logic provides an overall framework to represent the abstract components of computation and to assess the adequacy of each step. In von Neumann's view, it's only in terms of a mathematical-logical theory of computation that the limitations found in the automata of his time could be overcome. As he points out:

We have emphasized how the complication [complexity] is limited in artificial automata [...]. Two reasons that put a limit on complication [complexity] have already been given. They are the large size and the limited reliability of the componentry that we must use. [...] There is, however, a third important limiting factor [...]. This factor is of an intellectual, and not physical, character. The limitation which is due to *the lack of a logical theory of automata*. We are very far from possessing a theory of automata which deserves that name, that is, a properly *mathematical-logical* theory. (von Neumann 1951, p. 405; italics added.)

According to von Neumann, it is a *theoretical constraint* on the theory of automata that it be framed in terms of *mathematical logic*. But why should the theory satisfy this constraint?

This is a point where von Neumann's search for a unified account plays a significant role. A theory of automata should provide an account of reasoning processes, accommodating the way in which knowledge can be represented and inferences obtained. Mathematical logic is, of course, particularly useful for that, even though, given the way in which it has traditionally been formulated, it has a major limitation:

Everybody who has worked in formal logic will confirm that it is one of the technically most refractory parts of mathematics. The reason for this is that it deals with *rigid, all-or-none concepts*, and has *very little contact with the continuous concept of the real or of the complex number*, that is, with mathematical analysis. Yet analysis is the technically most successful and best-elaborated part of mathematics. (von Neumann 1951, p. 406; italics added.)

What von Neumann proposes is to re-conceptualize the logical tradition in terms of analysis, and elaborate a theory of automata in this new setting. Properly characterized, mathematical logic could overcome its traditional all too rigid outlook. By incorporating resources from real and complex analysis, mathematical logic could become still more useful

to model the complexities inherent in reasoning and in the representation and transferring of information.

The incorporation of analysis into logic is also achieved by the development of set theory, in which results from both real and complex analysis can be formulated and established. In the 1920's, von Neumann provided an extremely elegant axiomatization of set theory (von Neumann 1925), a system that is now called von Neumann-Bernays-Gödel. It was an important feature of von Neumann's work that his system was *finitely axiomatizable*, given that the main rival system of set theory at the time, the one provided by Zermelo, *couldn't* be finitely axiomatized (Zermelo 1908). With infinitely many axioms, it's not possible to express a system of set theory as the conjunction of its axioms – unless one invokes some admittedly artificial devices, such as introducing infinitary languages, that arguably no human could ever actually use.³ Given the motivation to use the resources of mathematical logic to develop a theory of computation, devices of this nature wouldn't be of much use for von Neumann.

The emphasis on continuous methods rather than discrete ones is an important component of von Neumann's overall approach, and it is a unifying theme throughout much of his work. This emerges from von Neumann's emphasis on the resources for modeling provided by analytical methods. For example, in the 1930's, von Neumann developed the theory of *continuous geometry*, a generalization of projective geometry involving a *continuous* number of dimensions (for an overview, see von Neumann 1960 and 1981). The development of this kind of geometry emerged from von Neumann's work in the foundations of quantum mechanics. It was the result of his attempt to develop a mathematically unified account of quantum theory, going beyond his previous work on the Hilbert spaces approach (von Neumann 1932). In terms of continuous geometry, and using what we now call von Neumann algebras, von Neumann showed how quantum probability could emerge from the formalism of quantum theory in a natural way – even when one considered quantum systems with infinite degrees of freedom. This result couldn't be obtained using the Hilbert space formalism (see Rédei 1997 and 1998).

It is in this context of trying to extend the logical paradigm of his time to incorporate analysis, and searching for a better, more sophisticated theory of automata that von Neumann faced an additional alleged limitation to that theory. Given the analogy with living organisms that motivated so many aspects of the theory of automata, it's not surprising that von Neumann considered an additional putative dissimilarity between living organisms and computing machines. Living organisms have the ability to reproduce, and some to self-reproduce. Given that automata are artificial entities, does that mean that they are in principle unable to self-reproduce? In von Neumann's view, the answer is *negative*. This provides, of course, additional evidence for the analogy between living organisms and computers. To show why this is the case, von Neumann was led to study the properties of self-reproduction in the context of his theory of automata.

3. Von Neumann and Self-Reproduction

Von Neumann starts his analysis of the notion of self-reproduction by identifying a difficulty that the notion seems to face. It addresses the very possibility of devising self-reproducing automata, given a “degenerating tendency” regarding the complexity of the automata involved in the task:

If an automaton has the ability to construct another one, there must be a decrease in complication [complexity] as we go from the parent to the construct. That is, if A can produce B, then A in some way must have contained a complete description of B. [...] In this sense, it would therefore seem that a certain degenerating tendency must

be expected, some decrease in complexity as one automaton makes another automaton. (von Neumann 1951, p. 415)

This is, of course, an objection against the possibility, in principle, of self-reproducing automata. If the degree of complexity has to decrease as we move from the parent automaton to the offspring, we won't have a case of self-reproduction, given that the offspring is not of the same kind as the parent, but is a less complex type of object.

In response to this objection, von Neumann relied, once again, on the analogy with biological organisms:

Although this has some indefinite plausibility to it, it is in clear contradiction with the most obvious things that go on in nature. Organisms reproduce themselves, that is, they produce new organisms with no decrease in complexity. (von Neumann 1951, p. 415)

But this response doesn't completely settle the issue, as von Neumann was certainly aware. After all, even if organisms reproduce themselves without decreasing the complexity of the offspring, why would that establish that *artifacts*, such as *automata*, could also self-reproduce?

To answer this question, von Neumann has to tackle head-on the problem of the possibility of self-reproducing automata. In fact, he proves that it is *mathematically* possible for an automaton to self-reproduce. To establish this result, von Neumann generalizes a theorem first proved by Turing regarding the existence of "universal automata" (a particularly strong kind of Turing machine). An automaton is said to be *universal* if it can produce any sequence that can be produced by any automaton. In other words, a universal automaton is at least as effective as any conceivable automaton – including one that is twice its size and complexity! How is this possible? By using an idea of Turing's:

Turing observed that a completely general description of any conceivable automaton can be [...] given in a finite number of words. This description will contain certain empty passages – those referring to the functions [...] which specify the actual functioning of the automaton. When these empty passages are filled in, we deal with a specific automaton. As long as they are left empty, this schema represents the general definition of the general automaton.

Now it becomes possible to describe an automaton which has the ability to interpret such a definition. In other words, which, when fed the functions that [...] define a specific automaton, will thereupon function like the object described. [...] This automaton, which is constructed to read a description and to imitate the object described, is then the universal automaton in the sense of Turing. (von Neumann 1951, p. 417)

But there is a significant limitation in Turing's conception. As von Neumann notes, Turing's proposal is too narrow in one important respect. To function as a self-reproducing automaton, a computing machine has to yield as output *another automaton*, rather than, say, simply a sequence of numbers (typically, zeros and ones). Talking about Turing's machines, von Neumann insists:

His automata are purely computing machines. Their output is a piece of tape with zeros and ones on it. What is needed [...] is an automaton whose output is other automata. (von Neumann 1951, p. 418)

To establish the possibility of automata that generate other automata, and thus to dispel any worries regarding the latter, while substantially extending Turing's view, von Neumann provides his theorem regarding self-reproduction.

The key ideas of the theorem are very clear, as von Neumann clearly indicates (see von Neumann 1951, p. 420). Let A be an automaton with the property that, when supplied with the description of any other automaton, it constructs that object. Let B be an automaton that can copy any instruction I that is furnished to it. Combine the automata A and B with each other, and with a control mechanism C . C does the following. Let A be supplied with an instruction I . Then C will first make A construct the automaton described by the instruction I . Then C will make B copy the instruction I , and insert the copy into the automaton that has just been constructed by A . Finally, C will separate this construction from the system $A+B+C$, and take it as an independent object. Call D the total aggregate $A+B+C$.

In order to function, the aggregate $D = A+B+C$ must be supplied with an instruction I . Of course, this instruction has to be inserted into A . Now form an instruction I_D , which describes this automaton D , and insert I_D into A within D . Denote the aggregate which now results by E .

E is clearly self-reproductive. Note that no vicious circle is involved. The decisive step occurs in E , when the instruction I_D , describing D , is constructed and attached to D . When the construction (the copying) of I_D is called for, D exists already, and it is in no [way] modified by the construction I_D . I_D is simply added to form E . Thus there is a definite chronological and logical order in which D and I_D have to be formed, and the process is legitimate and proper according to the rules of logic. (von Neumann 1951, p. 420)

Note the role played by mathematical logic throughout this construction. The process of construction of self-reproducing automata is modeled by the process of construction of the cumulative hierarchy in set theory (whose development von Neumann was, in part, responsible for in the 1920's). The set-theoretic cumulative hierarchy is constructed by stages, and at each stage, only sets that have already been constructed in previous stages can be used. (In this way, set-theoretical paradoxes can be avoided.) Similarly, to avoid a vicious circle in the construction of self-reproducing automata, von Neumann is very clear about what is constructed in each stage. As he makes it clear, the construction of the new automaton E is only possible *after* the construction of the automaton D and the instruction I_D , and D and I_D basically encompass *all* that is needed to construct E . So, the possibility of constructing self-reproducing automata is definitely open.

This result raises a number of questions, and someone may be tempted to use them to undermine the significance of the theorem. For example, what is special about the fact that it is mathematically possible to construct an automaton that self-reproduces? To be completely convinced of the possibility of self-reproduction isn't it enough just to look at nature, with the astonishing spectacle of organisms that reproduce themselves? Why do we need a mathematical theorem to prove such an obvious fact?

It's important to note, in response, that these questions miss the point of von Neumann's result. There is no doubt that nature provides a remarkable variety of self-reproducing systems. But, as noted above, in nature, we are not talking about *artifacts*; we are considering *living creatures*. There is no doubt that living beings of the appropriate sort (e.g. which are members of the same species) can reproduce, and in some cases even self-reproduce. What is definitely *not* obvious is that *artifacts*, such as an automaton, could do the same – even in principle. And this is the point of establishing von Neumann's theorem.

I'm here assuming, with von Neumann, a distinction between *natural* and *artificial* systems. The distinction is, of course, *vague*. It's vague in the technical sense that there are clear-cut cases of natural systems (such as untouched parts of the *Amazon jungle*); clear-cut cases of artificial systems (such as the *software* I am using to edit this paper); and cases in which it is not clearly determined whether they constitute natural or artificial systems (such as a *glass of beer*). Despite the vagueness of the distinction between the natural and the

artificial, it is important to recognize that *there is still a distinction*. Typically, those who deny the natural/artificial distinction are only denying that there is a *sharp* distinction here.⁴ But to appreciate the significance of von Neumann's theorem, all that is needed is the existence of an *unsharp* distinction. After all, as long as some automata are on the artificial side of the divide – and this is precisely the case considered by von Neumann – it is indeed not obvious why they should self-reproduce.

Note also that granting the existence of the distinction between the natural and the artificial in *no way* undermines von Neumann's use of natural processes to model various aspects of artificial systems (such as the automata he studies). Any analogy has its limitations – there are always *negative* analogies – and, as noted above, von Neumann is perfectly aware of them. But these limitations don't undermine the existence of the *positive* analogies: the common features that natural and artificial systems share, despite their differences. And these common features ground, in part, the way in which von Neumann models his automata.

Finally, note that von Neumann is particularly concerned with establishing the logical – but also mathematical – possibility of self-reproducing automata. This is the reason why he emphasizes the fact that *no vicious circle* is involved in the process of construction of a new automaton from another. So, in principle, it's not *logically* impossible to develop self-reproducing automata. And it's not *mathematically* impossible either. The construction carried out in von Neumann's proof is articulated in a simple mathematical setting. In fact, as already noted, the construction is modeled in set theory. As a result, nothing in the proof is incompatible with classical mathematics.

This raises the issue of what is mathematically and logically *impossible* to achieve according to von Neumann's approach to self-reproduction. The answer emerges from the mathematical framework von Neumann uses to articulate his proof. The limitative results from mathematical logic regarding what *cannot* be computed clearly apply to the program of self-reproduction he devised. Von Neumann is, of course, perfectly aware of this fact as well. And he tries to overcome some of these results by insisting that a new framework for computation is required, one that is based on analysis rather than on combinatorial systems. In this way, by emphasizing the continuous nature of the computational processes, a more refined, and more powerful, approach to computation could be provided.

To sum up the discussion so far: von Neumann employed, in a particularly fruitful way, structures from mathematical logic, such as Turing machines suitably adapted and set-theoretical constructions. These structures provided an important *constraint* at the *theoretical level* for his work. Clearly, von Neumann's contribution sides with the *logic* tradition of computer making. But von Neumann is also changing and restructuring this tradition, by broadening the logical tools used, and bringing logic closer to analysis than to combinatorics. Moreover, von Neumann also emphasized the *instrumental constraints* imposed by the *materials* used in the construction of computing machines and the *scale* of the components that were employed at the time. He clearly highlighted the need for the development of better materials. Now, with the *mathematical* possibility of self-reproducing automata, the case is open for their *physical* construction. Although there is still a long way to go, at least the first step was taken.

4. Von Neumann, Drexler and Nanophenomena: Roots to Nanoscience

What is the impact that von Neumann's work had on nanoscience and nanotechnology? To answer this question, I will discuss the influence of this work in the development of a very interesting approach to nanoscale phenomena: Eric Drexler's vision for the field (see Drexler 1992 and 1986).⁵

Drexler is very clear about the nature of his investigation. It is what he calls *theoretical applied science* (Drexler 1992, pp. 489-491). This is a “mode of research which aims to describe technological *possibilities* as constrained not by present-day laboratory and factory techniques, but by physical law” (Drexler 1992, p. 489; emphasis added). The goal, then, is to examine what is feasible, given *physical* constraints on the phenomena under investigation, rather than technological limitations that might be present at the time of the research. The typical product of theoretical applied science, similarly to theoretical physics, is not a family of experimental results, but a “theoretical analysis demonstrating the *possibility* of a class of as-yet *unrealizable* devices, including estimated lower bounds on their performance” (Drexler 1992, p. 489; the first emphasis added). In other words, theoretical applied science is concerned with the study of technological *possibilities*, which immediately links it with research in science and engineering. Talking about theoretical applied science, Drexler points out that

Its technical content (drawing extensively from physical theory and experimental results) and the nature of its product (knowledge, rather than hardware) link it closely to scientific research. Yet it is also closely akin to engineering: studying technological possibilities poses problems of design and analysis. The products of theoretical applied science can be termed *exploratory designs*, although some take the form of a rather abstract analysis. (Drexler 1992, p. 490)

Now among these exploratory designs, Drexler studies nanomechanical computational systems (Drexler 1992, pp. 342-371), molecular assemblers (*ibid.*, pp. 372-410), and molecular manufacturing systems (*ibid.*, pp. 411-441). And throughout the elaboration of these designs and analyses, a crucial component plays a significant role. Just as von Neumann had done in the context of his theory of automata, Drexler also explores *analogies between biological phenomena and events at the nanoscale* as a guiding principle in theory construction. Similarly to von Neumann’s approach, this also includes examining significant *dissimilarities* between biological phenomena and some constructions at the nanoscale. For my current purposes, it is enough simply to illustrate this move with a typical example.

In his discussion of the research that forms the foundation for his own approach, Drexler notes:

Most experimental research in molecular electronics has focused on the development of molecules that exhibit useful electronic properties in thin films or in microscale aggregates; some proposals, however, have focused on the construction of computational devices in which individual molecules or moieties would serve as signal carrying and switching elements. (Drexler 1992, p. 509)

A seminal work by Robinson and Seeman is then referred to. In this work, the design of a biochip is described through the formulation of a self-assembling molecular-scale memory device (see Robinson and Seeman 1987). Clearly, the strategy consists in exploring biological grounds for molecular electronics. As Drexler notes, works such as this

have suggested various combinations of chemical synthesis, protein engineering, and DNA engineering to make *self-assembling systems on a broadly biological model*. This objective is a form of molecular systems engineering (though not of machines or manufacturing systems) and the capabilities required would resemble those discussed in Chapter 15 [the chapter on macromolecular engineering in Drexler’s 1992 book]. (Drexler 1992, p. 509; emphasis added.)

In other words, it is through a biological model that molecular systems engineering could be implemented, even though the particular goal that Drexler has – namely, to develop molecular manufacturing systems – had not been pursued before.

As passages such as the above indicate, in Drexler's approach to nanotechnology, there is a significant integration between several areas of research (Drexler 1992, pp. 507-511). In fact, the foundation for Drexler's approach emerges from related research on a number of areas, in particular, chemistry, molecular biology, protein and mechanical engineering, as well as computer science and proximal probe technologies (especially, the use of scanning tunneling and atomic force microscopes). Interestingly enough, the integration between these areas is achieved through an overarching vision, dominated by the goals of theoretical applied science, in which the autonomy of each area is preserved, and the relevant results from each area are invoked to establish the new outcomes. This means that a genuine 'trading zone' has to be created, which requires meeting constraints at the theoretical and instrumental levels.

Despite the fact that work in so many fields forms the foundation for Drexler's proposal, the direction he favors differs from the traditional approach. The divergence from the latter view emerges from an important methodological difference between the traditional approach, which is *top-down* oriented, and Drexler's *bottom-up* methodology (Drexler 1992, p. 508). According to the top-down approach, favored for example by microtechnology, we start with "large, complex, and irregular structures", and we try to reduce their sizes; the challenge, then, is to "make imprecise structures smaller" (*ibid.*, p. 508). This differs significantly from Drexler's bottom-up approach. According to this approach, which is ultimately grounded on chemistry, we start with "small, simple, and exact structures", and we try to increase their size; the challenge, then, is to "make precise structures larger" (*ibid.*, p. 508).

As we saw, in dealing with his theory of automata, von Neumann clearly recognized the importance of *size* as a limitative constraint on the efficiency of artificial computing machines. Even though von Neumann's overall approach seemed to be closer to the top-down strategy (recall his discussion of how different materials may allow a decrease in the automata's size), his theorem regarding self-reproducing automata was based on a clearly *bottom-up* construction. In fact, the whole point of using the set-theoretic cumulative hierarchy as a model for von Neumann's mathematical construction of self-reproducing automata was exactly to ensure a bottom-up approach. As we saw, in this way, von Neumann avoided the objection that self-reproducing automata involved a vicious circularity.

Given considerations such as these, it comes as no surprise that Drexler clearly acknowledged the importance of von Neumann's work for the development of his own approach to nanotechnology. First, von Neumann's work on the theory of automata is quoted in both *Nanosystems* (Drexler 1992) and in *Engines of Creation* (Drexler 1986). Moreover, in a private communication (September 12, 2003), Drexler pointed out: "I'd been familiar with the outlines of [von Neumann's] work on self-replicating systems before my own work turned toward nanotechnology, hence it was part of the intellectual foundation for that work." As for the significance to nanotechnology of von Neumann's work on self-reproduction, Drexler is also very clear: "[von Neumann's] work originated the idea of non-biological self-replicating systems, which was central to early concepts for the implementation and use of large-scale systems of productive nanomachinery." However, Drexler currently thinks that, contrary to "widespread impressions that [he, Drexler] had a role in forming", self-replication is "not, in fact, necessary for the implementation and use of large-scale systems of productive nanomachinery". In fact, in his present view, self-replication is feasible, potentially safe, but ultimately unnecessary (Phoenix and Drexler 2004). Despite this, Drexler notes that von Neumann's work "strongly influenced [nanotechnology]", even though, as far as he knows, it "did not anticipate its essential features".

I think this establishes, without doubt, the importance that von Neumann's work had in the constitution of a significant approach to nanotechnology – namely, Drexler's – and hence, indirectly, to the overall construction of the field. Far more could be said here, of

course, beyond the methodological and conceptual strategies linking von Neumann and Drexler.⁶ But the existence of these shared methodological strategies, although not conclusive on its own, is already significant. In fact, it would be misleading to claim that all that Drexler's and von Neumann's approaches had in common was the fact that they followed the old idea that 'technology imitates nature.' The way in which von Neumann and then Drexler use aspects of natural systems to model technical devices – being sensitive to *scale* and to the *materials* of the relevant objects – is remarkably similar. And together with Drexler's explicit acknowledgement of the role of von Neumann's work in his own, the shared methodological strategies undoubtedly establish the historical link between von Neumann and Drexler.

5. Conclusion

Von Neumann clearly had a unified approach to the various foundational issues he addressed, from quantum mechanics to the theory of automata. In his view, logic, mathematics, probability and the relevant scientific theories need to be articulated in a unified and well-motivated way. As noted above, in von Neumann's view, the notion of probability in quantum mechanics should emerge naturally from the formalism of the theory, even when we consider quantum systems with infinitely many degrees of freedom. To fully articulate this view, von Neumann then developed a completely new branch of mathematics: continuous geometry. Similarly, in the case of his theory of automata, by re-conceptualizing the paradigm of mathematical logic of his time – through the exploration of the resources of analysis and set theory – von Neumann was able to show the mathematical possibility of self-reproducing automata.

Von Neumann's work, and his unified vision for theoretical research, later informed important parts of Drexler's approach to nanotechnology. Just as von Neumann, Drexler also insisted on the importance of exploring analogies with biological systems in the modeling of nanophenomena. And just as von Neumann, Drexler also noted the important limitations of such analogies, and what can be learned from them as guidance for future research. Moreover, just as von Neumann had a unified picture of theoretical research, Drexler also has a unified picture of nanotechnology, one in which the various areas involved – from chemistry through molecular biology to computer science – have to be integrated, even though their autonomy should be preserved along the way. Trading zones have to be constructed to implement the details of such a vision, just as trading zones had to be elaborated in von Neumann's own implementation of his vision for the theory of automata.

Although there is much more to be said, I hope I said enough to *motivate* the idea that a slightly more unified picture of nanotechnology and nanoscience *can* emerge when these fields are examined from the historical perspective suggested here. Of course, identifying the particular historical trend highlighted here is only the first, but a necessary, step in this process – and I plan to explore these issues further in future work. The roots to nanoscience, from von Neumann to Drexler, are rich, sophisticated, unified, and definitely worth exploring. There is a lot there.

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their skepticism, and to Eric Drexler for particularly valuable information. Joachim Schummer commented on my paper in Darmstadt, raising thoughtful and challenging points. Support for this work was given by the National Science Foundation through a NIRT grant.

Notes

- ¹ I am not trying to provide here yet another ‘founding myth’ for nanoscience and nanotechnology. I’m only suggesting that, by exploring a particular trend in the recent history of these areas, it’s possible to conceive of a different, more unified, picture for nano-scale research. In this paper, I only identify this particular historical trend, and sketch its major features. To articulate the details of the resulting (more unified) picture will have to wait for another occasion.
- ² I owe this term to R.I.G. Hughes, who is currently developing a fascinating account of theoretical practice in physics (see Hughes 2004).
- ³ Other devices could be invoked here as well. For example, if the language in question has a truth predicate, it is possible to assert an axiom scheme that encompasses infinitely many sentences at once, such as ‘Every sentence of the form ‘ P or not- P ’ is true’. But with a truth predicate, problems such as the liar paradox emerge, and thus the truth predicate itself becomes suspicious. Alternatively, one could use a device such as the substitutional quantifier. Despite the name, this is not exactly a quantifier, but a technique to generate infinite conjunctions. As a result, roughly speaking, it ends up facing similar problems as the use of infinitary languages.
- ⁴ It is hard to believe that anyone would claim that untouched parts of the Amazon jungle form an *artificial* system, or that the software used to edit this paper is a *natural* system! This would be the outcome of the denial that there is *any* distinction between natural and artificial systems.
- ⁵ This is, of course, only one possible trend to explore. As Joachim Schummer pointed out to me, it’s worth examining the rediscovery of von Neumann’s theory of automata by people working on ‘Artificial Life’ in theoretical biology in the 1980s, and then studying the impact of their work in theoretical nanobiotechnology. I plan to explore this point in future work.
- ⁶ For example, one could analyze the details of the arguments used by Drexler for the possibility of assemblers and compare them with von Neumann’s argument for the existence of self-reproducing automata. Due to limitations of space, I’ll be unable to do that here, but I hope to explore this issue elsewhere.

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How Probe Microscopists Became Nanotechnologists

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Abstract. Nanoscale entities are by definition invisible to the unmediated senses. Yet generating images of these objects has been crucial to the rhetoric of nanotech boosters. Thus, bringing microscopes and microscopists under the nano umbrella has been central to the work of nano proponents. No instruments have been more crucial to this process than the scanning tunneling microscope (STM) and atomic force microscope (AFM). Yet STM and AFM have long histories that precede the advent of nano. I outline this history and show that the connection between probe microscopy and nano is contingent rather than self-evident. The drafting of the probe microscopy community into nano was inspired by role differentiation within that community following the widespread commercialization of the instruments in the early 1990s. As probe microscopists move into nano, it is likely they will remake the field in light of the history of their community.

Introduction

When we talk about nanoscience, there are a few images which often spring to mind, such as Eric Drexler's diagrams of molecular bearings (Drexler 1992), or Jim Gimzewski's fullerene abacus (Cuberes *et al.* 1996), or Don Eigler's famous "IBM" made from xenon atoms (Eigler & Schweizer 1990). Such atomic-scale images have a powerful pull, but their significance is sometimes taken as self-evident, rather than as historically and culturally situated. "Seeing" atoms is often treated, by both participants and analysts, as intrinsically meaningful and fascinating (Barad 1999, Hacking 1992, Buchwald 2000). Seeing and moving atoms is taken as an axiomatically nanotechnological activity, and images of the atom are seen to demonstrate both the reality and the potential of nanotechnology.

I want to problematize these notions by showing that images of the atom only have weight and meaning when mediated through various communities and subcultures. The interplay of different technical subcultures, and different kinds of actors within those subcultures frames how we see and understand the nanoscale. Nanotechnology is a community of communities, and the fields arrayed under its umbrella have long histories that precede their incorporation into nano. Conceptions of nano are diffracted through subcultures with different ways of generating and judging evidence, commercializing knowledge, training new members, and dealing with other communities. The social organization of these subcultures provides for quite different stakes in nano among different actors in those fields. Artifacts and techniques – "boundary objects" (Star & Griesemer 1989) – as well as mediating individuals – "boundary shifters" (Pinch & Trocco 2002, p. 313) – can travel between subcultures, quilting together different patches of the nano world. As analysts, we need to follow such travelers to understand how nano will or will not gather coherence over time. I will illustrate this point by telling a story about the history of scanning probe microscopy (SPM) – especially the scanning tunneling microscope (STM) and atomic force microscope (AFM) – and by showing how different kinds of actors have built different

(AFM) – and by showing how different kinds of actors have built different kinds of links between the nanoscience and SPM communities.

Despite the popularity of STM images of atoms, SPM research is still a small fraction of the work that counts as “nanoscience”. Moreover, the atomic manipulation touted as exemplary of nanoscience is still far from the mainstream of probe microscopy. Many SPMers use the microscopes to examine “nanoscale” objects, and might willingly be called “nanoscientists” on occasion, but for most it is still not a core identity. There are a few SPMers who enthusiastically espouse nanoscience, and many who are drawn to it, but there is still much ambiguity in this community about what nanoscience is.

It is clear, though, that instrumentation is central to nanoscience. The nanoscale is a mediated world, where most objects are visible only with the aid of esoteric technologies. In forming a new discipline (or transdisciplinary constellation), nanoscience’s proponents have marked its territory by giving mediated nanoscale entities an immediate “nanopresence”. Little nanoabacuses, nanoguitars, nanotrains, and nanoshovels have a familiarity, a present-at-handness, even if they’re only a few nanometers long; moving atoms around gives them reality and presence and even personality. This isn’t new – Eric Francoeur’s history of chemical models (Francoeur 1997), for instance, shows how important tangibility and familiarity can be in generating knowledge about intangibly small objects. For proponents of nanoscience, though, endowing small entities with this kind of presence has been an unusually effective rhetoric on the road to building a community.

Because nanoentities can only be seen via instrumentation, nano boosters have put enrolling instruments and instrument-builders (especially STM and AFM) at the heart of weaving nanoscience into a coherent practice (Baird & Shew 2004). This paper examines how the rhetoric and promises of nanoscience are perceived and taken up by instrumental communities. In the case of probe microscopy, social differentiation within the SPM community has made nanoscience an attractive proposition. In taking on differentiated roles with respect to building and using these instruments, many probe microscopists have seen the tools of “nanopresence”, and the nascent rhetoric and institutions of nanoscience, as an opportunity to plaster over fault lines within their community. In doing so, they may nudge nanoscience closer to reality, but they will likely remake it in the image of the practices and institutions in which their work originated, rather than taking up whole cloth the visions of people like Drexler and Feynman (Drexler 1990, Feynman 1999).

1. The STM and the 7x7

Although the STM had many forebears – notably the Topografiner at the US National Bureau of Standards in the late 1960s (Villarrubia 2001, Young *et al.* 1972) – it is today taken to be the ancestor of probe microscopy. Likewise, though it was not the first instrument to “see” atoms – the field ion microscope in the 1950s (Melmed 1996) and the electron microscope in the 1970s (Isaacson *et al.* 1976) both achieved this – STM’s atomic resolution is usually taken as what makes it special for nanotechnology. When it was invented at the IBM research lab in Zurich in 1982, though, it was intended as a moderate resolution industrial surface characterization tool (Binnig & Rohrer 1985, 1987). No one had any inkling of seeing atoms, nor of its relevance to nano. As the product of an IBM laboratory, STM was envisioned as relevant to only one customer – IBM. Bill Leslie and Russ Bassett have shown that IBM in the early ‘80s was so large, dominant, and inward-looking that it deliberately pursued narrowly-focused, idiosyncratic technological solutions to its particular problems (Knowles & Leslie 2001, Bassett 2002).

The STM was invented to solve an issue in IBM’s development of a Josephson junction-based high-speed computer. These junctions required very thin, extremely homogeneous oxide films. In practice, small defects (“pinholes”) in the oxide film were common and

routinely ruined junction performance. So the Josephson team at the IBM Zurich lab asked their colleague, Heini Rohrer, to come up with a way to inspect the films and analyze the defects. Rohrer hired a new Ph.D., Gerd Binnig, to work on the project; together, they realized that a sharp metal tip, lowered very close to the films, could locate pinholes by probing the electrical characteristics of the film using tunneling electrons.

When they started, Binnig and Rohrer calculated that the STM's resolution would not be much better than an ellipsometer or an electron microscope. Yet the Zurich lab had the resources to develop even this very expensive instrument in the hopes that it would provide the smallest extra help to a project into which the company had poured a significant fraction of its money, time, talent, and hope. Unfortunately for IBM, the Josephson project quickly ground to a halt in a way that signaled the problems that would decimate Big Blue a decade later. Fortunately for Binnig and Rohrer and the STM, though, it lasted long enough to allow them to build prototypes and develop a feel for the technical problems involved. In that time, Binnig came to the conclusion that the STM might be able to image individual atoms. No one else really believed this, so it became impossible for a while for Binnig to work on the STM full time; but Rohrer put him onto another project that was undemanding and allowed him the resources and the freedom to tinker with the tunneling microscope on a half-time basis while hiding the STM project from upper management.

As Binnig (and two technicians, Christoph Gerber and Eddie Weibel) developed expertise with the STM, they began to look for samples to image with the new instrument. Thus, they started talking with colleagues to find out what samples would be most interesting to them. At first, they asked *crystallographers* at Zurich and IBM Yorktown (in New York state) to prepare samples with large atomic steps that could be used to calibrate the STM. Yet articles presenting data on these materials generated little or no wider interest (Scheel *et al.* 1982). So Binnig and Rohrer next began asking the *surface scientists* at Zurich and Yorktown what samples would be most interesting to their discipline.

With the exception of participants' memoirs (King 1994, Lagally 2003), very little has been written about the history and sociology of surface science. Indeed, the best history of solid-state physics (Hoddeson *et al.* 1992) contains only a short paragraph on surface studies. Yet in the late 1960s, surface science was the nanotechnology of its day: an interdisciplinary umbrella at the intersection of basic research and pressing technological issues (the space race, industrial catalysis, semiconductor manufacturing), with massive corporate and government support, particularly at institutions like Bell Labs, IBM Research, and the National Bureau of Standards. The five years between 1968 and 1973 saw the blossoming of surface science as a discipline; one prominent historically-minded surface scientist has even classified it as a "Kuhnian revolution" (Duke 1984).

This new surface science attached itself to a constellation of instruments, technologies, computing power, theoretical machinery, exemplary problems, and applications. These included: a proliferation of various surface spectroscopies; the perfection of the art of low energy electron diffraction (LEED); to facilitate both of these, the invention of various ultrahigh vacuum (UHV) technologies; in tandem with LEED, spectroscopy, and UHV, a heightened appreciation of "well-defined", ultraclean surfaces, and the elaboration of recipes for preparing them; the coordination of these recipes with LEED patterns signifying various "surface reconstructions"; and the use of theoretical and computing power in pursuing the central problematic of the field, the atomic structure of these reconstructions (that is, a better understanding of how atoms at the surface of a material rearrange themselves into a pattern different from that of the underlying bulk material).

When Binnig and Rohrer approached IBM's surface scientists in 1982, they struggled to accommodate to the language and practices of surface science to make themselves and their instrument credible. Above all, this meant choosing *important, unsolved* surface reconstructions as test materials. At first, they looked at a gold surface – the (1,1,0) 1x2 –

because gold is inert and easily prepared, and, in fact, published an article claiming they had achieved atomic resolution and had actually solved the structure of the reconstruction (Binnig *et al.* 1983). Yet because surface scientists had no ongoing debates about this reconstruction, their reaction to the STM was unmitigated disinterest.

Thus, Binnig and Rohrer turned to *the* canonical unsolved reconstruction of the day: the silicon (1,1,1) 7x7, the “Rosetta stone” or “fruit fly” of surface science. This reconstruction had been known since the late ‘50s, and had proven extraordinarily generative for surface science, yet had resisted all attempts at solution. Because of its easy preparation and intricate LEED pattern, it was a convenient surface on which to test students, preparation techniques, theories, and instruments such as the STM. By 1982, a couple dozen models of the reconstruction competed, with no clear leader and no obvious experimental way to decide between them. So when Binnig and Rohrer published an atomic resolution image of two unit cells of the 7x7 (Binnig *et al.* 1983), surface scientists took notice. It is difficult to overstate the importance of the 7x7. Surface scientists only paid attention to the STM – whether they believed its results or not (Hessenbruch 2001) – when Binnig and Rohrer made it relevant to their most pressing questions; and although a couple non-surface scientists (notably Cal Quate) had shown an interest in replicating the STM before the 7x7, the subsequent history shows that they (and the Zurich group) would have had great difficulty developing and selling tunneling microscopy without the participation of surface scientists.

2. Replication and Pedagogy

With the 7x7, many people wanted to replicate the STM. When STM came to North America in 1982-3, the earliest work fell into two camps (Mody forthcoming). One was situated in corporate and national research labs – primarily IBM Yorktown, IBM Almaden, and Bell Labs, but also at Ford, Philips, Lawrence Berkeley National Labs, the Naval Research Lab, and the National Institute of Standards and Technology (successor to the National Bureau of Standards). The other was located in academic groups in the Western US – primarily Cal Quate’s at Stanford and Paul Hansma’s at the University of California at Santa Barbara, but also groups at Caltech, Berkeley, and Arizona State.

In both styles, the STM was as much a locus for training young scientists as it was a means for producing sound knowledge (Kaiser forthcoming). In the corporate labs, the STM was insinuated into well-established methods of creating productive corporate surface scientists, as well as into an entrenched culture of competition, within as well as between laboratories. Just as IBM’s control of the business computing market encouraged it to use one-of-a-kind technologies (and as Bill Leslie has noted, Bell’s telephone monopoly prompted the same attitude), so the dominance of surface science shared between IBM and Bell encouraged them to look only at each other to determine what would count as good surface science (Leslie 2001). This insularity made for a rigorous and sometimes narrow definition of the field. Thus, the work of the first STMers at Bell and IBM ran in similar directions, often organized around competition to achieve milestones such as being the first to get atomic resolution on various semiconductor reconstructions.

Here, the hard work of adapting the STM for surface science was done. Binnig and Rohrer had suggested STM’s surface science capabilities, but (not being surface scientists themselves) had not dwelt on making those suggestions reality. The people who did this work were postdocs and new staff scientists, people who had just arrived at the corporate labs and needed new projects. Building an instrument and making it produce credible, intelligible surface scientific data was an established way of turning a recent Ph.D. into a productive corporate researcher. Since the STM was still unproven, established surface scientists reserved their enthusiasm for the first few years; but for postdocs and new staff scientists trying desperately to survive and thrive in the corporate lab system, there were tempt-

ing potential rewards if the STM turned out to be the next big thing. So they built and rebuilt STMs, each time incorporating more and more surface science instrumentation (specimen preparation technologies, ultrahigh vacuum machinery, LEED, spectroscopies, etc.) and exploring more and more of the core problematics of surface science: reconstructions, spectroscopy, defects, crystal growth, adsorption, thin films and interfaces, etc. (Hamers *et al.* 1987, Feenstra & Stroscio 1987, Becker *et al.* 1985, Chiang & Wilson 1986).

The West Coast academic style of early STM was less tied to surface science and more in line with Binnig and Rohrer's own way of working. Initially, though – especially for the two-year period (ending in 1985) when no one in either camp could replicate atomic resolution of the 7×7 – both groups worked in parallel, and the West Coasters drew on surface science to help them get closer to their elusive goal. After replication, though, and especially after they discovered that the STM might work in air or even liquid (everything up to then had been in ultrahigh vacuum), they moved steadily away from surface science (Sonnenfeld & Hansma 1986, Elrod *et al.* 1986, West *et al.* 1986).

Ultrahigh vacuum chambers are large, cumbersome, finicky, time-consuming devices, so with air STM, it became possible to tinker with the instrument much more rapidly, to achieve a higher throughput of samples, and to look at samples too fragile for the UHV environment. In the West Coast academic labs, this allowed a reorganization of STM work and new ways of molding STM-building to the labs' pedagogical mission. Above all, graduate students worked to make the more flexible microscopes able to image a wider range of materials that would be relevant to a wider range of audiences. This drive to expand tunneling microscopy in all directions at once gave rise to STM in air, in oil, and in water, as well as new types of microscopes like the scanning ion conductance microscope and, most importantly, the atomic force microscope (which, unlike the STM, could image insulating materials as well as conductors).

Unlike the corporate labs, where researchers had a well-established surface science framework to guide their experiments, the academic labs were characterized by chaotic flux. Many instruments would be under construction at once, and when one was built, many different kinds of samples would be put into it. Especially after the advent of the AFM widened the range of imageable materials, students often resorted to “found” samples – polaroids ripped from cubicle walls, salt from the kitchen, liquid crystals broken out of watches, bone from rib-eye steak, the electrochemistry of Coke versus Pepsi, blood drawn from lab personnel, etc. In many of these cases, specimen preparation was non-existent; if, for example, students wanted to see what ice would look like in an AFM (as happened in the Quate lab), they simply stuffed a microscope into the nearest refrigerator and a couple hours later they had their answer. This bricolage (Knorr-Cetina 1981, p. 34) extended to the building of microscopes as well. Microscopes were put together rapidly (sometimes in less than 24 hours) and with all available cultural materiel. For example, the Baldeschwieler group at Caltech reported achieving atomic resolution using a pencil lead for a tip, while the Hansma group tried doing tunneling experiments with store-bought razor blades as tips, then moved on to making AFM probes out of pawn shop diamonds glued to aluminum foil cantilevers using brushes made from their own plucked eyebrow hairs.

The problem was, it was difficult to know what images meant that were produced in this way, and it was even more difficult to make them credible to anyone outside the group. Unlike the corporate labs, which could afford to be inward-looking because they had a large proportion of the surface science discipline in one place (and so credibility could be established at home rather than abroad), the academic groups had to look elsewhere for validation. So they set out to enroll a variety of disciplines in the use and promotion of probe microscopy. To this end, they constructed a local “trading zone” (Galison 1996), and instituted a division of labor within the lab to facilitate the exchange of knowledge and the gen-

eration of new designs. Students continued to build instruments, but now practitioners from various disciplines (usually postdocs and junior professors) would come into the lab for a few weeks or months, learn a bit of probe microscopy, teach the students some of their own techniques and knowledge, write a few articles (with a student), consult on the design of the next generation microscope (geared to their discipline), and then leave (often with a microscope) to set up their own STM or AFM group elsewhere.

Thus, in the late '80s and early '90s, a probe microscopy community coalesced, through, for example, the annual "STM Conferences" sponsored by the American Vacuum Society, the professional society of surface science. The Hansma and Quate groups became the centers of a dense network in this community. Postdocs, students, samples, preprints, information, and microscopes all flowed into and out of these groups. Around these foci, the probe microscopy community experienced a centripetal and centrifugal dynamic. *Centripetal* in that, as new communities of practice became interested in probe microscopy, they often approached Palo Alto or Santa Barbara for help; and, as probe microscopy became routine, there was a mass of people doing it who could exchange information, referee each other's articles, organize conferences with each other, exchange students and samples, etc. Practitioners developed thick ties to each other, often through key intermediaries such as Quate and Hansma. The *centrifugal* dynamic, though, was simply the flip side of this; as more and more disciplines became interested in probe microscopy, the instruments started to be used in an astonishing variety of ways. As new microscopes were developed for new techniques, "probe microscopy" flowered into a thicket of 30 or 40 different kinds of instruments, and hundreds of different operating modes. Researchers began to specialize in one or two of these modes, leading to a fragmented Babel in the SPM community. Also, as many SPMers came to rely on commercial, black-boxed microscopes, there was less reason for a separate "STM Conference" focused on innovations to the technique, and many users dispersed back to the professional conferences of their home disciplines – the American Physical Society, the Materials Research Society, etc.

3. The Gold Rush

Both the centripetal and centrifugal dynamics found even stronger expression as the West Coast groups spawned startup companies to manufacture commercial versions of the STM and AFM. At Stanford, former Quate students and postdocs founded Park Scientific Instruments in 1989; while at Santa Barbara, Virgil Elings, a physics professor with experience commercializing instruments, started Digital Instruments (or DI as it is usually called) in 1987; smaller companies also emerged at Berkeley, Caltech, and Arizona State. Several aspects of lab group culture encouraged commercialization: the need and desire to enroll new kinds of users (who now became *buyers*); the quick production of surplus images, instruments, and microscopists; and an outward orientation that encouraged collaboration with many different disciplines. Ironically, the inward-looking corporate labs commercialized virtually nothing. Belatedly, and largely unsuccessfully, IBM did a small-scale commercialization of the SXM, an industrial instrument developed for in-house use – and, significantly, its inventor was not a surface scientist but a former Quate postdoc.

Initially, start-ups and academic labs lived symbiotically and mostly harmoniously. At DI and Park, company culture was an extension of lab culture. Many students left the lab groups to work for the start-ups, and once in the company, they took up projects that resembled what they had worked on as graduate students. Moreover, the companies mirrored the academic groups' division of labor by setting up in-house applications labs to pioneer the technique in new areas. Often, former Quate and Hansma postdocs cycled through these applications labs after their stint with the academic groups.

One concern for the start-ups in the early 1990s was to find new “7x7s”. That is, these companies were looking for new samples to which the microscopes could bring experimental realism (“nanopresence”) and thus demonstrate the technique to new disciplines and markets. When STM moved into air, half this problem was solved by showing it could resolve atoms of graphite. Highly-oriented pyrolytic graphite (HOPG) had many advantages for STMers: it was a well-known substrate used in several disciplines; techniques were available for putting down different objects, especially biomolecules, onto an HOPG surface; and the HOPG itself was easily bought from lab supply companies.

There were two (related) problems with graphite, however. First, there was no discipline in which seeing the atoms of graphite was epistemically significant in the way seeing the 7x7 had been; there was no ongoing debate in which STM images of graphite made any difference. Besides, images of graphite were (unlike the 7x7) visually banal – just a close-packed surface with no defects. This lack of defects itself became a point of contention. Defects and contamination are a key part of the reality effect of STM images (Mody 2001). Thus, the consistent absence of defects in images of graphite indicated that “atomic resolution” of graphite was more artifact than reality (Mizes *et al.* 1987, Pethica 1986). Also, STM images did disagree with what was known about HOPG – they showed an extremely high atomic corrugation – but in the absence of any *disciplinary* debate about graphite the STMers were left to construct one on their own. This meant that, for those who cared about the anomaly, it was taken exclusively to indicate a quirk of the instrument rather than a new phenomenon. For the *surface science* STMers, in particular, this issue was taken to indicate the fallibility and non-rigor of doing STM in air.

Nevertheless, putting molecules on graphite and looking at them with an STM proved extraordinarily attractive in the early ‘90s. Hundreds of researchers joined the STM community just to do this, many by buying the new commercial instruments. A kind of “experimental vertigo” set in – it was too tempting not to look at biomolecules with an atomic resolution instrument; yet it was disconcerting to use a microscope and a substrate with so many unresolved ambiguities. These were the gold rush days of probe microscopy, as newcomers flooded in and articles and images flooded out, and the 24-karat experiment was atomic resolution of DNA. DNA was a well-studied molecule, but the possibility of seeing the helix, and perhaps even sequencing genetic material with an STM, had a magical grip on the probe microscopy community. The high stakes inherent in making the STM a routine tool of biophysics and genomics were a draw that rapidly expanded the field.

The boom and bust of air STM (particularly the drive to image DNA) says much about how the probe microscopy community was organized. The Quate and Hansma groups valued the quick production of microscopes, images, and articles. Newcomers had to compete with this flow, while also learning to use the instruments. The result was a flurry of experimental activity of uneven quality. Former members of the Quate and Hansma groups are the first to admit that some of what they published in this period was questionable; but error was basic to their lab culture. Hansma’s great proverbs, for instance, were: “do everything as poorly as you can” and “make as many mistakes as you can as fast as you can”. Sometimes this produced smashing successes. Sometimes – particularly when other groups tried to mimic this style – it could bring glaring failures.

Thus, there was tremendous excitement, but also intense skepticism, when a few groups published atomic resolution images of DNA (Driscoll *et al.* 1990, Beebe *et al.* 1989). This ambiguous reaction was partly due to difficulty in satisfying the contradictory demands of the various fields with an interest in STM – on the one hand, surface scientists found biological systems “dirty” and ill-defined, and, on the other hand, biologists found the whole language of electron tunneling obscure and unhelpful in interpreting these strange images. Skepticism was also a product, though, of tension between the pioneers of air STM and newcomers to the field. Binnig and other old-timers pointed out that you could

see “DNA” even on graphite surfaces that were ostensibly free of DNA molecules (Lindsay 1990, Heckl & Binnig 1992). Most people with experience in the area knew that graphite defects could easily mimic DNA in an STM image – the significant problem was not seeing “DNA”, but rather sorting DNA from defects. Crucially, this required much more meticulous experiments and much tighter ties to biology and biophysics than the instrument-building groups were willing to take on at the time.

Thus, air STM evaporated almost overnight (at least in Europe and North America). Groups like Quate’s and Hansma’s were content to try a technique out on the samples particular to various disciplines, and to close up shop if doing so proved too contentious. Their interest was in enrolling various communities, not in debating them. Thus, it was still *possible* to do air STM, even on DNA, and a few marginal groups continued working on the problem with eventual success (Guckenberger *et al.* 1994); but, unlike the 7x7, with DNA there was no community with the resources and the desire to make air STM a fluent biophysical tool. Rather, with so many different kinds of probe microscopes available, it made little sense to dwell on a technique that so many communities found problematic. The outcome of the DNA crisis was a reorganization of the probe microscopy community that eased many of the frictions brought on by the initial differences between the California academic groups and the corporate surface scientists, as well as by the influx of newcomers attracted by air STM on graphite. Henceforth, the dichotomy between STMers and AFMers became much more pronounced. STM was consigned almost exclusively to surface scientists and electrochemists, and commercialization of the microscopes proceeded more slowly and cautiously in those fields. The rest of the probe microscopy community migrated quickly to AFM, and the vast majority AFMers began buying, rather than building, their microscopes. Thus, the task of welcoming newcomers to the field, ensuring their practices fell in line with community standards, and further innovating the technique fell to the microscope manufacturers and to a very small, elite residue of groups (such as Quate’s and Hansma’s) that continued to build all or part of their instruments.

4. Problems of Role

The DNA and 7x7 stories provide a glimpse of the social organization of probe microscopy that can help us understand the field’s relationship to nanotechnology. Who, we should first ask, are the actors in these stories? The Hansma group, for one, divided itself into “builders” and “runners”. “Builders” included group leaders like Quate, Hansma, and Binnig, as well as their students and technicians. Builders formed the core of the group, to which runners were added later; when they graduated, builders joined (or founded) the start-ups, or went to places where they could continue developing instruments (*e.g.* IBM Almaden or manufacturers like KLA-Tencor). A few took academic jobs in physics or engineering departments where they founded their own “builder” groups. *Runners* were the postdocs or junior professors who passed through the builder groups and helped integrate the microscopes with the practice of various disciplines – geology, surface science, biology, biophysics, electrochemistry, etc. After collaborating with the builders, runners usually went to academic jobs in their respective disciplinary homes – chemistry or physics or engineering departments, medical schools, etc. Others joined the start-ups as applications scientists, continuing the work of incorporating the microscopes into new fields.

At the corporate labs, builders and runners were less distinct categories. Building an instrument was a test of a young scientist’s abilities, but it was skill as a runner – generating credible, intelligible, disciplined surface science knowledge from the microscope – that made a corporate researcher’s career. Still, building instruments was key to these people’s identities and most of them have continued to build their own instruments through their careers or have only recently transitioned to commercial microscopes.

As commercial instruments became widely available, a new category emerged – “users”. These people never worked directly with builders, but rather learned probe microscopy by interacting with manufacturers’ representatives. Their ties to STM and AFM were generally loose – some bought the instruments with leftover research funds, or just to see what they could do, or chipped in to share with other groups or even whole departments. Learning to use a probe microscope is relatively easy, so such users risked little by assigning one technician or student to add the technique to their portfolio and provide SPM services to the whole lab. Relatively few of these users would go to an STM Conference, or privilege their AFM or STM over any of the other instruments they relied on. Rather, probe microscopes became routine, taken-for-granted tools – maybe less routine than a centrifuge or a light microscope, but not much so.

There were, in addition, “exceptional users” with special ties to the manufacturers and a special place in the SPM community. Many were early adopters of the commercial instruments, and, like the runners, they were often the first to push the microscopes into a new community. Indeed, in the earliest days, one way to get bumped up long waiting lists for a microscope was to name the manufacturer’s employees as coauthors on papers generated with their AFM – *i.e.*, to form a typical exceptional user relationship. Exceptional users are the type of people who write applications notes (which the manufacturers distribute widely), supply manufacturers with interesting samples (which manufacturers use in their advertising), beta test commercial instruments, develop add-ons and modules for the commercial models, act as references for potential customers, and train graduate students who then join the companies’ applications labs. In return, exceptional users get cheap instruments, free publicity, jobs for students, research funding, and a privileged position within the scanning probe community.

One privilege over which exceptional users and manufacturers bargain is knowledge of the inner workings of the commercial instruments. DI (the largest SPM company) built its reputation on tightly black-boxed instruments. Users were told little about the electronics, and serial numbers were even filed off of controller chips. Being an exceptional user for DI, however, could mean access to the secrets of the Nanoscope controller. It could also mean a right to tinker with the controller and still have a guarantee of customer support (where, for unexceptional users, tinkering with the controller meant writing off the warranty). Other companies like Topometrix and RHK created a market niche selling instruments with a more open, flexible architecture somewhat more conducive to tinkering. For these companies, the line between ordinary users and exceptional users is more blurred, and the constant chatter between company and user created by an open architecture often turns up innovations to fold into the next generation microscope.

There are difficulties, though, in *maintaining* the roles of builder, runner, and exceptional user. The existence of microscope manufacturers, and of a large user base for them to supply, destabilizes the positions of these people. For instance, people who formerly built their own instruments now have to deal with the existence of (relatively cheap) commercial instruments that (in most cases) can do everything a home-built instrument can. Some have chosen to go over to the commercial products, but this means ceding hard-won expertise and an investment of technical identity (Haring 2002) as an instrument-builder. Some have used their special knowledge and long-standing acquaintance with the manufacturers to become “exceptional users”. Others continue to build instruments, but now have to produce more elaborate justifications for doing so.

For groups like Quate or Hansma’s, the justification is that they are engineering the next generation of probe microscopes (and derivative technologies). There is such disincentive to build one’s own microscope at this point, though, that unless a new advance is seen as orders of magnitude better than what the manufacturers are selling (or as easy to adapt from a commercial instrument), few research groups follow up. So the audience then be-

comes the manufacturers themselves, and symbiotic relationships between builder groups and companies like DI spring up to extend and commercialize builders' innovations. If DI doesn't incorporate an innovation, though, then the builder group may decide to spin off its own company to sell its idea (or, alternatively, if DI is interested then the group may still spin off a company to handle the commercial relationship with the larger manufacturer). So groups that have traditionally built their own microscopes and still want to do so are one source of the dozens of little startups that are populating the probe microscopy community.

Alternatively, builder groups may depict the commercial instruments as inadequate in some way. They describe a "mass" marketed instrument as necessarily built for the needs and skills of what the manufacturers perceive to be the average microscope. Certain modes of operation may be elided from such instruments, and for some research groups those modes may then become experimental niches. Such groups often say they are doing high-end, sophisticated science – and careers can be made quickly with such machines. The design, construction, and care of such microscopes take up much of the time of such groups. Thus, the language of craftsmanship and artistry surrounds their work – both in terms of the instruments and the images they produce. For instance, where users of commercial instruments usually rely on the default color settings and image rendering algorithms, groups that build their own instruments also invest time and energy in making their images highly rendered and aesthetically pleasing. As artisans, some builders have positioned themselves as a craft elite within the probe microscopy community. Through spectacular images (such as Eigler's atomic corrals), they generate much of the publicity the community receives; and they take on leadership roles in the planning of STM Conferences, in editing volumes and journals related to the field, and in founding companies to market to small niches within the SPM community.

For "runners" and "exceptional users", the existence of relatively cheap, high-quality, widely available commercial instruments presents other difficulties. Bringing probe microscopy into a discipline can make a career, but it can rarely sustain it. Once manufacturers figure out how to sell and market to that discipline, and a wide cross-section of the field follows a runner's lead and figures out how to use the instruments, then being the first is no longer as helpful in getting new grants accepted or articles published. Such people walk a difficult line, as illustrated vividly for them by the history of electron and light microscopy. On one side lies the danger of being tied to the technology, of producing nothing new of one's own by, for example, running a microscopy core to which other groups bring samples or send students – as has happened with light and electron microscopy. On the other side is the danger of distancing oneself from the technology and losing an important tool in the struggle to compete and survive within one's subdiscipline – runners made their reputations with the STM or AFM, and are loathe to loosen their ties *either* to the instrument or to their home community. Runners and exceptional users face the choice of developing the technology, often by *constructing* modifications and taking on the role of a builder, or focusing more on the samples specific to their subdiscipline and treating the STM or AFM as one tool among many.

Interestingly, the solution to this problem frames differences between runners and exceptional users (who, in other ways, are quite similar), particularly in terms of how they view nanotechnology. The old runners who worked with Quate and Hansma in the early '90s tend to be more cautious about nano than exceptional users. Runners expended such effort translating probe microscopy into the terms of their home communities that they don't have any desire to further disturb the structure of those disciplines. Runners are most skeptical of nano's rhetoric of a revolutionary interdisciplinarity that will dissolve the traditional disciplines. Some runners, and some builders, yearn for the early '90s as a charismatic golden age – as evidenced, for example, by a revolt at DI in 2000, when former runners and early DI employees formed a startup, *Asylum* Research (pun intended) to recapture

the free-form instrument-building culture of the early '90s. "Exceptional users" though, are more opportunistic about nano – they've tied themselves strongly to the manufacturers who have cultivated the growth of the nano community. Thus, exceptional users tend to be some of the most enthusiastic nanoists in the probe microscopy field and, more than anyone, have done the work of figuring out how to implement the manufacturers' products in ways that would count as nano – that is, they aren't building new nano instruments themselves, but they've been most successful at taking products that are already there and using them in canonically "nano" ways.

5. Nanoscience and Probe Microscopy

For many ordinary users, meanwhile, AFM has become an easy entrée to the nano. I have done ethnographic work, for instance, with materials scientists at Cornell who are using very old techniques to produce small structures that they can now call "nanohills" or "nanoropes". Before the AFM, these structures would have had very little "nanopresence" – it would have been very difficult to visualize them and make plausible arguments about their usefulness. By buying an off-the-shelf AFM, training a student to use it, and producing very ordinary nanoscale images, though, these groups are able to connect themselves to a community of people who work on other entities which have a similar nanopresence (which, at Cornell, is quite a large community). The AFM is hardly central to their work – their knowledge of it is fairly circumscribed, only one or two of their students may be adept with it, most of their group's time is spent preparing samples that will very quickly be put through the AFM *as well as* other instruments, and they have little intention of ever tinkering with the instrument. It does, however, help them lay claim to the money, attention, facilities, and community that are growing up around nanoscience.

For those with deeper roots in probe microscopy, responses to nanoscience are shaped by the centrifugal and centripetal dynamics of routinization and commercialization, and the role instabilities they create. As a community, probe microscopy is disintegrating in places. SPM no longer has the instant appeal it did in the gold rush of the early '90s, and most users see it as a benchtop tool rather than as their primary locus for innovation and research. At the same time, many builders and runners have made STM and AFM the center of their work for so long that they feel detached from their original disciplinary homes. Thus, many of these people have rallied to "nano" as a way to shore up some of their role instabilities and to make the existence of a probe microscopy *community* more palpable. For those who have positioned themselves as a craft elite, "nano" provides the framework for a community to be the elite *of*. For those who have positioned themselves as mediators between users and the manufacturers, "nano" can be both carrot and stick in their relations with the manufacturers. The carrot is the lavish, coordinated funding the government is pumping into nanoscience. The stick is that this funding helps coalesce a nanoscience community that still puts a premium on *making* epistemically interesting artifacts, many of which derive from probe microscopy techniques (*e.g.* molecule pullers, artificial noses, millipede storage devices, nanotube transistors, nanomanipulators, etc.). Builders and runners can direct their work to the nano community as much as to the manufacturers; and if the nano community likes what they hear, then these groups have an added leverage in their relationships with the manufacturers.

For SPM manufacturers, too, nano has many attractions. For DI, in particular, nano is a tool to regulate the centripetal and centrifugal dynamics of an instrument-oriented community. By virtue of its size and influence and tremendous number of users, DI sits at or near the center around which probe microscopy revolves. Nano means funding and publicity and interest that DI sees as pulling more people into that orbit. Perhaps more importantly, nano provides a unifying rhetoric that keeps people who are already using AFMs

from drifting back into their own disciplines. As long as DI can convince these people that they are *nanotechnologists* (rather than just physicists or chemists or biologists) then it can hold their attention for an ever-expanding line of nanotechnology instrumentation. Thus, it's interesting to notice that in the past few years, DI's new products have been much more oriented to sensing and force-pulling and nanomanipulation (*i.e.*, a whole family of nano-oriented products) rather than just microscopy.

For the smaller manufacturers, nano holds the promise of a ready-made community with niches and wrinkles where DI doesn't compete and in which they can survive. These manufacturers, for instance, have helped maintain the annual STM Conferences while steering them toward nano. In part, these meetings represent the densest concentration of probe microscope users and innovators – the people from whom manufacturers draw their patents, people, and ideas. Yet manufacturers realize the tensions inherent in prolonging the existence of a dedicated STM Conference when the number of builder groups is dwindling, so SPM manufacturers have been key in transforming these meetings into “NANO Conferences”. They see nano as transcending the connection to any particular instrument, and therefore as providing a more sustainable basis for the ongoing existence of an expanding community of practitioners who will be interested in their wares, and who will still have enough builder groups to yield up commercializeable innovations.

So the incorporation of instrumental communities such as the STM/AFM field is one mechanism for the growth of nanotechnology. For several reasons this is a highly attractive method for nano leaders. First, one nagging problem of nano at this early stage is that there is little that connects together all of its disparate parts. By identifying instruments such as the AFM that are common to different patches of the nano quilt, nano leaders, particularly at the National Science Foundation and NSF-sponsored university nanocenters, can encourage coordinated work across the nano community by funding the purchase of microscopes that are shared across interdisciplinary groups. Since probe microscopy manufacturers and elite builder groups have a long tradition of encouraging the passing of these instruments across disciplinary boundaries, nano can incorporate tried and true pathways for tying together disparate subcultures through common instrumentation.

This process, in turn, encourages those probe microscopy elites and manufacturers to seek out the nano community. “Nano” provides a way out of the role dilemmas arising from commercialization of the microscopes. That is, by encouraging ordinary users of commercial microscopes to build networks through shared instrumentation, nano offers STM and AFM manufacturers a much larger market than they have seen before. At the same time, nanotechnology attracts probe microscopists because its canonical activity centers on making knowledge-generating *things* – whether macroscale artifacts like microscopes and diffractometers, or nanoscale artifacts like nanotubes and quantum dots. Closure has not been reached on what counts as nanotechnology (whereas closure has, more or less, been reached on what counts as a good STM or AFM), so *builders* have much more room within nanotechnology to continue building, tinkering, and modifying a wide range of instruments. In the meantime, those who routinely use commercial instruments can concentrate on creating novel nanoscale artifacts and characterizing them with their store-bought STM or AFM. Indeed, this process leads to new rounds of collaboration – as has happened so often in the history of STM and AFM, *builders* are looking to work with people who know how to make novel nanoscale objects, and instrument *users* are looking to work with people who can build instruments that will make novel measurements.

There are also other mechanisms for the growth of nanotechnology. In particular, nano leaders have seeded their discipline by appropriating whole subdisciplines. STM and AFM have played an important role in this process, especially in the conversion of surface science discourse into nano discourse. Surface science has changed dramatically since the introduction of STM and AFM. To some extent, the new microscopes reoriented the impor-

tant problematics of the field – in the late ‘70s, for instance, you could get a Ph.D. for proposing a new model for an unsolved reconstruction, whereas in the ‘90s that would only be one chapter of a surface science dissertation. More important to the cohesiveness of the discipline, though, was the massive scaling back of corporate research in the early ‘90s. Though they were by no means the entirety of the field, Bell Labs and IBM were the centers around which the field revolved. With their decline, the set of activities that count as good surface science has become broader and more diffuse.

Indeed, surface science’s institutional ties to probe microscopy were one mechanism for this blurring of the field’s focus. When the STM first made inroads into surface science, it attracted the attention of the Naval Research Lab (an eminent center of surface science), the Office of Naval Research (the primary funder of non-corporate surface science), and the American Vacuum Society (the primary institutional home of surface science and the sponsor of the field’s major journal, the *Journal of Vacuum Science and Technology*). Two people at the top of these organizations, Jim Murday and Rich Colton, made STM the baby of both the AVS and ONR. Thus, the ONR became a major funder of people like Quate and Hansma, and the AVS became the major sponsor of the annual STM Conferences, with most of the proceedings of these conferences appearing in JVST. As we have seen, though, the probe microscopy community included a lot of people who were no surface scientists; and especially after the advent of the AFM, the STM Conferences became filled with people with no interest in surface science or its traditional mainstays (vacuum technology, spectroscopic and diffraction techniques, metals and semiconductors, well-defined surfaces). Thus, the *Journal of Vacuum Science and Technology* found itself publishing vast numbers of articles on work done in air and liquid environments.

For Murday, “nano” is a way to maintain the cohesiveness of both the surface science and probe microscopy communities. It was Murday and Colton, for instance, who hosted the 1990 STM Conference and changed its name to the STM/NANO Conference (and effected the switch from then on to alternating STM and NANO meetings). 1990 is very early in the takeoff of nano, a period when the word was still fairly disreputable, so it was a big step for a well-known scientist and grant officer to put such a stake in it. Today, this stake continues – Murday is now one of the key players in the National Nanoinitiative, and one of his pet projects is to transform the AVS into a Nanoscale Science and Technology Society. Now, in some sense this part of the story is the work of a very few individuals – Murday and Colton showed extraordinary vision in making STM their protégé early on, and they took a remarkable gamble in foreseeing how important “nano” rhetoric would become. At the same time, “nano” was in some ways a handy solution to a problem of their own making – by tying the AVS so strongly to an instrument that very quickly exploded out of surface science, they helped lay the grounds for the AVS’ existential crisis. Given that they wanted to preserve both the nascent probe microscopy community and the well-established AVS, “nano” was an easy choice of a discursive means to do so.

So what are the lessons of the STM and AFM story for nanoscience? Well, from this last piece, we can see first of all the importance of institutions and subdisciplines that predate nano – nanoscience has had to wait for its opening, an opening afforded by changes in the status of (among others) the corporate research labs, the discipline of surface science, and the relationship between industry and the academy. We have also seen the importance of commercialization, and the tremendous problems and opportunities that commercialization presents for a wide range of researchers. In this case, nano has been an extremely flexible rallying cry for all of the parties to the commercialization process; for some, it may provide a way to smooth some of the fault lines created by commercialization. Finally, we’ve seen the extent to which “nano” is a moveable feast, a rhetoric that can be massaged and transformed to fit the needs of various parties in a community. These people have many orientations to nano, and many different emotions about it; and those emotions surround

nano's role in defining their future practice and community. Whatever that role, it is clear that the nano they are trying to create is their own nano, deeply rooted in the traditions (of, e.g., instrument-building or surface science) in which they have trained and worked. Many of these people are quite cynical, if not dismissive, of a grand nano rhetoric à la Drexler or Roco; but at the same time they project ways in which nano is their future, once it has been properly specified relative to their local practices. This transformation of a grand discourse into local practice is one of the most interesting parts of the nano phenomenon, and one that bears much further analysis.

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Nanotechnology and the Negotiation of Novelty

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Abstract. Much of the hype around nanotechnology relies on the notion that it is novel and revolutionary. A large part of that in turn relies on the purportedly revolutionary ability of the Scanning Tunneling Microscope to manipulate individual atoms. However, novelty always involves a comparison of similarity and difference with what came before. Furthermore, the novelty of the STM was negotiated and renegotiated from the very beginning – just as the nature of nanotechnology continues to be negotiated to this day. The history of the STM sheds light on the role of promise and hype in science in general and directs our attention towards science in the public sphere.

1. The Etymology of Nano

In our culture, the negotiation of novelty is commonplace. Patenting, for example, is a process to decide what counts as novel. Innovations are compared against predecessors and consequential decisions are made on the basis of similarity and difference. The same is true of the Nobel Prizes. One might even argue that all arguments can be recast as a negotiation of similarity and difference.

Nanoscience and nanotechnology are often claimed to be novel and also often claimed to not be so. In this paper I want to outline the history of nano with respect to the ongoing negotiation of its novelty. The *Oxford English Dictionary* is a useful first port of call for this kind of endeavor: The first use of the word was already in 1974 but in an obscure publication, the *Proceedings of the International Conference of Production Engineers*. The second recorded use is Eric Drexler's 1986 *Engines of Creation*, and that is of course the most important locus because this book was widely read. After 1986, one can see the word spread to publications with large readerships: *The New Scientist*, the *Times Higher Education Supplement*, the *Washington Post*, the *Sunday Times*, and *Nature*.

Drexler's *Engines of Creation* is a tremendously successful book, written in an upbeat tone of voice painting a rosy future of tremendous technological ability. Drexler argued that we can now build structures on the nanoscale, meaning that we can move and combine atoms and molecules as we do with Lego™-blocks, as long as the resultant molecules are energetically stable. We can build molecules that have similar functions as the DNA-RNA-protein system found in nature, that is to say our new molecules may be engineered so as to be parts of a self-reproducing system. From this will flow new materials, new drugs, new information technologies, new human tissues, new just about everything. In the introduction to the book, Marvin Minsky, Professor at MIT (and so a credible individual in matters technical), emphasized that Drexler's vision was not fanciful but based on a thorough knowledge of the current science and technology. The vision was compelling for two reasons. 1) The tool for moving individual atoms, the scanning tunneling microscope (STM), became well-known at just this time – it received the Nobel Prize in the same year that *Engines of Creation* was published (1986). 2) The combination of molecular biology, the in-

cient human genome project, and the understanding of biochemical pathways made it feasible that a slightly different ensemble than the DNA-RNA-protein one could be produced and have the same kind of tremendous power as life. Much of Drexler's book thus addresses the issue of figuring out what kinds of molecules we would want to assemble given our knowledge of molecular biology and biochemical pathways, and how to ensure that the research would be beneficial. At the very same time, in the mid-1980s, the field of artificial life came into being (Helmreich 2000; Fox-Keller 2002, pp. 269-76). Nano and A-life are natural bedfellows: one predicts new forms of life created in the laboratory, the other simulates new forms of life on the computer. Both make the creation of new forms of life in the laboratory seem less fanciful.

So, much of the feasibility of the vision depended upon the feasibility of the STM's purported control over individual atoms and upon the feasibility of alternative forms of life. And the novelty of Drexler's vision traded upon the novelty of the STM and A-life. In this paper I will focus upon the novelty of the former. As ever, this was negotiated and renegotiated.

2. The Scanning Tunneling Microscope

What is an STM and how does it work? It was described in the following way in *Scientific American* (Figure 1).

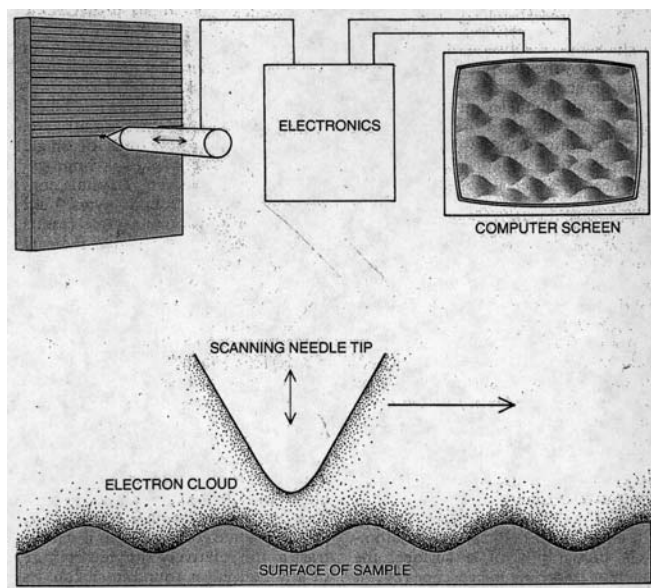


Figure 1: *Scientific American's* depiction of the STM in 1985, cf. Binnig & Rohrer 1985, p. 53. Courtesy of Ian Worpole and *Scientific American Magazine*.

A very fine needle is brought very close to a sample surface, for example a crystal surface whose structure is to be examined. When very close, electrons might jump across the gap from sample to tip; especially if an electrical potential is applied (e.g. by connecting the tip to a battery and the sample to earth). The jump across the gap is explained within quantum mechanical theory by the phenomenon of tunneling. The electrons tunnel through the vacuum despite the classical, non-quantum mechanical theory predicting that they do not have the energy to surmount the obstacle provided by the vacuum. The tunneling electrons amount to an electrical current that can be measured with great precision. Quantum theory predicts that the tunneling current is very sensitive to the distance between tip and sample: proportional to the inverse of the distance squared. If one scans the tip across the surface,

the distance between tip and sample will oscillate and so will the current. The correlation of tip position and current can thus be used to produce an image on the computer screen giving a rendition of the topology of the sample surface.

The STM was invented by Gerd Binnig and Heinrich Rohrer at IBM Zurich in 1981. Their very first paper was concerned with a tunneling microscope (Binnig *et al* 1982a). They argued that they were able to reduce the distance between probe and surface to the dimensions of a single atom. The proof of this lay in the tunneling current measured (inversely proportional to the distance squared, a proportionality that is theoretically explainable only with the quantum mechanical notion of electrons tunneling across the vacuum between probe and surface). The main point here is that they relied on quantum mechanics. They themselves highlighted the fact of atomic resolution (Binnig *et al* 1982b, emphasis in original): “Surface microscopy using vacuum tunneling is demonstrated for the first time. Topographic pictures of surfaces on an *atomic scale* have been obtained.”

3. The Holy Grail of Atomic Resolution

In order to understand this, let us examine the significance of the term “atomic resolution” for the audiences that Binnig and Rohrer addressed. With some hyperbole one might say that atomic resolution had been the holy grail in the natural sciences for at least a hundred years. 19th-century scientists developed a language based on atoms as elementary building blocks with which all sorts of analytical and industrial chemistry was carried out. The concepts of the atom and of Mendeleev’s elementary table were tremendously useful. But it was agreed that there was no direct evidence of atoms and many scientists developed a pragmatic attitude, dismissing all discussions of atoms as metaphysical – beyond measurement, beyond our ken (Nye 1984). In the early 20th century, much experimental evidence emerged with radioactivity and x-rays. The visible tracks made by alpha particles in cloud chambers were very powerful (Galison 1997), and atom-talk became kosher once more. William Henry Bragg, for instance spent much of his career popularizing such talk, lecturing on BBC radio and at the Royal Institution on individual particles flying through a gas (Bragg 1925). He also spent much time developing x-rays as an analytical tool in crystallography (Andrade 1943). A broadside of x-rays will be deflected at a crystal surface, and the many deflected waves combine to produce a pattern on a photographic plate. The power of X-rays lay precisely in their atomic resolution: they yielded information on the average distances between atoms in the crystal lattice. Many similar techniques were developed to explore surfaces, especially with the growth of the semiconductor industry in the 1950s and ‘60s (Duke 1984). Scientists used light, electrons, or ions of all kinds of wavelengths or energies shooting at all kinds of angles at the surface, sometimes measuring the particles transmitted through the target, sometimes those reflected back. Knowledge of the structure of semiconductor surfaces was obviously of tremendous financial importance and so this armory of techniques became large and very sophisticated. The same techniques were used to examine metallic surfaces for which there was also tremendous industrial interest.

4. The Novelty of the Scanning Tunneling Microscope

So, by the early 1980s, there was a large, if diffuse, social grouping of surface scientists, united by an understanding of, and a commitment to, an array of techniques yielding information about surfaces, often with atomic resolution, but always averaged over many atoms. In the following years, Binnig and Rohrer worked also to explain just what constituted the novelty of their new instrument. In the abstract of one paper (Binnig & Rohrer 1982) they referred to “unprecedented resolution in real space on an atomic scale” (real space in con-

trast to the conceptual “reciprocal space” used with diffraction techniques). They now explain: “The usual experimental methods to investigate surface structures (*e.g.* LEED, atom diffraction, ion channeling) are indirect in the sense that ‘test models’ are used to calculate the scattered intensity profile which is then compared with the one measured. In addition, these methods usually require periodic surface structures. The STM, on the other hand, gives 3d pictures of surface structures direct in real space” (Binnig & Rohrer 1982, p. 730).

Binnig and Rohrer not only advertised their new instrument to a busy but potentially interested audience, they also had to convince them that they were credible. Some scientists directly accused them of fraud and some reviewers rejected their papers. A knee-jerk reaction of many scientists was that the resolution of an individual atom was impossible, due to the uncertainty principle, a fundamental tenet of quantum mechanics. The fact that the quantum mechanical effect of tunneling was centrally involved will have given scientists the immediate association of quantum mechanics and its somewhat different laws for the atomic length scales. The uncertainty principle may be explained in the following way. If one were to determine the position of an individual atom, then one could send out light (a photon) which, if impinging upon the atom, would change direction. The deflection of the photon would yield information about the atom’s position, but unfortunately the deflection of the photon entails the slight movement also of the atom. Thus, some uncertainty will always remain about such issues as the position of individual atoms. Most scientists learning quantum physics will learn about the uncertainty principle with examples such as the one just given. Nowadays STM users will learn that the uncertainty principle does not apply for the case of atoms embedded in a solid and that the examples used to explain the uncertainty principle apply only to free atoms. In other words, while the photon might nudge the atom, the neighboring atoms will push it back into place. But in the early 1980s, the audience will have consisted of many busy scientists whose knee-jerk reaction when hearing of atomic resolution of individual atoms was to dismiss it.

Some scientists will also have had much investment in the existing techniques and have been reluctant to accept a new one that might render their expertise obsolete. Surface scientists and crystallographers were, generally speaking, proud of their facility to think in terms of both real and reciprocal space. And so Binnig and Rohrer needed to build up their own credibility. For instance, they needed a convincing theory based on quantum mechanics explaining the tunneling process. According to this theory (developed in 1983 and 1984) it is not just a question of “feeling” the topography of the surface but rather a result of the overlap of electron orbitals of the tip and sample atoms with the greatest proximity (Tersoff & Hamann 1983, García *et al* 1983, García *et al* 1984). The bottom line is that STM measurements require interpretation according to a theoretical model, and that it is not immediately obvious which model is the most appropriate. On top of all this, it is difficult to get the STM to work properly: proficient users will tell you that it might measure junk for hours and then suddenly yield sensible information. (This phenomenon, so the explanation goes, is due to the chance placement of an atom on the tip that gives it the required sharpness. That is to say, when scanning across the surface very closely, a surface atom might jump from the surface to the tip and sit in such a way as to jut out and give the tip the desired sharpness.)

All of this means that other scientists had plenty of reason to dismiss Binnig and Rohrer’s results, and one might expect that those with a career invested in existing techniques would feel threatened by an instrument promising markedly better performance. Many surface scientists thus had both the motivation and the arguments to reject the STM. The politic reaction of Binnig and Rohrer was of the kind: ‘okay guys, it’s not that novel, really – relax and give us a break’ (Binnig & Rohrer 2001; the accusations of fraud are also discussed in Binnig 1989).

They wrote (cf. Figure 2): “we understand the STM as a complement to present microscopy rather than a competitor. For many applications, the STM is best used in combination with another microscope” (Binnig & Rohrer 1982, p. 734). And indeed everyone used the STM in conjunction with another microscope. The proficient new STM user was able to discern obvious noise from a proper measurement by comparing the result with that obtained from another tool.

The evidence yielded by the STM is mediated through quantum theoretical understanding and a profound pre-existing understanding of surfaces. (For the importance of the pre-existing understanding of surfaces, cf. Steensgaard 2001.) And importantly, the novelty of the STM was negotiated: at times it was emphasized, at times downplayed. The novelty sometimes focused on the atomic resolution but it didn't have to. For example, the AFM, the sibling of the STM and much more widely used, does not yield atomic resolution. The utility of the instrument doesn't require atomic resolution. But symbolically, atomic resolution mattered greatly – comparing it to the holy grail is not too much of a hyperbole, after all.

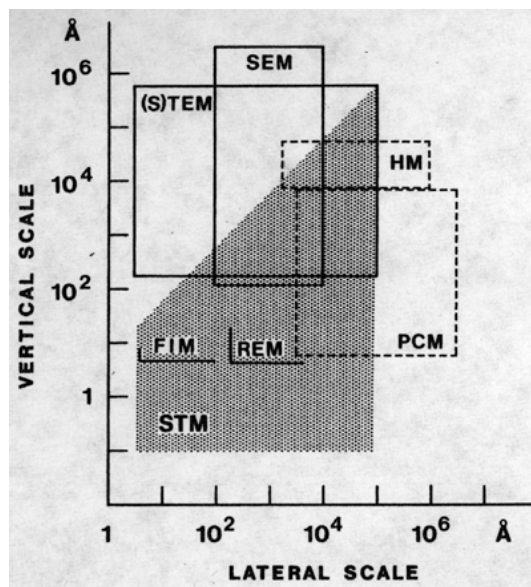


Figure 2: The resolution of various microscopic techniques in 1982. The shaded area is the resolution that the STM was capable of; SEM refers to the Scanning Electron Microscope, FIM to the Field Ion Microscope and so on (Binnig & Rohrer 1982, p. 734). Courtesy of Birkhäuser Publishers Ltd.

As always, a new technique becomes credible only when replicable (Collins 1985, esp. chapter 2, “The Idea of Replication”, pp. 29-49), and it took years for an STM to be built successfully outside IBM Zurich. Other IBM labs came first and by 1985 there was a small community of STM users. At this point, *Scientific American* picked up the story. Binnig and Rohrer wrote the article jointly with the staff of *Scientific American*. The staff of course knew how to address a broader audience than just the surface science community, and so the language shifted importantly. The new kind of microscope enables one to “see” surfaces “atom by atom”. The article also advertised the instrument’s versatility: it “may extend to investigators in the fields of physics, chemistry, and biology”.

The next year, 1986, was the STM’s breakthrough year. Binnig and Rohrer received the Nobel Prize, and Eric Drexler published his influential *Engines of Creation* that also popularized the notion of nanotechnology. Drexler does refer to the STM, but not centrally. The manipulation of individual atoms is pretty much taken for granted, and he focuses

much more on the implications of that purported ability, thus shifting the discourse towards artificial life and the creation of alternative life forms.

5. The Hying of the Scanning Tunneling Microscope

The story of the scanning tunneling microscope and its new siblings (collectively called scanning probe microscopes, or SPM) after 1986 primarily went off in the direction of immediate utility that is discussed by Cyrus Mody (in this volume). One might posit a continued disconnect between the actual work done with SPMs and the LEGO™-style construction of life-like molecular systems at the foundation of the Drexlerian vision. Even the historian of science, Jed Buchwald has contributed to this disconnect by rendering an illustration of “Zippenfeld’s amazing atomic etcher”, purportedly for touching up the family’s greeting cards (Buchwald 2000, p. 205). The illustration is unreferenced and Buchwald in fact made it up himself (Buchwald 2003).

One event has enhanced this disconnect more than others: IBM employees’ media stunt, writing IBM with individual atoms (Eigler & Schweizer 1990). They used “the STM at low temperatures (4K) to position individual xenon atoms on a single-crystal nickel surface with atomic precision. This capacity has allowed us to fabricate rudimentary structures of our own design, atom by atom ... the possibilities for perhaps the ultimate in device miniaturization is evident.” The paper made it straight to the front page of the issue of *Nature* in which it was published. The reason for its media success was of course its relevance for the Drexlerian promise/hype. It is of methodological advantage to talk about promise/hype, to retain a Janus-faced ambiguity and not decide in advance whether nanotechnology will succeed or fail (Latour 1987, p. 4). The nature of the promise requires no further explication at this point, whereas the nature of the hype does.

First of all, the IBM experiment worked only at 4K, an extremely low temperature, and at high vacuum. One of Drexler’s points was that we would only be able to assemble energetically stable molecules, and IBM’s surface with patterns made by xenon atoms is not energetically stable except at these low temperatures. Furthermore, Eigler *et al.* were able to move atoms laterally on a surface, which is rather different from assembling a three-dimensional molecule – DNA, RNA, and proteins are of course not flat. In a word, there is a tremendous disconnect between moving xenon atoms on a surface at 4K, if that is what Eigler actually does, and building large complex bio-molecules LEGO™-style. Xenon, after all, is an inert gas, meaning that it prefers not to bond chemically. Nudging along an atom that skates on the surface without any propensity to engage with the substrate is comparatively easy; picking up a chemically active atom and placing it somewhere in a huge chemically active three-dimensional molecule is completely different.

Don Eigler has continued to popularize this experiment. Visitors may experience the set-up at IBM’s Almaden Research Center in San Jose, California, and a virtual art gallery of STM-renditions of xenon atoms on a nickel surface has come into existence. In 1996, Charles Siebert “flew across the country to move an atom” and to write about it in the *New York Times*. That he had to fly from New York City to San Francisco indicates that we are not talking about an experiment that has proliferated greatly. Others have written or drawn other words and images with a similar set-up, but this technique is not being worked on for industrial application. Siebert ignored, and perhaps didn’t even understand, the mediated nature of his movement of single atoms. All he did was to “nudge around a single atom of the element xenon, to pick it up and put it back down, to will that atom where I wanted”. There’s no talk of a hand using a mouse in coordination with an image on a computer screen, and still less talk of what goes into the making of that image (Siebert 1996). Eigler’s program for moving the atom with the mouse even has a chirpy sound, when the atom falls into place, just as LEGO™-bricks click when slotted together (Mody 2003). Even more

than the *Scientific American* article of 1986, articles like Siebert's elide the disconnect. Obviously, promise/hype sells better than pedantic arguments.

But it is precisely the elision of the pedantic argument that is of interest here, the elision of the differences between atomic resolution, atomic manipulability, and the ability to assemble self-replicating molecular systems LEGO™-style out of individual atoms. The word nanotechnology focuses our attention on the nanoscale, the scale of atoms, and this term covers a multitude of sins. Nano is simultaneously scanning probe microscopy, Egle-rian atom nudging and Drexlerian hype.

6. Science Fiction

In a very interesting article, Colin Milburn has disclosed the close relationship between Drexler's arguments and the genre of science fiction. Science fiction is identified by the narratological deployment of a novum – a scientific or technological innovation extrapolated from present-day realities – that entails a change in the whole universe of the tale. “Science fiction assumes an element of transgression from contemporary scientific thought that in itself brings about the transformation of the world. It follows that nanowriting, in positing the world turned upside down by the future advent of fully functional nanomachines, thereby falls into the domain of science fiction” (Milburn 2002; reference is made to Suvin 1979, pp. 64 and 75; nanowriting is Milburn's term for popular and professional writing about nanotechnology).

Milburn shows that *Engines of Creation* is composed of a series of science-fictional vignettes, providing a veritable checklist of science-fictional clichés. He finds the same elements in the technical writings of Ralph Merkle, Markus Krummenacker, Richard Smalley, Daniel Colbert, Robert Freitas, Jr., J. Storrs Hall, “and other prophets of the nanofuture [...] Matter compilers, molecular surgeons, spaceships, space colonies, cryonics, smart utility fogs, extraterrestrial technological civilizations, and utopias abound in these papers, borrowing unabashedly from the repertoire of the twentieth-century science-fictional repertoire”. Milburn even shows that Feynman's famous 1959 lecture “There is plenty of room at the bottom”, which is routinely deployed as an origin myth, belongs in the same category. It too is structured in a series of science fictional vignettes and it too draws on science fiction themes of its time (*ibid.* pp. 282-4).

The genre is visible in official literature too, for example in that of the munificently endowed National Nanotechnology Initiative – witness its brochure *Nanotechnology: Shaping the World Atom by Atom* (NNI 1999) the main author of which seems to be Ivan Amato, an author who has also written a book extolling the virtues and promise of materials research (Amato 1997). Drexler himself has institutionalized his bolstering role with the foundation of the Foresight Institute (<http://www.foresight.org>). There can be no doubt that the promise/hype of a Drexlerian vision has helped direct funding in a certain direction.

7. Technological Futures

Lest this sound like a dismissal of the promise/hype surrounding nanotechnology, I want to finish with some remarks on the general role of utopian visions in science and technology. In a book entitled, *Imagining the Future*, Joseph Corn has assembled half a dozen histories of technological promise/hype (Corn 1986). There is for example a story about the early discourse on x-rays for therapeutical purposes (where the promise was to eliminate disease *tout court*), the electrical home (to eliminate domestic labor), or nuclear power (to eliminate war and even social strife). In the epilogue, Corn sums up the imagined technological futures as each fitting at least one of three fallacies. The first is the fallacy of total revolution;

that a new technology was expected to herald tremendous change whereas the change in fact turned out to be less significant. The second fallacy is that of social continuity; whereas in fact all new technologies altered the society into which they were introduced. The third is the fallacy of the technological fix or the expectation that the new technologies would strengthen the values of old existing social patterns, whereas they turned out to introduce novel and unintended ones. The Drexlerian vision certainly heralds revolutionary change, and it talks only about the technological changes in store, ignoring and thus not expecting attendant social changes. And the latter part of *Engines of Creation* discusses how to set up an institution of oversight to ensure that the nanotechnological revolution brings only what we desire and none of the technological nightmare conjured up by, say, *Prey* (Crichton 2002).¹ In this sense, the Drexlerian vision seems to conform to other technological visions.

But why should technological visions have to come true? Their purpose is not to predict but to enroll. They invite other researchers to jump on the bandwagon by depicting an exciting and fruitful field. Whether or not the visions are related to science fiction does not really matter, except to the extent that they help and hinder the political project of bringing allies together. The genre of science fiction explores just what will cause broad excitement, and as such it provides a natural resource for promise/hype. But it is clearly a double-edged sword, especially because of the term “fiction”. Much of the discourse around Drexler negotiates the proper boundary of reality and fiction. This is Milburn’s main concern, along with his argument that the difficulty of maintaining that boundary contributes to a post-modern breakdown of hitherto established identities. At the same time, this negotiation is simultaneously a political dance that makes and breaks alliances.

8. The Role of Visions

Most importantly, visions aim to increase the chances of funding. The National Nanotechnology Initiative’s programmatic statement, *Shaping the World Atom by Atom*, is illustrative. The vision is science fictional in the above sense. The argument is then made that R&D funding has been geared to short-term projects with specific goals defined in a cost benefit analysis, but that the promise of nanotechnology couldn’t be realized with such funding because the tremendous practical difficulties render the likelihood of short-term marketability unlikely. The role of the government, so the NNI-report, is to step in precisely in such cases as nanotechnology, where the absence of short-term returns prevent investment from private enterprise, but where the promise of long-term benefit makes it worthwhile. No vision, no funding.

In the 1990s physicists in particular have become accustomed to cuts in funding, and this may well be related to the lack of a compelling vision. The National Ignition Facility (NIF) is an interesting contemporary example (Gusterson 2003). This is a facility with the aim of achieving fusion by focusing many high-energy lasers very precisely on a very small area in space, thus providing enough energy to overcome the threshold for fusion. If successful, the system would unlock even more energy than fission, and thus tremendous amounts of energy could be obtained from hydrogen atoms, far more energy than the input to start the fusion process. The investment for the NIF is several billions of dollars and even if fusion were to be achieved, the engineering task of putting that energy to good use would only just have begun. Thus, in order to attract long-term funding, the vision has to contain much promise. Now, the promise/hype of the NIF is very similar to that for nuclear power in the 1950s. It promises the most powerful weapon ever, and thus a US monopoly, in turn ensuring global peace through deterrence. It will also provide an abundance of energy for civilian use, providing affluence to all, eventually resulting in the end of social strife. Presumably the similarity with the chiliastic nuclear vision is both a source of strength and weakness. The many political alliances that are already in place sustaining nuclear power

are likely candidates for enrolment, but for the same reason the well-organized enemies of nuclear power will be enrolled just as easily. Furthermore, the similarity to an older and failed vision makes the NIF project look less than exhilarating. By contrast, the Drexlerian vision's piggy-backing on the promise/hype of fashionable molecular biology gives it sheen and luster.

Technological visions of the future are alive and well, but of course not any vision will do. And as predictions, they are bound to fail: sophisticated notions of the interaction between technological and social change would be counterproductive. The visions are intended to tie together the elements of a heterogeneous network that requires constant maintenance in order to hang together (Latour 2002, 2004). The claim of novelty is essential for technological visions: the elision of the connectedness with practices and theories of the past is as productive as is the claim that success has been shown to be possible in principle, requiring from now on merely developmental labor. The role of promise/hype in motivating researchers and funding bodies discussed here has not been the subject of much research so far. Studies that examine the role of the public sphere instead tend to focus upon the issue of consensus. The topic of nano provides plentiful material for future analysis.

Notes

- ¹ It seems that Drexler's vision is now being ostracized because of its association with the sorcerer's apprentice narrative of *Prey*. At a March 2004 conference at the University of South Carolina ("Imaging and Imagining – Nanoscience and Engineering"), Drexler explained that Michael Crichton's novel has caused fear of a technophobic reaction to nanotechnology. He argued that because Crichton's havoc-wreaking nanobots resemble Drexler's, many in the nanoresearch community have reacted by distancing themselves from his vision.

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Probing the History of Scanning Tunneling Microscopy

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Abstract. We present a brief history of the development of scanning tunneling microscopy (STM). These microscopes, developed in 1981 by Gerd Binnig and Heinrich Rohrer (Nobel prize 1986), are capable of imaging and manipulating at an atomic level. STMs, and the group of instruments corporately referred to as scanning probe microscopes that evolved from them, are part of the instrumentation that has enabled nanotechnology. In our history we examine how these instruments have been used (perhaps wrongly) in the “standard story” of the emergence of nanotechnology. Nanotechnology has developed in a context sometimes referred to as “post-academic”, because of the increased emphasis on aspects of commercialization. We examine how this “post-academic” context has influenced the development of these instruments. Our history of STM shows an epistemological shift that is part of post-academic science and nanotechnology policy.

1. In the Beginning was Little Big Blue

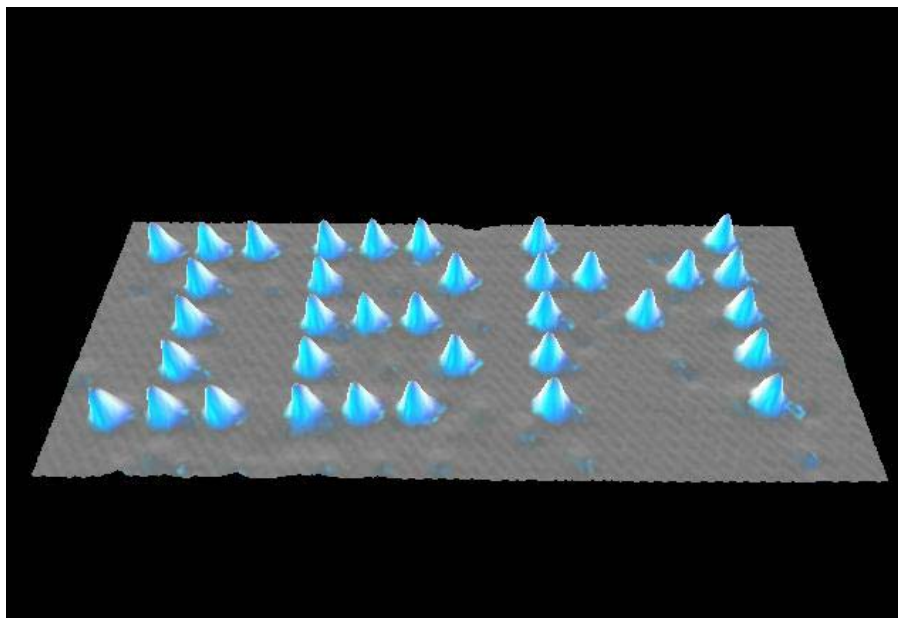


Figure 1 ‘The Beginning’. Courtesy: IBM Research, Almaden Research Center.

In 1990 in the journal *Nature* D. M. Eigler and E. K. Schweizer first published this now well known image of I.B.M.’s initials spelled out with 35 individual xenon atoms.¹ The image now ‘hangs’ in I.B.M.’s ‘STM Image Gallery’ where it joins 15 other striking, and in many ways beautiful images of the atomic world (Eigler and Schweizer 1990). The images are made with a scanning tunneling microscope [STM], which was invented in 1981 by

Gerd Binnig and Heinrich Rohrer, both employed by I.B.M. Research in Zurich. Binnig and Rohrer won the 1986 Nobel Prize in physics for their invention.

There is much that is remarkable about Eigler and Schweizer's 'IBM.' Most immediately it is the interlocked precision technology and science allowing us to 'see' these individual xenon atoms that we marvel at. But we are not just seeing them; we are placing them just so. The image shows our hands and eyes reaching to an atomic level of precision. 'An atomic level of precision' now is more commonly called 'nanoscale precision.' A nanometer, one-billionth of a meter, is roughly ten hydrogen atoms side-by-side. 'Nanotechnology' is the study and exercise of hands and eyes with sufficient precision to 'see,' and in some cases manipulate, individual atoms.

In I.B.M.'s STM Image Gallery, Eigler and Schweizer's 'IBM' is titled, 'The Beginning.' It is an appropriate, if immodest, title, for 'The Beginning' is emblematic of the beginning of genuine atomic precision, genuine nanotechnology. There are 'nano-visionaries' who see in nanotechnology nothing short of a complete transformation in human life on Earth, with nanotech solutions to energy, disease, pollution, even mortality. 'IBM' is a crude beginning indeed.

In viewing this image one also may be struck by the notion that in the beginning was a corporation, IBM. To be sure, nanotechnology is pursued in academic settings where the unfettered pursuit of truth at least is the stated ideal. IBM, along with the raft of other high tech companies that are pursuing nanotechnology, no doubt seeks truth, but not at the expense of shareholder value. Indeed, Eigler and Schweizer say of their image:

Artists have almost always needed the support of patrons (scientists too!). Here, the artist, shortly after discovering how to move atoms with the STM, found a way to give something back to the corporation which gave him a job when he needed one and provided him with the tools he needed in order to be successful.

(www.almaden.ibm.com/vis/stm/gallery).

Nanotechnology, including the instruments that make it possible, such as the scanning tunneling microscope, is developing in a much more thoroughly integrated academic/commercial matrix. One nanotech researcher tells us, tongue only half in cheek, that an assistant professor probably should not get tenure unless he or she has two 'start-ups' to show for him- or herself (Tour 2002). John Ziman calls this 'post-academic science' (Ziman 2000, ch. 4).

We are interested here in the development of scanning tunneling microscopy, and in particular how its development in a 'post academic' context impacts the design constraints on STMs, and the various off-shoots, generically called 'scanning probe microscopy' [SPM]. We argue that the epistemic needs that underlie commercial development differ from those that underlie academic development. Thus, through our examination of STM and its relation to nanotechnology, we articulate a key epistemological difference between 'academic' and 'post-academic' science.

2. Scanning Tunneling Microscopy²

Scanning tunneling microscopy is conceptually simple. Imaging with STM involves moving a tip over a surface to obtain topographic information about the surface. One can compare STM to Braille reading or the way the tumblers in a lock 'read' a key's shape. STM relies on the phenomenon of electron tunneling to image surfaces. Tunneling is a quantum-mechanical phenomenon that is manifested in a current induced by a voltage differential between the scanning tip and the sample (Chen 1993). The level of the tunneling current is directly proportional to the distance between the tip and the surface. The closer the tip is to the surface the higher the current.

The components of an STM include a probe tip, a piezo-electric material that controls the tip's location in all three dimensions, a voltage source, a means to measure current flow from sample to tip, and finally computing power both to transform current data into an image and to control tip movement (Chen 1993). The scanning tip, which ideally is atomically sharp, is usually made of tungsten or platinum-iridium. Typically, a topographic image is produced by running the tip back and forth over the sample surface such that, by means of an electronic feedback loop, the tip is moved up or down to keep the tunneling current – and consequently the tip's distance above the surface – at a constant value. By taking note of the amount the tip has had to be moved up or down, a topographic image of the surface can be produced with the aid of computer imaging software (Griffith & Kochanski 1990). When all works right, we see on the computer screen an image that looks as though we were looking at the landscape of atoms on the sample surface.

Although simple in concept, the researchers creating STM had to solve several difficult problems: precise control of the tip's location and movement, control of vibration, and making a tip with the necessary atomic sharpness. The tip must come within a few nanometers of the surface. Finding a material that can move the tip without crashing the tip into the surface – or worse – was a huge problem. Piezoelectric ceramics were the answer. Piezoelectric ceramics deform only slightly when an electric voltage is passed through them. By appropriately varying the voltage in the piezoelectric positioner, an STM achieves precise control over the tip's location over the sample. The tunneling voltage, working in conjunction with the feedback system and the piezoelectric material, allows for precise control of the tip's height and placement over the surface.

Because STM is done with such a high degree of precision, where the tip is only nanometers from a surface, external and internal vibrations can present substantial problems.³ Early STMs were operated at night with everyone silent. Vibration also can be reduced by building the instrument with sufficient mechanical rigidity and through an appropriate configuration of the piezoelectric transducers. Sometimes STMs are hung on a double bungee cord sling to manage vibration. Further vibration isolation systems have also been made with springs and frames (Baum 1986).

Making tips remains something of a dark art. One takes a piece of tungsten or platinum-iridium wire and cuts it with wire cutters, being careful to pull away from the end that will serve as the tip. Some researchers develop a good knack at this, while others do not. While tips are usually diagramed as nice symmetrical ice-cream cone structures, in reality they are messy affairs resembling a jagged mountain range. But what is crucial is that one peak from this range be sufficiently higher than all the others and itself be atomically sharp; it then can serve as the point through which the tunneling current passes (Myrick 2002a).

There was some lag between Binnig and Rohrer's development of STM in 1981 and its acceptance. Initially surface scientists were skeptical, but when Binnig and Rohrer solved a well-known outstanding problem in surface science – the structure of so called crystalline silicon (1,1,1) 7×7 – they began to take notice (Mody 2004). As the 1980s progressed, Binnig and other collaborators developed the scanning tunneling microscope in a variety of directions, including atomic force microscopy (AFM). Because STM depends on a current passing from sample to tip, only conducting samples could be imaged. AFM, which Binnig, Christoph Gerber and Calvin Quate developed in 1986 (Binnig, Quate & Gerber 1986), avoids this limitation by measuring the tiny deflections that a sharp probe experiences when dragged over a surface. As the surface goes up in elevation, the probe is deflected up, and this deflection can be measured. Combining measurements from the whole surface allows researchers to produce an image of the topography of the surface.

3. Elements of the Commercial History to STM

While STM and its early siblings, AFM and the other techniques of probe microscopy, were developed in what officially is a corporate context – IBM – the work was essentially academic research pursued in an industrial research lab. Through most of the 1980s, STM and AFM remained primarily of academic interest. It took some time for the technique to catch on. There are a variety of reasons for this.⁴ Some are disciplinary or structural. While the first arena where STM could and did make a significant contribution was surface science, neither Binnig nor Rohrer came from this academic community, and their claims for STM were not, for this reason, immediately accepted by the surface science community. There were epistemological hurdles to jump as well. The images that one can produce with a STM are very nice, but on what grounds are they to be believed to be genuine images of individual atoms? Finally there were pragmatic reasons that slowed the development and acceptance of STM. Prior to the commercialization of STM in the late 1980s, the STM probe was not integrated with a computer, and this made the instrument much more difficult and time consuming to use (Myrick 2002b).

These issues – disciplinary insulation, epistemological acceptability and pragmatic ease of use – create a kind of ‘chicken and egg’ problem for the commercialization of STM and SPM more generally. Profits require a large enough market to offset the costs of research and development. Broad markets, by their nature, cross disciplinary boundaries, but they also require instruments whose results can be relied on, and which can be used by people other than those academics willing to spend hours coaxing the instrument to work. Fascination with instrumental possibility, with pushing the limits of resolution, of what it is possible to ‘see,’ makes for good academic research, but not for an instrument that serves ‘transparently’ or ‘instrumentally’ in the pursuit of other concerns with broad market appeal. At the same time, these broad markets will not develop unless there are instruments available ‘off the shelf.’ Such instruments are for people who are not themselves interested in instrumental development. Navigating this chicken and egg problem is the fundamental story of the commercialization of STM and SPM during the late 1980s and 1990s.

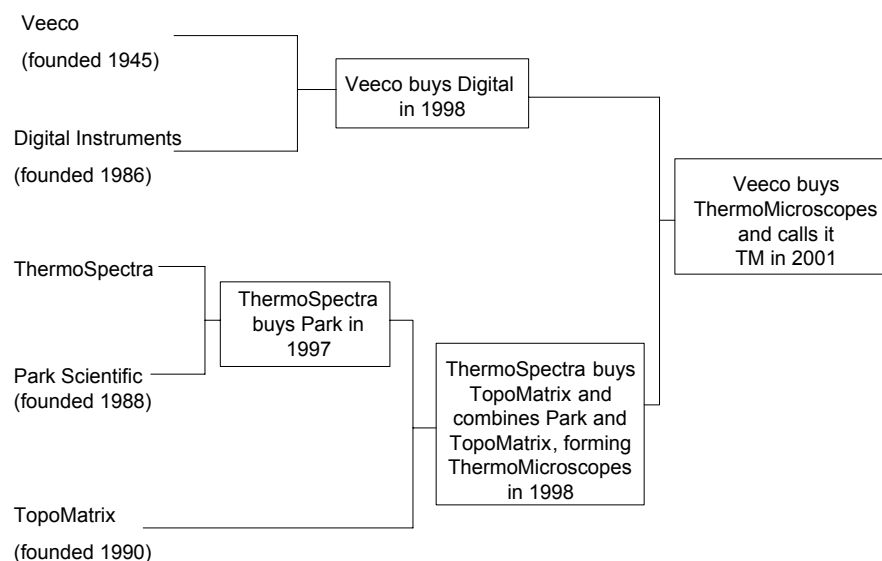


Figure 2. Veeco's Story.

Although some researchers still chose to build their own STMs or SPMs, a large number of commercial instrument makers have gone into the SPM market. By the late 1990s some instruments could be purchased for as little as \$50,000 (Amato 1997) or even less – \$15,000 – for a ‘teaching instrument.’⁵ Most instrument makers are willing to customize their instruments to the specifications of the buyer. The main players in the SPM market have been Digital Instruments (DI) (founded in 1986), Omicron Nanotechnology (founded in 1984), RHK Technology (founded in 1977), Park Scientific (founded in 1988), TopoMatrix (founded in 1990), and Molecular Imaging (founded in 1993). During the 1990s, through a series of mergers, this diversity of individual makers has been concentrated in a much smaller number of major players in the SPM market. See figure 2. Veeco has become the 2,500-pound gorilla in the SPM world, and this has implications for how the instruments develop. For example, Veeco’s coloring scheme – taken over from DI – has become a de facto standard in SPM images. More generally, a smaller number of makers will lead to more standardization and less diversity.

4. Post Academic Science

Understanding the context in which the history of STM is taking place is essential to understanding the history of STM. Stated most generally this context involves a much closer relationship between academic scientists and commercial concerns. There are a variety of forces driving the move to ‘post-academic science,’ and a full discussion would go well beyond the scope of this paper. Here we briefly discuss three salient points: the Bayh-Dole act of 1980, the National Nanotechnology Initiative of 2000, and ‘nanovisionary hype.’

The Bayh-Dole Act of 1980 allowed Universities to patent and collect royalties on the fruits of research conducted with federal funds. In this way universities were pushed to partner with the industrial sector to transfer the fruits of federally funded research in the academy, and thereby to profit from them in the commercial sector. Bayh-Dole accelerates ‘technology transfer,’ and has had a broad impact. Prior to 1980 it was a rare event for a university to patent – fewer than 250 patents were issued to universities per year. Now the number of patents issued to universities is nearly 2,000. According to the Cornell Research Foundation:

Academic technology transfer in FY 1999, specifically the licensing of innovations by U.S. universities, teaching hospitals, research institutes, and patent management firms, added about \$40 billion to the U.S. economy and supported 260,000 jobs. It has helped to spawn new businesses, create industries, and open new markets. Moreover, it has led to new products and services that save lives, reduce suffering, and improve our quality of life. (Cornell Research Foundation 2001, p. 2)

Of course in addition to these cheery consequences of Bayh-Dole are consequences about how universities function. Bayh-Dole pushes universities toward a more corporate profit-centered style of operation, and this is having – and will continue to have – fundamental consequences for the way research is done (Press and Washburn 2000).

There has been a concerted effort through legislation such as Bayh-Dole to increase the rate of technology transfer, or, put in other terms, to decrease the ‘time-to-market’ for discoveries. The National Nanotechnology Initiative [NNI] takes another big step in this direction. At the end of his presidency, Bill Clinton proposed the NNI with a \$225 million dollar budget for FY 2001 – an 83% increase over expenditures on nanotechnology in the previous year – and hefty budget increases projected into the first decade of the new century (National Science and Technology Council 2000). The initiative is a large project involving numerous governmental agencies. It is managed by the National Science and Technology Council, which coordinates nanotechnology initiatives at a large number of gov-

ernment agencies, including the Departments of Defense, Energy, Justice, Transportation, Agriculture, the Environmental Protection Agency, NASA, the National Institutes of Health, the National Institute of Standards and Technology, and the National Science Foundation. The budget devoted to nanotechnology at these institutes in FY 2002 was \$604 million dollars, and this is projected to increase to nearly a billion million dollars in FY 2004 (National Science and Technology Council 2002, p. 5; Kanellos 2004). While the U. S. investment in nanotechnology in FY 2000 exceeded all other countries, in FY 2001, Japan took the lead in nanotechnology investment, and a recent publication by the European Nanobusiness Association argues that the European Union is now investing more heavily in nanotechnology than the United States (Roman 2002). According to a recent publication, "Corporations, governments, universities and others are expected to spend an estimated \$8.6 billion on nanotechnology research and development in 2004, and the private sector will account for a bigger proportion of the total" (Kanellos 2004).

It is no accident that the NNI is a *nanotechnology* and not a *nanoscience* initiative. This was a point of discussion in its development, and those with a focus on technology won the day (Lane 2002). While work at the nanoscale holds some interest because the behavior of nano-sized materials (objects 1-100 nanometers in size) cannot be explained by current quantum mechanical models, it is the technological promise of work at the nanoscale that is compelling. A central aim of the NNI is to quickly move nanoscientific discoveries into commercial development. In 2002 the Massachusetts Institute of Technology received a 50 million dollar grant from the US Army to develop better uniforms, uniforms that would use nanotechnology to stop bullets and other toxins, to monitor the health status of the wearer, to provide extra strength to the wearer, and to communicate with remote sites. But, M.I.T. materials scientist Edwin Thomas notes, the Army "didn't want just papers in *Science* and *Nature*. They wanted real stuff" (quoted in Talbot 2002, p. 46). It took 24 years to take the discovery of the semiconducting properties of germanium in 1931 to the production of a commercial transistor in 1954; it took nine years to take the discovery of carbon nanotubes in 1991 to the production of a commercial nanotube product in 2000 (National Science and Technology Council 2002, p. 79). Technological visionaries expect this 'time-to-market' to continue to decrease, and the NNI is pushing this trend. Ray Kurzweil has a whole futurology divined from this kind of exponential increase in the rate of discovery and decrease in the time for technology transfer and commercialization (Kurzweil 1999).

Much is expected from nanotechnology. In a recent report from the United States Government National Nanotechnology Initiative we read: "The impact of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in the century just past" (National Science and Technology Council 2002, p. 11). But, relative to the predictions of some 'nano-visionaries' these governmental predictions can seem modest. There are serious theoreticians who suggest that a 'universal assembler' is not science fiction, but less than a generation or two away (Drexler 1986, 1992). What is a 'universal assembler'? Roughly put, it is a device that can be programmed to mechanically place individual atoms (or the assembled parts made by standard chemistry) in specified places. Since everything in our material world consists of particular arrangements of atoms – into molecules and thence concatenations of bulk materials, in theory a universal assembler should be able to make anything, and make it with atomic precision. Give the device enough raw materials, and a (no-doubt very complex) blueprint or assembly program, and it will assemble anything you want. In theory it will be possible to do this inexpensively and quickly: dirt in, couches, cars and carrots out. At a theoretical level, these 'nano-visionaries' argue, biology provides an existence proof for such an assembler: Given a DNA program and the right materials and conditions provided in a womb

and our ‘biological assembler’ puts together a human baby. In his 1986 book, *Engines of Creation*, written for a popular audience, Eric Drexler spelled out how we are on the verge of being able to do biology one better. The vision is breathtaking, and if true it would radically and fundamentally transform everything.

Not surprisingly, there have been many skeptics. But in the afterword to the second, 1990, edition of *Engines of Creation*, Drexler remained convinced:

To summarize some indicators of technological progress: *Engines* speculates about when we might reach the milestone of designing a protein molecule from scratch, but this was actually accomplished in 1988 by William F. DeGrado of Du Pont and his colleagues. ... At IBM, John Foster’s group has observed and modified individual molecules using the technology of the scanning tunneling microscope [work that led to Eigler and Schweizer’s ‘IBM’]; this (or the related atomic force microscope) may within a few years provide a positioning mechanism for a crude protoassembler. (Drexler 1986, pp. 240-241)

Through the 1990s our understanding, and more importantly our ability in the lab to intervene and control atoms, while nothing remotely like Drexler’s assembler, has moved steadily ahead. In 1991 Robert F. Curl, Harold W. Kroto and Richard Smalley discovered carbon nanotubes. These are tubular structures made of carbon atoms. Like graphite and diamond, they are another crystalline form of molecular carbon. Carbon nanotubes are a few nanometers in diameter. We are steadily moving ahead on controlling the synthesis of carbon nanotubes and on increasing their length. They have remarkable properties in terms of strength to weight, conductivity, magnetic properties, etc. Radically new and useful materials made with carbon nanotubes will be commercially available in the near term. Whether by way of a ‘universal assembler’ that seems like science fiction or by way of more prosaic incremental technological development, such as carbon nanotubes, nanotechnology is having and will have a significant impact on society’s technological infrastructure.

5. The Standard Story

There is a standard story about how nanotechnology appeared, and scanning tunneling microscopy plays a central role in this story (National Science and Technology Council 2000; Drexler, 1986). It starts with a talk Richard Feynman gave to the American Physical Society on December 29, 1959, ‘Plenty of Room at the Bottom’ (Feynman 1960). Feynman discusses how much space it would take to store written material on the nanoscale:

For each bit I allow 100 atoms. And it turns out that all of the information that man has carefully accumulated in all the books in the world can be written in this form in a cube of material one two-hundredth of an inch wide – which is the barest piece of dust that can be made out by the human eye. So there is *plenty* of room at the bottom! Don’t tell me about microfilm! (Feynman 1960, p. 3)

He goes on, as the standard story goes, to prophetically suggest how real progress could be made:

We have friends in other fields – in biology, for instance. We physicists often look at them and say, “You know the reason you fellows are making so little progress?” (Actually I don’t know any field where they are making more rapid progress than they are in biology today.) “You should use more mathematics, like we do.” They could answer us – but they’re polite, so I’ll answer for them: “What *you* should do in order for *us* to make more rapid progress is to make the electron microscope 100 times better. (Feynman 1960, p. 5)

With such a microscope we could see individual atoms, and then we would really be able to do things. Feynman talks about how this would help biology, how we could make miniature computers, surgeons that one would swallow, and which would then do their work from the inside. He discusses problems of manufacture at the nanoscale. In short, 40 years before we began to get there, he imagined the possibilities that nanotechnology is now opening up. And, while there have been advances on many fronts, the scanning tunneling microscope – not quite Feynman’s electron microscope, but with some of the same abilities he talks about – is widely hailed as the first major step down this road.

So the standard story has Feynman mapping the way to nanotechnology. First we need a microscope. Binnig and Rohrer gave us that in 1981. Then we start to design and manufacture on the nanoscale. Drexler’s *Engines of Creation* and – more fundamentally – *Nanosystems* begin the design process for atomic manufacture. Eigler and Schweizer’s ‘IBM’ shows genuine atomic scale writing. Given enough time, we could imagine all the words written in the world in a dust particle. By the beginning of the new millennium we have the National Nanotechnology Initiative harnessing a powerful economic motivator to push the development of nanotechnology.

There are many problems with the standard story. The electron microscope has provided atomic level resolution – in the best circumstances – since the 1950s, and it is a much more stable instrumental technology than SPM is at this point. Dana Dunkleberger, Director of USC’s Electron Microscopy Lab is not impressed with SPM. He tells us that it can take two days fiddling with an STM to get something that *might* be useful, whereas 10 minutes with one of his electron microscopes will produce the goods (Dunkleberger 2002). And, indeed, the electron microscope is itself very useful in nanoscale research.

Talk to nearly any lab scientist and they will express substantial skepticism over Drexler’s notion of a universal assembler. New York University chemist Nadrian Seeman can construct a variety of nanoscale structures using DNA as the primary building material. But he has been struggling with this for nearly 20 years and as he says, most of the time you work in the lab for several months and, if you are lucky, one of 500 carefully controlled chemical constructions will work. His methods remain biochemical, not ‘nano-engineered’ or ‘assembled’ (Seeman 1999, 2002, Liu *et al.* 1999; Winfree *et al.* 1998, Mao *et al.* 1999). Despite the remarkable, but special case of Eigler and Schweizer’s ‘IBM,’ we do not have the ability to place atoms just as we please.

The fact that there are problems with the standard story makes it all the more interesting why this story is so widely reported. Drexler uses it. It is used in the narrative of the National Nanotechnology Initiative. It is used in numerous articles that provide a potted history of how we got to nanotechnology. Why not report advances in electron microscopy? What is so special about STM?

As Eigler and Schweizer’s ‘IBM’ proves, STM – as opposed to electron microscopy – is not simply an imaging technique, but a ‘touching and rearranging’ technique as well. It is, in a sense, appropriate for Drexler to say that it may lead to a ‘proto-assembler.’ This is central to Feynman’s vision. It is central to Drexler’s vision. It is central to the fact that we have a national *nanotechnology* and not a *nanoscience* initiative. On this vision, nanotechnology is chemistry *by other means*. We are not just mixing, heating, stirring and generally coaxing atoms to rearrange themselves in desirable ways – following standard chemical practice – but we are in some sense directly touching and placing atoms. This is what is so striking about nanotechnology and why, despite its problems as a genuine historical narrative, the standard story is so compelling.

6. Post Academic Innovation

We came to write this paper as part of an effort to understand the instrumental basis for nanotechnology. This itself is part of a larger project that seeks to show how societal understanding and control of this new and potentially transformative technology can and should be informed by the instrumental and theoretical understanding and control of nanotechnological phenomena.⁶ We were introduced to STM through ‘the standard story’ – as anyone would be from reading of the nanotechnology literature. Consequently, we were very surprised to hear Dana Dunkleberger, Head of USC’s Electron Microscopy Lab dismiss probe microscopy. He called SPMs “squirrely” (Dunkleberger 2002). There are, no doubt, reasons for his dislike of probe microscopes to be found in his background and training, which started in the 1960s and has focused almost exclusively on electron microscopy. But we believe there is more here, and we close this paper considering what this ‘more’ could be.

To put the matter in a nutshell, electron microscopy has developed to the stage where, for the scientist and industrial researcher, it is akin to a ‘one-hour photo lab.’ The analogy operates on several levels. First, like a one-hour photo lab, researchers can send materials to an e/m lab and expect to get back useful results – e/m images – in fairly short order. Useful results do not depend on the technician operating the microscope knowing much about the source of the sample. Second, the technicians also do not have to know much about the operation of the microscope. It is possible for them to produce good images through fairly routine adjustments to the instrument, adjustments that can be made with a minimal knowledge of the principles behind the instrument’s operation. Consequently – and third – it is possible for any reasonable competent researcher to take a sample to an e/m lab and to get useful results him- or herself, without extensive training and experience with the instrument. Indeed, USC’s e/m lab is set up for just this kind of use.

None of this is true for probe microscopy. The instruments are finicky, requiring an experienced hand to operate. Those using them have to have some initial understanding of what they are looking for to get useful results, and it takes a good bit of time to get these results. Properly interpreting the results themselves requires a nuanced understanding of the sample under investigation and the way in which the instrument interacts with the sample. There have been notorious misreadings of STM images, including an image presented on the cover of *Nature* (Driscoll *et al.* 1990) that purported to show DNA, but which very likely is an artifact (Myrick 2002a).

We can characterize the difference between electron microscopy and probe microscopy in terms of six points:

1. Robustness of structure;
2. Ease of operation;
3. Through-put;
4. Versatility of use;
5. Ease of reliable interpretation of the output;
6. Ability of the output to ‘stand on its own’ as ‘a fact.’

In 2002, Professor Harry Ploehn of USC’s Department of Chemical Engineering, purchased two STMs. Two graduate students were assigned to learn how to work with them so they could be used in research applications. Both were soon broken (Myrick 2002b). This is not to be blamed on clumsy graduate students, but rather on the state of the art of STM instrumentation. STMs require an experienced hand, and are easy to break in inexperienced hands. Even then, they are difficult to use, and they take a long time to produce useful images. While STMs have been used on nearly everything under the sun (Mody 2004), they do not regularly produce useful results across this spectrum of uses. Finally, despite the striking successes of such images as Eigler and Schweizer’s IBM, the images that one can

get from an STM are not routinely reliable, and cannot now be interpreted independently of a prior understanding of the sample being imaged.

From the point of view of someone with little interest in probe microscopy *per se*, but for whom images – and possibly even manipulation – of atoms is a desired end, probe microscopy is deficient in regard to these six points. Among those who have been working on SPMs since their inception, Stanford researcher, Calvin Quate recently has concerned himself attacking these issues:

The major limitation for scanning probe imaging and lithography is throughput. A major thrust of the work in our group is geared toward increasing throughput by scanning simultaneously with multiple probes all moving at high speeds. (Quate 2002).⁷

Other researchers have pointed out to us how difficult overcoming these obstacles will be for SPM (Myrick 2002b). A significant difference between the electron microscope and probe microscopes is the ability to radically alter the field of vision. With an electron microscope one can put a specimen in the instrument and ‘see it’ with a field of vision large enough to allow comparison with images of the same specimen produced by more ordinary means, such as light microscopy. Then one can ‘zoom in’ on a particular feature, producing magnification beyond what is possible with light microscopy. This ability to ‘zoom in’ has two epistemologically important consequences. First, it provides compelling evidence that what the scope shows is not an artifact of the instrument. Here we can compare and calibrate (some of) the output of an electron microscope against the output of older and more established light microscopes. Second, it provides those using the instrument the ability to know where on the specimen they are looking, and this in turn provides more confidence in the interpretation of the resulting image.

We are not here concerned with making predictions about whether or when SPMs will be developed that resolve these issues. But we are concerned with making two points about them. First, the success of SPMs as commercial products depends on improvements on the six points we spell out above. Second, these points are not epistemologically neutral, but involve developing SPMs to satisfy certain epistemological ends and not other possible epistemological ends. Together these points articulate one respect in which ‘post academic science,’ and in particular its instantiation in the development of SPMs, is not epistemologically neutral.

There is a general term of art from the science studies literature that is used to describe resolving the six points we identify above: black boxing (Latour 1987, 1996, Baird 2004). Typically, in the science studies literature, the rhetorical strategy has been to open up, or ‘deconstruct,’ a black-boxed theory or instrument. Our interest, however, is in the process of closing the box, and what this means on an epistemological level. The on-going story of SPMs is an excellent case to follow to see the epistemology of post academic science in action.

Perhaps the most epistemologically compelling aspect to black boxing SPM is in the interpretation of the images. Images are not neutral data. They immediately invoke our powerful and experienced neural systems for processing and interpreting visual data. SPMs, in terms of their epistemological basis, are not visual – and in this respect they differ fundamentally from electron microscopy – they are tactile. But we present this “tactile data” visually, and we do this because, as human beings, we can quickly and easily – virtually transparently – ‘know what we are seeing.’ For this reason, it is not enough to make images from SPM data. The images have to accommodate our built-in or experientially acquired *way of understanding images*. Of course, it is possible for an expert on probe microscopy to train him- or herself to ‘see the visual data’ as it ‘should be seen’ given an understanding of how the data were acquired. But, if the instrument is going to be used by

‘non-SPM-experts,’ this can pose substantial problems. Thus, the kinds of images that a black-boxed SPM produces are significantly constrained by how humans interpret images. Indeed, part of our interpretation of images is our ability to move and see how the visual impression correlates with our motion. In this way SPMs are one important device for what Alfred Nordmann describes as “inhabiting the nanoscale” (Nordmann 2004). Thus it is no small difference that the electron microscope allows for more significant control over the field of vision. On similar grounds, it was no small improvement in SPMs when DI developed computer assisted digital controllers for their SPMs. These controllers allowed users to interact with SPM images in a manner more like the way we have become accustomed to interacting with other visual images.

One could imagine a world – indeed this was the world of the 1980s – when each researcher who wanted to use an SPM made it him- or herself. The instrument would be tailored to the specific research concerns because of which the researcher wished to use the SPM in the first place, and the output of the instrument could be in any format, because the researcher would know how the image was generated and what aspects of the output represented genuine interactions with the sample. In such a world one would expect a proliferation of SPMs varying in numerous respects from each other. In the world of commercial SPMs, with a need for broad markets and a need to deskill the instrument – both in terms of its use and the interpretation of its data – one expects less variation. Here, then, in the case of the developing story of SPMs, is a significant epistemological consequence of our move to post academic science.

Notes

- ¹ It is important to note that ‘IBM’ was created at very low temperatures, roughly 4 degrees Kelvin, in part to control for thermal motion.
- ² There is an excellent overview of the operation and history of STM as part of the Dibner Institute’s “History of Recent Science and Technology” website. There the development of scanning tunneling microscopy figures prominently in their history of materials research (hrst.mit.edu/hrs/materials/public/STM_intro). Another excellent source of information on STM/SPM put together by John Cross is the website www.mobot.org/jwcross/spm.
- ³ Binnig and Rohrer 1986.
- ⁴ Cyrus Mody explores this history very nicely in his essay in this volume (Mody 2004).
- ⁵ Burleigh Instruments, founded in 1972, started making SPMs for educational use in 1992. In a December 1992 advertisement, Burleigh advertised an Instructional STM for less than \$15,000 (Burleigh Instruments 1992).
- ⁶ This is a large multidisciplinary project funded by the National Science Foundation at the University of South Carolina (www.cla.sc.edu/cpecs/nirt/index.html).
- ⁷ Quate’s work also is quote on the Dibner Institute website (Dibner 2002).

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The Epistemology of the Very Small

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Abstract. The question is how do Scanning Electron Microscopes (SEMs) give us access to the nano world? The images these instruments produce, I argue, do not allow us to see atoms in the same way that we see trees. To the extent that SEMs and STMs allow us to see the occupants of the nano world it is by way of metaphorical extension of the concept of “seeing”. The more general claim is that changes in scientific instrumentation effect changes in the concepts central to our understanding of scientific results.

Introduction

The world of nanotechnology is the world of the very small. According to Eugene Wong in his testimony to the Subcommittee on Basic Research of the U.S. House of Representatives Committee on Science in June 1999,

One nanometer is 1-billionth of a meter. To get an idea of the size, we can compare some familiar things. The diameter of an atom is about 1/4 of 1 nanometer. The diameter of a human hair of 10,000 nanometers. The protein molecules, which are so important, so critical to life, are several nanometers in size. Moving to man-made things. The smallest devices on commercially available chips are about 200 nanometers, whereas the smallest experimental chips are approximately 10 nanometers in their smallest dimension. (*Nanotechnology*, p. 3)

The question I want to investigate here is “how can we come to know what is going on in this domain of tiny things?” There are a couple of issues to be examined: (a) what do we mean by “know”? and (b) how do we access this domain? Some would argue that the two are separate – that we can come to an agreement on the meaning of “knowledge” independently of settling the question of how we can access the nano-world. I want to argue that this is not the case. What we come to know about the nano-world is very much a direct function of how we access it and the criteria we bring with us that allow us to evaluate that access. This claim is part of a larger thesis: that we also modify our conception of knowledge as we develop criteria for calibrating our instruments.

1. Seeing the Unobservable

One would think that there really isn't a problem here since, for the last 60-70 years in the philosophy of science there has been an on-going argument over the status of objects smaller than what we can see with the naked eye. Basically the question to be answered is this: if you can't see it, is it real? The question actually is somewhat more complicated than the formulation just provided. It is usually couched in the context of determining whether or not entities proposed by true scientific theories exist. This question cannot be reduced to the question of observability alone, for not all theoretical entities are unobservable, *e.g.*, galax-

ies, and not all unobservable theoretical entities are very small, *e.g.*, black holes. Further, scientific theories are not the sorts of things of which we know with absolute confidence that they are true. They are constantly being challenged, modified, changed, and revised. Further, given the constant state of flux of theories in use, no one really knows what the theory is at the time at which it is being worked out. We finalize the content and form of a theory only after we have rejected it and moved on to something else – we finalize these versions of theories in textbooks.¹ All this being the case, it is no wonder that the status of theoretical entities, entities proposed by scientific theories that have yet to be proven to be completely true, is in question, in particular, those very small entities, the ones we can't see.

But it might be objected, that we *can* see them by way of various microscopes – devices that by their very names are designed to scope (see) the very small (micro). Here is where things get sticky, however. The crux of the matter has to do with the meaning of “to see”. The meaning of the verb “to see” has changed over time. Further, I would argue, what it means to see something has changed precisely because we have developed instruments to help us “see” more and more in different ways. Moreover, we have come to call this “seeing” without attending to the fact that it is not “seeing” in the usual way. Further, because we are usually inattentive to that fact, we fail to capture the nuances of the conceptual difficulties we should encounter when we talk about seeing things through a microscope. Let me explain.

2. The Role of Metaphor

The sense in which we “see” through a microscope is different than the sense in which we “see” a tree or a coffee cup. Or to put it another way, we have extended the meaning of the verb “to see” to accommodate our use of microscopes. Or to put it a third way, to talk about “seeing through a microscope” is to employ a metaphor. A metaphor is a way of easing our way into an understanding of the unknown by applying the familiar to the unfamiliar. We call a number of things “seeing” today because we metaphorically equate what we are doing with seeing as we naturally understand it.

For example, seeing through a microscope differs from seeing a tree with the naked eye because we don't have to learn how to see a tree. We may have to learn that that thing there is a tree, which is learning how to use our language – but you can run into a tree and hurt yourself and know that that thing there is what hurt you and not know that it is a tree. But can you do that when looking through a microscope? I would argue “no”. It is not because you cannot run into microscopic entities – it is rather that you can't see them at all until a couple of things happen that aren't required for seeing in the macro-world (that is, the world of tables, chairs, trees – the world in which we live): (i) you have to learn how to use the instrument; (ii) you have to learn how to see what is there.

3. Learning to See through Microscopes

Learning how to see through the microscope for the first time is difficult. You have to learn how to do a number of things, for example, not to get your eye too close to the lens, and keeping your head still and turning the focus knob at the same time. Those things take a little while to master. But the truly hard part is learning to see what is on the slide. This problem was with us from the start. Consider what Hooke had to say in the *Micrographia* in 1665.

What each of the delineated Subjects are, the following descriptions annext to each will inform. Of which I shall here, only once for all add. That in divers of them the

Gravers have pretty well followed my directions and draughts; and that in making of them I have endeavored (as far as I was able) first to discover the true appearance, and next to make a plain representation of it. This I mention the rather, because of these kinds of Objects there is much more difficulty to discover the true shape, then of those visible to the naked eye, the same Object seeming quite differing, in one position of Light, from what it really is and may be discover'd in another. And therefore, I never began to make any draught before by many examinations in several lights, and in several positions to those lights, I had discover'd the true form. For it is exceeding difficult in some Objects, to distinguish between a prominency and a depression, between a shadow and a black stain, or a reflection and a whiteness in the colour. Besides, the transparency of most Objects renders them yet much more difficult then if they were opacous.

Leeuwenhoek who is sometimes called the father of the microscope, complained of the same problem in a letter to Oldenburg: "...some of the forms I see are so fine and small, that I don't know how even a good draughtsman could trace them, unless he make them bigger."

But yet we have learned how to see using a microscope – partially it required the development of cell-theory and later, the theory of crystals. That is, once we had a way of understanding the sorts of things we were looking at, we had the means to see them as separate and distinct items, possessed of various properties, shapes, and appendages. This requires theory. It is not enough to know how to use a microscope, one must know what to look for. What to look for is dictated by various theories about the domain of the small.

But even the possession of theory is not enough, we also must develop the means of separating out individuals one from another. In the case of biological organisms, for example, we rely on staining techniques. And further, we had to learn to rely on the credibility of staining techniques. This is not a trivial matter. Let me relay a true story. Mike was a MS student in biology working on the eye of the Hackfish. He was having trouble staining his slides, so when he had the opportunity to attend a conference where he could ask for some help he leapt at it. At the conference he managed to corner the acknowledged expert on staining slides and explained his problem. The expert reportedly told Mike the secret to success: "first, turn off all the lights in the lab and make sure the windows are darkened. Then close your eyes and raise your left foot. Then, hopping on your right foot, make a 360 turn to the left. Then lift your right foot and do a 360 to the right. Then stain your slides." Mike was crushed. After he returned from the conference we had numerous discussions about what kind of a message the great man could have thought he was conveying, but never figured it out. Mike finished his degree, but he had lost his faith in science and left to go work for British Petroleum.

The moral of the story I take to be this: some of what we do in the process of seeing the very small involves a skill that cannot be taught by rote. That being the case, you would expect the results of using stains on slides to be doubtful, but, interestingly, they are not. Part of what is involved in seeing with a microscope involves accepting the fact that some people are better at staining slides than others, and we rely on them to prepare the slides. In a crucial way we have extended the concept of seeing by accepting the fact that it may take more than one person for seeing to occur and, further, that not both might actually do the seeing.

In addition to learning to rely on staining techniques to provide us with access to the very small, we also have to accommodate what I will call the problem of focus. Prior to 1702, focusing was done the old fashioned way: you brought the object to be examined into focus by holding the object in one hand, the lens through which you were looking in the other, and adjusted them until something recognizable came into view. According to Gerard L'E. Turner, Leeuwenhoek's microscope was "A tiny lens contained in a metal plat, with a

spike to hold the specimen close to the lens; the instrument was then handheld immediately in front of the eye” (in Bud and Warner 1998). James Wilson, an Englishman, developed the screw-barrel roughly forty years later in 1702. The screw-barrel allowed for mechanical focusing. With the development of mechanical focusing, stability became a factor that could be mastered. So, as we have seen, learning how to see through the microscope involved a number of steps, advances in theory, skill, and in the mechanical arts themselves.

I would like to look closer at the problem of focusing. Learning to focus an instrument is now an accepted part of seeing. But consider how strange this is. You don't have to be taught to focus your eyes to see macro objects like tables and mountains. What occurs is a natural phenomenon. Our biology takes over. And when you think of it, it is a rather amazing feature of our bodies. Focusing a seeing instrument, however, is an unnatural act. And yet, because it is integral to seeing with that instrument, it has become accepted as part of what we do when we use an instrument to see. And it is all part of the extended metaphor we now employ when we talk about seeing through a microscope or a telescope. It includes staining slides (or in the case of a telescope, computer enhancing photographs or using color filters), focusing instruments, theory, etc., all by way of accommodating what we do to what our eyes do.

4. Learning to See with Electron Microscopes

In his fascinating study *Picture Control*, Nicolas Rasmussen examines in great detail a number of these issues as they pertain to the electron microscope. In particular, he focuses on how criteria for acceptance are established, that is, on the social domain. Allow me to offer a lengthy quote:

[...] early biological electron microscopy involved a struggle for picture control on a number of levels. ...picture control figured in a biologist's subjective experience of the electron microscope as one of three relevant readouts, and along with focus, one of the two open to intervention. Of course, there was no such thing among the seven indicators and nineteen switches and knobs on the console of the Radio Corporation of America (RCA) EMU microscope [...] Control of who could make pictures with the electron microscope, how pictures should be made, what pictures would be printed, and how those pictures ought to be used in establishing biological facts were the dominant issues when the new instrument was introduced to biologists at the onset of the Second World War [...] By the end of the war, a community of scientists in whom expertise was vested [...] was established, and assumed a basic level of regulatory control. But for individual microscopists, control of the characteristics and interpretation of pictures remained a problem, and one that was divergently addressed in different biological subfields, even in different research programs within them. (Rasmussen 1997, p. 1)

Now Rasmussen is talking about the social evolution of standards in the same breath as the social evolution of consensus over who had access to the machines etc, and it sounds very social constructivist. The battles and issues he identifies are appropriately discussed as issues of power, access, and interpretation. Perhaps key among them is power. For what we are talking about is who sets the criteria and on what grounds. But no matter what the politics may be, there is a world out there that sets the bottom line. Or does it?

It is at this point that we need to distinguish between optical and electron microscopy. With optical microscopes we are actually looking at something. We prepare a slide by putting something on it. Further we are aware of the fact that when, for example, we stain a slide, we have introduced something to the slide and we can test to determine how that affects the specimen. What exactly we are seeing is a function of how we interpret what we

see using theory, but that there is something there to see is clear. With an electron microscope, on the other hand, we do not “see” the specimen. The machine uses an extremely fine point on a stylus to reveal the contours of a surface without actually touching the surface. Instead of dealing with the physics of light and the properties of specimens as we do with an optical microscope, with the electron microscope we get a “picture” of that surface through the use of various computer programs which take the input from the stylus running over the surface, then use the physical theory of the properties of matter to “interpret” the results, thus producing an image.

The question here is the extent to which the machine creates the phenomena. There is a weak and a strong version of this claim. The weak version holds that without the machine we would not be able to see what we see. This would suggest that the things we see with the machine are there in the world, but we don’t have the means to access them without the machine. That claim is fairly innocuous. The problem arises because of the stronger interpretation of the claim that the machine creates the phenomena, which is: what we see is an artifact of the machine itself – if doesn’t exist in the real world until we have the machine. If that is true, then the next question becomes “well, what kind of a thing is it? Does it exist or not?” To address this let us consider in slightly greater detail what it is that an electron microscope does.

Rasmussen and Hawkes give a rather succinct account that will assist us:

An electron microscope produces a magnified image through a specimen’s interaction with a beam of high energy electrons, usually 50-200 kilovolts. There are two principle forms of this instrument. In a transmission electron microscope (TEM), an electron beam at least as large as the imaged area passes through the specimen and forms an image on a fluorescent screen or photographic film. In a scanning electron microscope (SEM), an electron beam that is small compared with the imaged area passes over the specimen in a regular pattern, and a picture of the specimen surface is reconstructed on a video tube. Image contrast is formed in many ways. In the TEM, electrons are deflected by atoms inside the specimen, without absorption, creating a shadow pattern of greater and lesser electron transmission. In the SEM, interaction of the beam with the specimen surface produces varying intensities of backscattered and secondarily released electrons for each position in the scan, and these are registered by a detector placed appropriately near the specimen. (in Bud & Warner 1998, p. 382)

In each type of electron microscope, we end up with an image. But it is not an image directly obtained by seeing. The image is the result of a process in which the object under examination is not “caught” but rather reflected. But it is not reflected as a mirror reflects your face. It is a secondary reflection, almost like trying to draw the right hand wall of a handball court by observing where the ball lands on the front court after angling it off the right hand wall. The assumption is that the image represents the object. But it is not a representation such as we find when we draw a picture or produce a painting, say, a still life. And yet, we are content to say that the images are reasonable pictures of the objects – even though we can’t see the objects directly. Under normal circumstances, common sense would contest the claim that an image produced by an electron microscope is an accurate representation of a very small object that cannot be seen. But we accept the claim. Why? The question becomes more demanding when we consider some further complications. Rasmussen and Hawkes lay out some of the problems for seeing biological specimens:

The electron beam demands a vacuum, so specimens cannot be alive and require drying in some minimally destructive way. Since electrons interact strongly with matter, the beam penetrates only very thin specimens. Moreover, *the beam heats specimens, and so can alter volatile biological materials*. Contrast is another obstacle, since the

different substances in living things vary little in opacity to electrons. (in Bud and Warner 1998, p. 384, emphasis added)

So an early major problem was the modification of the specimen by the electron beam. The solution was to find a way to fix the specimen. In the biological sciences the solution was initially chemical, then supplemented by freezing. In the physical sciences this involved the development of techniques for coating the specimen with a thin film.

What is of interest to us is the fact that the development of means to stabilize the specimen did not alter the initial problem of the manner in which the electron microscope produces an image. The reliability of the image was not the issue, the stability of the specimen was. Essentially, we find the same situation as with the optical microscope: an evolving set of techniques and standards that fundamentally change our conception of seeing. But, what is interesting is that the sense of seeing evolves together with the standards and techniques. This results in a consensus on what a good image looks like, even though it is not an image in the earlier, pre-electron microscope, sense.

5. The Nano Scale and Nano Technology

So let us now return to the nano scale and nano technology. Nano technology is the construction of very small artifacts and systems of artifacts. It is miniaturization taken to the max.² And our question is how do we know that the things are working at the nano level as they are supposed to? One way is to look and see. And this is what we cannot do with electron microscopes or STMs without begging the question. A second way, much more economical and intellectually sound, is to wait and see whether what these mini machines are supposed to do actually happens. It is a pragmatic solution. William James' most notable contribution to philosophy was the aphorism: For a thing to make a difference, there must be a difference. I do not believe that we will have a problem knowing whether the nano machines are doing their job.

However, our understanding of our interaction with the nano world shares similar characteristics with what we mean when we see through a microscope. I quote again from the Congressional hearings on nanotechnology, and ask you to listen to the language carefully. Richard Smalley, Nobel Laureate, is discussing the impact of carbon nanotubes. He is discussing a slide he has put up on the screen.

As individual nanoscale molecules, these carbon nanotubes are unique. Just think of one at a time. They have been shown – here you see one draped across a few electrodes. They have been shown to be true molecular wires, to conduct electricity like copper – in fact, even better – and have already been assembled into the first molecular transistor ever built; with just a single molecule. (*Nanotechnology*, p. 9)

What struck me was the casual manner in which Smalley refers to seeing a single molecule. The idea that a single molecule could be a transistor is itself difficult to grasp. More significantly, the ease with which he speaks of seeing the molecule is of a piece with how he speaks of manipulating them. It is both natural and, in the context of what we mean by “see”, illustrative of the point I have been trying to make. The methods, standards and implications of modifying the language to accommodate the new technology comes slowly but of a piece.

The stronger thesis that it is a metaphorical extension of standard usage will have to wait for another time for its defense. But just consider another familiar nanotechnology claim. This simple statement, so straight forward, and yet so misleading, makes the point. I know what it means to divert a small stream of water threatening to destroy my driveway by removing a tree limb that has blocked a drainage ditch. I pick it up and toss it into the

field. By analogy I think I know what it means to put an atom where you want it to go, but I doubt that it is as simple as picking up a stick. Yet, the language of “putting atoms where you want them to go” makes it sound so familiar. What is really entailed? All we are talking about is manipulating atoms. Atoms, remember, are 1/4 of a nanometer in diameter. A nanometer is 1 billionth of a meter. To unpack the claim about putting atoms where you want them means understanding a lot about the means we have devised for doing this sort of work, the tools we have built and the assumptions we employ about what we are doing. My guess is that putting molecules where you want them is much like seeing through a microscope, it is now a team activity, involving sophisticated instruments and subsidiary techniques, a lot of theory, many theories, a lot of skill, and a lot of luck.

That seeing in the context of using SEMs and very large telescopes has become a team activity is not in itself something negative. The point here is that it is a different sort of thing than seeing a tree. It is important to note this difference because it helps us understand how science changes. In particular, what has changed is not just that what we mean by “see”. The introduction of these instruments also changes how we do science. This is not the obvious point that science is increasingly a team activity, it is that we have a new way of understanding scientific change. The moral of the story is that the older theories of scientific change proposed by Kuhn, Lakatos, and Laudan, seen in the light of the impact of new and innovative technologies such as scientific instruments, are deeply flawed. Scientific change is not merely a matter of the logical conditions under which scientific theories can be abandoned or accepted. It is a far more complicated process heavily influenced by the role of innovative instruments and other technologies that not only change the nature of the enterprise, but change the meaning of concepts like scientific observation, evidence, experiment.³ The impact of the new techniques required for a robust set of nanotechnologies will be important to watch as they will make a difference also in the manner in which we do the science of the very small.

Notes

¹ It is an interesting feature of undergraduate science education that undergraduate students are rarely, if ever, taught the latest, most up-to-date theories. The textbooks, I would argue, are out of date by the time they are published. This is one reason why getting undergraduate science students involved in research in an active laboratory is so important to the future of the scientific enterprise.

² It is important to note that this is as far as we can go in miniaturization given our current state of technology since the next level down is the quantum level, where stability of the material is itself in doubt.

³ For an elaboration of this theme see my *Thinking About Technology*.

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Images in NanoScience/Technology

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Abstract. This essay explores what it means to see and how contemporary technology is changing the tools and the methods of the way we perceive. The widespread desire for effective scientific visualization along with increasing sensitivity to popular attention has created a reckless culture of image manipulation. Scientists, illustrators, and artists take broad license in how they manipulate images to their purpose, but few viewers are aware of or alerted to what has been changed. The resulting images are often, unintentionally, more confusing and misleading than helpful.

Introduction

Images are playing a significant role in the development of nanoscience/technology. These images are also changing what we mean by and understand about seeing. Like the tremendous effect of the camera and photography, algorithmic microscopy is changing the culture of what we mean when we say 'see'. The images are no longer a reasonable extension of our eye and are forming a fundamental change in both the physiological and perceptual aspects of what it means to see.

People are surprised and suspicious when an artist ventures into the realms of science and technology. Humanists are suspicious of an artist interested in science and scientists don't trust artists. The arts, however, have a long and renowned tradition of creative curiosity in scientific development and a strong interest in culture. Obvious examples include the Renaissance investigations of Leonardo, paintings such as Rembrandt's 'Anatomy Lesson', and popular speculation that Picasso's Cubist concept, of seeing objects from multiple points of view at one instant, was an intuitive visual version of the complicated concepts of quantum physics.

This is not the popular, pedestrian art that hangs over the sofa, rather an art that establishes pathways, an art with meaning and purpose, an art that competes in a fast paced world. This awareness comes from art that, as a discipline, helps mediate complex and complicated issues for a public that is often technologically alienated. It is art that provides for alternate forms and methods of discovery. Contemporary conceptual art seeks not only the visual aspects of seeing, but also seeing as a means of understanding. These artists typically understand the formal aspects of image presentation, but also have a sincere interest in how their images communicate with, relate to, and influence contemporary culture.

1. Illusion

Reacting in painting to the power of the camera, twentieth century artists René Magritte and M. C. Escher showed us how easy it is to fool or misunderstand the differences between the expectations of what we know and the 'truth' of what we see – teasing us about the difference between these realities. Magritte's painting 'Euclidean' makes us question where the painting begins and shows us how easy it is to misperceive. 'Ceci n'est pas une pipe' re-

minds and warns us that an image, no matter how accurate, is only a representation, not the thing itself.

Optical illusions make the potential of misunderstanding even more apparent with images that can be perceived in two distinct and different ways – a woman sitting at a vanity becomes an ominous skull ('All is Vanity', Charles Allen Gillbert). Salvador Dali repeatedly played with these dual, often contradictory concepts in his Surrealist paintings. Other illusions take advantage of the physical nature of how our eyes process information with after-images of black dots where none exist, and parallel lines that surely seem to slant. They take advantage not only of what, but how our brain translates what we see.

Some of the most interesting illusions play the left, logical, analytic hemisphere of our brain against the right, visual, perceiving half. One classic example prints the names of multiple colors in inks of differing colors. The viewer is asked to recite the actual printed color of each word, but our schooled and practiced left brain rebels, wanting to read and state the word. These also provide important lessons for images in science.

2. Microscopy

The world at the nanoscale is hard to perceive. Recent generations have become accustomed to concepts of the infinite and the vast realms of space, measuring these distances in years at the speed of light. The new worlds being discovered at the nanoscale are even harder to imagine – 10^{-9} meters, one billionth of a meter. To put this into perspective, a second at the speed of light would encompass a distance of 186,000 miles; a nanosecond at the speed of light would be a mere eleven inches. Insightful books such as Philip and Phyllis Morrison's 'Powers of Ten' take us 10^{25} meters (1 billion light years) to the vast reaches of space, but only 10^{-16} meters (0.1 femto) into little worlds previously unknown.

The nanoscale, though far from the smallest of our awareness, is unique in that it is where we find and explore the fundamental building blocks of our lives, manipulating molecules, literally one atom at a time.

The microscopy necessary to 'see' and confirm these occurrences no longer employs optical or visual magnification. Rather, these microscopes are highly specialized devices used on samples in carefully controlled environments, usually under vacuum, and often at very low temperatures to slow the normal motions inherent in objects at that scale. They use touch versus sight, usually a mechanical stylus, probe or electron beam. The stylus reflects topological information to a reader that establishes a 3-dimensional surface map. There is a wide range of specialized, purpose specific, microscopy instruments, designed to 'see' varying specialized aspects of the nanoscale.

The resulting information is interpreted, with the help of computers, through mathematical algorithms, generating a visual image that can be viewed in many forms, from a numeric grid or value map to a 3-dimensional environment. The design of the instrument, the questions that interest the investigator, the skill of the operator, the information sought, the portion of the sample selected, and even the depth of focus all affect the resulting appearance. Value and color are common tools used to distinguish important or meaningful elements. The use of the latter is especially interesting in that the nanoscale is smaller than wavelengths of light, making it a colorless world.

Yet, with all this alteration, scientists and engineers tell us we are 'seeing' individual atoms. The nature of the instrument does not allow for recognition of undercuts, so atoms, which are generally thought to be spherical, are represented as organic, rather than purely geometric, cones. It is almost as if we do everything we can to confuse the image while ignoring many things we could do to make it more accurate. Shapes are constructed by carefully and selectively manipulating individual atoms on a uniform surface.

It is even hard to find uniform understanding among various scientists and engineers regarding what portions of an image have been manipulated and how they may have been altered. Verbal descriptions usually speak more to the materials of the sample rather than the undocumented visual alterations. There is a growing need for some simple, common conventions of categorization, communication, and understanding about what the image seeks to convey and how it may have been changed.

3. Images

Many nanoscale images are colorless, visually bland versions of ordered atoms or simple surface topologies, exhibiting the ability to order or control our environment, others take extensive license in making an image that is often more visually interesting than scientifically informative – see the website, ‘NanoPicture of the Day’ (www.nanopicoftheday.org/) for some of the most interesting. Break-through images such as Don Eigler’s now famous corporate logo, ‘IBM’ attest to the ability to manipulate our world one atom at a time – albeit very slowly and at very low temperature. This was quickly followed by a competition from ‘Intel’ and a change of subject to representation of self in the ‘Carbon Monoxide Man’. It is interesting to note that the images seem to recapitulate the development of Western art, starting with marks, images of our environment, moving to representations of self, and finally seeking more creative and visually exciting variations.

Dr. James Tour of Rice University has created a series of substantive figures called ‘NanoKids’, refining a nano-figure while communicating with, captivating, and educating middle school children, from whom will come tomorrow’s scientists. Tour laments that many elementary school, but few high school students are excited about becoming scientists, and one wonders where and how the interest is lost. These visual efforts in public education also become effective devices for educating their parents and mediating this information to an ever curious, and often technically naive, public.

4. Image typology

An initial typology of these varied images includes: Schematics, Documentation, Fantasy, and Fine Art.

SCHEMATICS represent an idealized version of an image through graphs, diagrams, stick and ball models, and simulations. These are the more traditional, guarded images of scientific visualization with little visual drama. Other examples include line drawings and molecular models of the DNA spiral, or a simulation of a fine motion controller potentially used for future molecular manufacturing.

DOCUMENTATION attempts to characterize how the image really is and includes photography, microscopy, illustration, and animation. Examples range from a wide variety of nanolithography to Eigler’s ‘Electron Corrals’. The very nature of these topographies allow for fly-through animations, another perfect, yet uncertain postmodern manifestation. Many of these animations seem to be done simply because we know how to create them and because they look ‘cool’, rather than because they offer any additional insight or illumination.

Like the frenetic wanderings of the National Aeronautics and Space Administration of late, contemporary scientists feel compelled, often rightly, to interest a largely uninformed public, to assure some form of public understanding and to develop the enthusiasm that will help influence decision makers, thus maintaining a continuous flow of research dollars. But are these highly manipulated and often-inaccurate images still evidence of good science and the right approach?

Even the most cautious investigators believe that this science and technology will influence every aspect of our lives and be the great social leveler, but the process of development is slow, and the need for tangible results overwhelming. This balance between basic research and practical application is an increasingly contentious subject on university campuses as well as in corporate laboratories. Hopes for the rags to riches growth like that of the digital industry along with the fear of unintended and possibly illicit use complicate the debate even more.

FANTASY includes a wide range of illustrative speculation that is not necessarily based on hard science and captivates at the risk of misinforming. Here we find a wild collection of monster-like mechanical devices, often shown in veins and arteries, attacking plaque and cholesterol. An award winning transparent ‘nanolouse’ uses pinchers and a needle-like probe to grab and sample a red blood cell. Another image shows two humans with virtual control over human-like nanobots. The sad irony in this message is that there is little or no apparent relationship between the position of the human driver and the machines they supposedly control. These images are popular, attractive, and intriguing, but not very informative and dangerously misleading.

FINE ART with respect to nanoscience seeks some form of meaningful and long-term effect on culture. It is, however, almost nonexistent, and leaves plenty of opportunity for aspiring young artists who dare to enter this complex field. Some well-known contemporary artists such as Gerhard Richter have utilized microscopy images from the nanoscale. Previous work in art & technology, installation, and conceptual art offer effective models for meaningful artistic progress and development.

The general public is mostly unaware of this rapidly developing technology, the art world perhaps even more so, potentially influenced by a fear of what technology portends for them and a reactive desire for the warmth and certainty of the hand-made. But, who better than the arts to evaluate and mediate the cultural role inherent in these developments?

Artists can and should be involved in scientific visualization, illustration, as well as the resulting fine art. They have the ability to mediate complex information and assist in the public’s understanding. Cooperative, creative and interdisciplinary work in this area also offers the opportunity for inventive visual discovery.

Nanoscale images can function in various combinations of these four categories and have the potential to change designation over time, but this outline of a typology should help us understand how an image operates and what information it intends to convey. In his book *The Structure of Art* Jack Burnham showed how an artwork can be categorized as natural or cultural and moves between these two areas as the public absorbs and assesses them over time.

Visual images in general are often misused or misunderstood, and this is especially true in nanoscience. Both popular publications and respected scientific periodicals have run dangerously misleading cover images. The cover of ‘Scientific American’ (June 2000) shows a molecule at the nanoscale poised between two gold tips; the individual atoms are a rich variety of colors, and show highlight and shadow – none of which exists at this scale. The gold tips show a uniform surface more in the realm of a human scale and show no individual atoms or molecules.

Similarly, ‘Science’ (9 November 2001, Vol. 284, No. 5545) shows neutral colored nanoscale carbon nanotubes clamped in place with the characteristics of human scale clamps and surfaces, all surfaces are replete with color, highlights, shadows, and reflections.

These sorts of misunderstandings may be even more dramatically magnified as Michael Crichton’s popular book ‘Prey’ becomes a major motion picture with swarming nanobots mercilessly killing their creators and others. Images are powerful. Add to that Hollywood moving pictures, sound, and a good story, and the public blurs fact and fiction

ever more readily. Where should we draw the line regarding responsible conveyance of information?

5. Conclusions

Cameras have come to be accepted as an extension of the eye and have preceded us to places we hoped to go to such as the moon and Mars. While not perfect, photography presents reasonable facts of what we trust we can, and ultimately will, confirm with our own eyes. The microscopy that allows us to see the nanoscale is distinctly different, increasing the distance between technological device and our eye, and posing some interesting questions. Will we ever be able to visually confirm these images? What unexpected changes might allow us to actually see what is now unseen?

NanoScience is changing how we see and what it means to see. In the development of our species, we started with vision; 2-D reflection was the beginning of interpretation, followed by marks, cave paintings, and continually refined illusory representation through art. Telescopes and microscopy provided for a new world of visual magnification that enhanced the resources of our eyes. Then photography offered an accurate rendering or reasonable visual truth, a significant cultural change. The camera often led where we trust the eye would follow – distant landscape, our own circulatory system, deep sea, the Moon, and Mars. Will we ever be able to confirm the nanoscale with our naked eye and do we need visual confirmation? We are generating images well beyond our current perceptual ability.

Digital manipulation, which allows for sophisticated alteration of a photographic image created a loss of trust in the visual truth of photographs. Algorithmic microscopy represents a significant change in the convention of seeing and requires broad trust in the accuracy of science and mathematics. While this trust may be warranted, much needs to be done to bridge the potential gap of understanding.

Should we fear these changes? Should we fear that humans will become obsolete and computers will take over the world? There are some compelling arguments that start in small packages – our dependence on technological devices, first for physical assistance and later for careful calculation, is subtly invasive. If we can exhibit no better control of the images supporting nanoscience, what subtle message do we send the public about our ability to control the broader development of the science?

The twentieth century artist, Marcel Duchamp sends an opportune message in ‘With Hidden Noise’. An enigmatic ball of string clamped between two metal plates. We can shake the object and know there is something inside the void of the ball of string. We don’t know what it is. Duchamp envisioned our dilemma. He created the artwork, but had a friend place a secret object inside, fully aware that one can fool others, but also oneself.

As we work to communicate the power and potential of nanoscience/technology, we must also work to assure that the creative work serves a broader interest. We must be careful not to fool ourselves, as well as an unsuspecting public, in the process.

Scientists should consider and encourage artistic participation in the popular interdisciplinary, collaborative work of nanoscience. It will certainly enhance the images and may lead to unexpected new discoveries.

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The Rhetoric of Nanotechnology

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Abstract. The following examines the special needs for communicating risk, especially risks associated with newly emerging technologies such as nanotechnology. The public is not receiving a lucid message from the many narratives. Scientists have begun to address the public directly with mixed results especially since the public is unprepared for the messages and the media fails to offer much assistance. The rhetorical strategies undertaken by proponents are examined with a case study. K. Eric Drexler advocated a self-assembling nanobot molecular manufacturing brand of nanotechnology. His rhetoric has buried the concept under layers of metaphorical obfuscation and has been detrimental to a coherent message.

Introduction

Technology is neither inherently liberating nor enslaving, neither decentralizing nor centralizing. Which approach to technology is embraced and the process of its implementation determine the relationship between purveyors and consumers. Whether democracy in the current millennium more reflects its roots found in the Athens city-states or the constitutional Republicanism of post World War II America and Western Europe may depend on technology related decisions. Well into the Information Age, it may be too late to smash the machines – eradication is no longer an option. What must be done probably involves citizen-consumers becoming integrated into the decision-making process. When technological discourse happens, citizen-consumers need to participate in these discussions and when decisions are to be made; citizen-consumers must be empowered to affect decisions.

Contemporary technological discourse is shameful. Leaders who wish to recommend options and sometimes policy call upon experts. Heavily biased by personal and professional interests, experts craft their messages so they are resistant to most counterclaims. For example, by using excessively technical vocabulary, their arguments become arguments from authority. When asked “why is that true?” their response generally is “Don’t you understand? I do. I have an advanced degree!” As a result, citizen-consumers are frozen out of depthful discussions on issues involving science and technology, especially those related to decision-making. When an occasional miscreant speaks up, he is derided, labeled, or patronizingly dismissed.

Unsurprisingly, when citizen-consumers are involved in science and technology decision-making, it is usually during the post-decision implementation phase. For example, a decision might be reached to build a toxic waste incinerator with citizen-consumers only called in for input on deciding where it might be located. Even then, in many cases, the location has already been decided and citizen-consumers vent their reservations in public meetings and are lectured to by public relations specialists whose job it is to sate, defuse, and demobilize opposition. In some cases, the means they employ may involve misrepresentations and downright lies.

The challenge for today’s developed and developing world must be to find ways for citizen-consumers to become entrenched in the decision-making process early enough to counteract, at least restrain, the interests of transnational corporate profit making. There

have been too many examples of selfishness, greed, and apathy by corporate structures toward the social, environmental and economic interests of the citizen-consumers on whom they often prey. Bhopal, India, Times Beach, Missouri, and Niagara Falls (Love Canal), New York, are only three illustrations, but they suggest that corporatism cannot be depended on to check itself.

In response, we have mostly opted for increasing government oversight and regulation. Though not an apparently undesirable response, it tends to further centralize power vertically.

However, we are at a crossroad. We may want to reduce pressures for greater authority as a weapon against irresponsible corporate action. By becoming involved in the earliest decisions, citizen-consumers can do their part to preclude the growth of governmental regulatory hierarchies. Authority is more likely to become more powerful as responses become more remedial in nature.

1. Foundations

While the rhetoric of science has been approached in the works of Alan Gross (1996) and Lawrence Prelli (1989), much less emphasis has been given to the rhetorical dynamics associated with technology. (In all honesty, it must be observed that the primary source of much that can be found in the rhetoric of science has been borrowed unabashedly from the philosophy of science).

It seems that scholars in communication have decided that the only voices associated with technology are those of its proponents and opponents. Proponents include chief operating officers of private companies seeking venture capital, government officials supporting policies that would serve technological firms in their home districts, public relations officers often acting as apologists, and technophiliacs, including grant directors, who preach technology as the cure-all for society's woes. Opponents include critics suspicious of the overclaims associated with technology, pragmatists who are responsible for coordinating government budgets against technological promises, and technophobes (Neo-Luddites) some Green some not who blame technology for most of the world's ills.

2. New Challenges

Rhetoric is no longer defined as the art of discovering the available means of persuasion. In more recent times, it has been defined as the constructive art of making knowledge. While traditional rhetorical studies have examined speakers and audiences, technology has a voice as important as the technologists' in terms of its impact on our lives.

Technology as artifact is highly suasive. If technology is the art of producing useful objects and we can accept the basic premise that rhetoric goes beyond the podium and includes such things as design discourse and scientific discovery, then the rhetoric of technology has to do with ways we use discourse to construct objects both metaphorically, if not metaphysically, and meaningfully.

The rhetoric from technology includes arguments that characterize our way of thinking as consumers of technology; especially in the way we devalue our abilities to control technology by delegating our agency to the machines and placing ourselves in subordinate or passive roles.

3. New Technologies

When it comes to nanotechnology, it becomes much more complicated. Nanotechnology speaks with a unique voice. Beyond scientists, venture capitalists, and science journalists, nanotechnology as an artifact of science has its own voice; it speaks as a plethora of actual nano-discoveries and virtual nano-promises, especially the assembler. The audience is composed of investors, the media, competitors, and policy-makers as well. While the arguments are built of speculative data and tentative warrants, they seem to be attracting larger audiences, the psychology of which is too dense to examine here. Simply put, a strangely weak argument is highly effective and that may be due to some extraordinary characteristics of the nanotechnology debate, especially within the United States.

Some of the characteristics of this debate that are confounding communication scholarship include but are not limited to the following.

First, the field is multi- or interdisciplinary, hence the voices come from a jumble of fields and disciplines. While the chemist may understand the biologist and the engineer, they do not make the same types of arguments. Further complicating the discord is the intersectional voice coming from chemical engineers, biotechnologists, and others who are in interdisciplinary fields already but find themselves hip deep in another multidisciplinary one.

Second, nanotechnology is here in size only. Simply put, nanoscience functions in the realm associated with the prefix nano-. However, the technologies that are likely to fulfill some of the claims made by proponents have not materialized. The assembler remains a pipedream and mass production of nanobots a fantasy construct. Nonetheless, the claims and counterclaims of benefits and risks associated with applied nanotechnology continue unabated. Critics of technology have found another artifact to flog.

Third, there seems to be some legitimate concern within the halls of Congress at least that mature nanotechnology might be problematic. Neal Lane and Mihail Roco notwithstanding, government regulators remain unconvinced that nano is the word. See, for example, recent demands that a bona fide SBE component (social, behavior and economic sciences) be included in NSF grant applications, including the NNIN (National Nanotechnology Infrastructure Network). As such, the debate over benefits and risks is being fed from above as well.

Fourth and associated with SBE concerns, many individuals and institutions seem concerned with the absence of a legitimate public sphere that can intelligently debate nanotechnology. As Americans become less and less versed in issues associated with science and technology beyond the least expensive mobile phone service and Internet service provider, science and technology plod onward. Some scientists and technologists are equally fretful that the reaction to genetically modified organisms, especially foods, may be repeated with the advent of nanotechnological products.

4. Communication Studies

Most communication studies of technology have been associated with risks and crises. They are subject specific, such as “The Challenger Disaster” or “Three Mile Island” or they are general examinations of the impact of technology on traditional political rhetoric, especially democracy and the public sphere. The two leading fields of communication are outlined below.

5. Crisis Communication

Crisis communication comes in pre-emptive and reactive flavors. In general, it refers to emergencies like fires, bomb threats, natural disasters, or major crimes. Controversial issues may include police investigations, protests or other situations that demand a public response. The directives hands-on consultants advocate are pretty much the same. Crisis means victims and explosive visibility. Bosses need trusted advisors and counselors who can offer focused, pragmatic, and useful advice that help them deal with difficult situations strategically and immediately, while limiting collateral damage. Using powerful case examples, participants will explore a series of crisis communication management problems and strategies while immersed in the same management struggles, confusion, decision-making, dilemmas, and moral challenges managers face. Case studies involve managing victims, reducing litigation, recovering reputation, healing corporate wounds, dealing with organized opposition, selectively engaging the media, Web attack survival, and influencing employee, community, and public attitudes.

The following was drawn from North Carolina State University's crisis policy¹

1. To factually assess the situation and determine whether a communications response is warranted.
2. To assemble a Crisis Communication Team that will make recommendations on appropriate responses.
3. To implement immediate action to:
 - a. Identify constituencies that should be informed about the situation.
 - b. Communicate facts about the crisis.
 - c. Minimize rumors.
 - d. Restore order and/or confidence.

While hardly insightful, recommendations like these stoke the coffers of small communication firms run by self-acclaimed experts and are the product of government grants newly supported by the Department of Homeland Security.

6. Risk Communication

Both Ehrlich and Ornstein argue humankind has a difficult time evaluating incremental risks. They claim we are developmentally much like our forebears who were creatures who reacted to threats and crises. When a bear appeared at the mouth of our cave, we hid or tried to fight it off (Ehrlich & Ornstein 1989). When we are confronted by events we do not understand, we lash out at it a lot like Cro-Magnon man, poking at a mass with his stone axe and clubbing it once it moved.

7. Defining Risk: A Primer on the Language of Risk

Risk pervades the world we inhabit. Whether of small or large magnitude, risk is a concept that everyone encounters (consciously or unconsciously) regularly and often.

In addition, public knowledge about science is limited, especially a subject as exotic as nanotechnology. Frank Press, President of the National Academy of Sciences, writes: "Opinion surveys and tests of U.S. students' knowledge show that public understanding of science and technology is weak. Even Americans with advanced training in non-scientific fields often know little about the revolution in biology or the amazing new materials being produced in laboratories" (Press 1991, p. ix). Indeed, if persons actually attempt to read or learn about science and the risks associated with it, they often have "limited access to ex-

pert opinion leaders to help interpret scientific and technical information” (Hornig 1990, p. 768).

Enter the public sphere. Traditionally, journalists replaced scientists as the “experts” defining risk levels. This has begun to change as third culture intellectuals, including Drexler, came along. Nevertheless, both use language. Whether intentionally or not, journalists and Drexler, himself, sometime obscure meaning by using words and terms, which underplay a problem and overplay a benefit. This framing process of encoding messages is hardly accommodating informed consent.

However, removing scientists from the calculus is not an answer. Moreover, there are times when the scientific community itself can be locked out in the decision-making processes. For example, “metaphors in science journalism cluster and reinforce one another, creating consistent, coherent, and therefore more powerful images which often have strategic policy implications” (Nelkin 1987, p. 81). The resulting communication tends to move towards polarization, generally becoming either overly complex or overly simplistic. Since simplified language is more approachable, it crowds out complex, though much more accurate and meaningful, scientific language.

Even the best public relations professionals have been unable to communicate objective assessments of risks, especially after a crisis. For example, in 1989, at the peak of its nuclear power usage, “nuclear generation produced only 18 percent of American electricity” (Jasper 1990, p. 90). Given the accidents at Three Mile Island and Chernobyl, and the realization that nuclear power accidents were bound to continue to occur as long as nuclear power is in use, the public became leery about accepting nuclear power as an alternative energy source, particularly in their surrounding communities. In response, industries’ risk communication strategies attempted to change this mindset and promote nuclear power as a safe, environmentally friendly choice for the world’s energy needs. Attempts failed to strike a proper balance between concern and fear, and the inadequate use of language is largely responsible.

The business and regulatory communities and their public relations professionals had many options but selected some poorly conceived and executed strategies. For example, one strategy involved oversimplifying the language. Presumably, communication based on simplistic language would ease the public’s understanding of a technical subject. Of course, this is true only when simple language can communicate the true risks effectively. Also, oversimplification may serve only to mask actual risks. Using simplistic language, public relations experts tended to have made nuclear power risks seem less significant.

Purposeful obfuscation was another tactic. The public relations officer of Pacific Gas and Electric proposed that industry spokesmen eliminate images and language that might work against them. He recommended that the Atomic Energy Commission (AEC) cancel a study on reactor accidents that could be used by antinuclear activists and that firms do “some semantic soul searching” to eliminate objectionable language: “palatable synonyms for scare words such as ‘hazard’ or ‘criticality’” would facilitate public understanding of nuclear energy. Thus, nuclear plant sites became ‘nuclear parks’ and accidents became ‘normal aberrations’ (Nelkin 1987, p. 146).

Nuclear power risk communicators also used doublespeak and it led to some increasing public support. Ethical issues aside, the communication did achieve some of its goals. Eventually, limitations to the use of doublespeak were apparent. The public became desensitized to the ‘more palatable’ terminology. Attempting to find novel metaphors for doublespeak to relay the risks (or lack thereof) to the public became an enormous challenge. The public seemed to tire of one catch phrase, and the communicators were on the chase again for another appealing metaphor. Each subsequent generalization became less effective.

Nonetheless, the public seems to feel more secure in its level of knowledge with simplified information. Its perspective, based on a two-dimensional representation of reality

often fails to engage the debate. Consequently, when consensus is forged, it comes through few discriminating channels and is fragile.

There is the obverse, a second problem for communicators. Communication through complexity makes understanding appreciably more difficult to achieve. Discussions about the risks associated with nuclear power generation can center on highly technical issues which few members of the public are familiar with. Metzler singled out technical jargon as a formidable obstacle to communicating risk.

Furthermore, there is evidence that technical and scientific jargon is counterproductive in risk communication for the majority of the public. The information must be unpacked into terms that the specific audience will understand. Typically this means explaining the risks in terms of how they directly affect those involved, such as that a worker has a 10% chance of being injured while performing a certain task. If people do not understand risk information, they can't make responsible decisions and will act on fear.

Add the observation that excessive use of acronyms, mathematical equations, and field terminology may also lock the public out of the debate. Not only are the concepts difficult to grasp, a third obstacle of risk language needs to be considered: some of the public may be unable to decipher meaning from the rhetoric itself. Numbers presented a unique problem in the nuclear power field. Science uses a plethora of numbers in its reports and assessments. Communication suffers because "most people find very large and very small numbers difficult to grasp" (Shortland & Gregory 1990, p. 87). For example, it is as difficult to imagine a 1 in 230,000,000 chance of electrocution as it is to imagine a .0000000007 (7×10^{-11}) chance of it. Risk is particularly susceptible to this type of reporting. Risks are frequently expressed in numbers or probabilities.

Finally, science and technology has a language of its own. Though confounding for anyone without scientific and technological training and expertise, its precision serves the technical community very well. Unfortunately, this level of specialization has marginalized a preponderant fraction of the population and they are at risk. By refusing "to integrate the scientific culture into the understanding [of the non-scientific one]... [t]he effect has been to spread misconceptions about science among the non-scientific public and has inhibited the full realization of science as a human institution" (MAST 1989, p. 26).

Learning from the case of nuclear fission power generation, risk communication in nanotechnology must use its resources carefully to reject oversimplification and technical jargon. Risk communication must be careful to avoid one excess in favor of another equally unfavorable excess. Since language is vital to express any concept, it is important to recognize the strengths of using appropriate language in relaying difficult concepts to the public and the weaknesses of using overly simplistic or technical language. Both seem to increase confusion, resentment, and may lead to rejection of bona fide desirable policies.

Though risk and crisis communication do examine some of the variables coupled with catastrophes, little scholarship examines less provocative scenarios. When it does, very little critical scholarship goes beyond ubiquitous computing or the enveloping nature of the Internet and its hypertextuality. While it may be true that your microwave oven or cell phone has changed your life, few scholars have detailed the rhetorical character of the changes, hence this project that draws on the history of domestic nuclear fission energy generation and the introduction of genetically modified foods.

Since risk is a prominent theme in discussions regarding nanotechnology, it is important that communicators recognize the role played by communication in alleviating or propounding public fears about new technologies. This will prove to be especially true regarding nanotechnology.

The MAST project reported its conclusions on risk perception of nanotechnology.

First, "technologies or activities that are familiar, well understood, controllable, or provide clear benefits are perceived as less risky than similar activities that are unfamiliar,

poorly understood, uncontrollable, or without benefits to offset the risks” (MAST 1989, p. 10). Nanotechnology clearly belongs to the second category.

Second, “risk perception is also colored by the ethical complications that may be entailed in deploying a new technology. If it is likely to exacerbate differences between rich and poor, or to raise difficult questions about life and death, people will perceive it as less desirable” (MAST 1989, p. 10). With the economic and metaphysical implications of nanotechnology, the public may exaggerate risks.

Third, “when risks are exotic, difficult to understand, and very difficult to calculate while benefits are diffuse and unclear, the public is likely to interpret the risks as unacceptable” (MAST 1989, p. 59). The speculative nature of nanotechnology and its substantial dark side makes it a serious candidate for inappropriate risk assessment.

8. Framing the Public Sphere Issues

Scott Montgomery and Steve Fuller have led the pack in discussing public sphere related concerns associated with the rhetoric of science. Scott Montgomery made two substantive criticisms of science and technology speak. First, he indicted traditional science discourse as “roughly performative”.

Scientific information is conceived in and through a discourse that has undergone tremendous compression; it is a language that, over time, has been made super heavy by modes of short-hand condensation, substitution, fusional reduction, and by the elimination of any lighter, non-technical gestures of speech. (Montgomery 1989, p. 48)

Illustration and imagery are not being used to illuminate complex demonstrations. The audience has shrunken to an expert few. Anyone straining to decode scientific messages is left ill equipped and underinformed. As modes of shorthand become more prevalent, discourse becomes more and more privatized.

Second, Montgomery extended his claim by complaining that scientific discourse has actually become increasingly jargonized.

If, as some maintain, contemporary science has become more “subjectified” than in previous decades, less dependent on the mythology of the “detached observer” and more willing to admit the truth of “probable knowledge”, its voice has on the whole continued to travel the opposite road, becoming still more jargon-filled, less expressive, less allowing overt references outside itself. (Montgomery 1989, p. 53)

At some point, the jargon so privatizes the discourse that the audience becomes discounted. Viable claims tend to go unheard, incorrect claims unrebutted, implausible claims unfalsified, and outrageous claims mediated as events.

As a result of government regulation, rhetors in science and technology have been compelled to speak to the public. Though they are speaking more, the settings in which they speak continue to marginalize the public from the decision making process.

Steve Fuller explained this phenomenon in his 1993 book. Fuller distinguishes between prolescience and plebscience. He blames this distinction on a “mutation of representative democracy [into] corporatism” (Fuller 1993, p. xviii). Fuller advocates science and technologies studies (STS) as a way to check corporate decision-making. To help characterize the status quo as opposed to one legitimized by citizen-consumer input, he bifurcated science policy into the two approaches.²

Supporting Feyerabend’s perspectives whereby “the democratization of science is simply the reflexive application of the scientific ethos of free inquiry to science itself” (Fuller 1993, p. 283 & Feyerabend 1975), Fuller seems to feel “research agendas and fund-

ing requests [should] have to be justified to a board of non experts, not simply a panel of experts” (Fuller 1993, p. xviii). Those non-experts are citizen-consumers and Fuller assumes they will use free inquiry to resolve implications of science and technology.³

Sagan warns scientists against keeping science generally incomprehensible for citizen-consumers. “This is a prescription for disaster. We might get away with it for a while, but sooner or later, this combustible mixture of ignorance and power is going to blow up in our faces” (Sagan 1995, p. 26). He argues our global civilization is integrated into science and technology as well as the reverse. In turn, it is beginning to seem as if political decisions and scientific ones are more difficulty to separate. Popular support will become a co-requisite of science decision making especially as resources for expensive and exotic scientific investigations become more troublesome to find. It seems insolent to presume the public will continue to support science and technology policy just because scientists told them to. Witness what recently happened to the Texas Supercollider project.

Since there are powerful reasons to broaden the decision making population to include citizen-consumers, those interested in foresight and specific policy making options have a special obligation to make participation as open as possible. The citizen-consumer will need to learn about governing, and as issues become especially complex, they may even need to develop special fields of expertise that might have seemed esoteric and irrelevant before. While there is a reciprocal duty on the part of the citizen-consumer to strive to understand, it is very easy for the technoliterate to place ideas, concepts, and issues beyond their reach. For example, while discipline specific terminology is often obscure, it is further complicated by terminology associated with methodologies. While anyone can learn to understand the terminology of meteorology – high pressure, temperature inversion etc., this is not sufficient when these terms are buried under a blanket of jargon like multi-variate analysis, multiple regression, etc.

9. C. P. Snow and a Third Culture

C. P. Snow portrayed twentieth-century British and, by filiality, American intelligentsia, stratified into two “cultures”: literary and scientified (Snow 1963). Snow blamed the resultant “gulf of mutual incomprehension between scientists and humanists largely on the refusal of humanists to integrate the scientific culture into their understanding” (MAST 1989, p. 26). John Brockman took Snow’s second essay on culture (“A Second Look”) and suggested that a third culture has recently begun to emerge that is somewhat unlike Snow’s vision. Whereby Snow felt the “third culture” would involve “literary intellectuals ... on speaking terms with the scientists” (Brockman 1992, p. 16), Brockman says this is not the case but that “[s]cientists are communicating directly to the general public” (Brockman 1992, p. 16).

The third culture consists only of those scientists and others who reside in the empirical world, who through their work and expository writing are taking the place of the traditional intellectuals and media in rendering visible the deeper meanings of our lives, redefining who and what we are in terms of our own species, the planet, the biosphere, and the cosmos. (Brockman 1992, p. 16)

Brockman believes “in the past few years, the playing field of American intellectual life has shifted, and the traditional intellectual has become increasingly marginalized” (Brockman 1995, p. 17). While traditional intellectuals bemoan this trend, it suggests a very intriguing phenomenon: “The emergence of this third-culture activity is evidence that many people have a great intellectual hunger for new and important ideas and are willing to make the effort to educate themselves” (Brockman 1995, p. 18). Rebutting elitists’ claim that the public is naive and disinterested, we continue to see “scientific topics receiving prominent

play in newspapers and magazines over the past several years including ... nanotechnology” (Brockman 1995, p. 19).

Brockman includes Stephen Jay Gould, Freeman Dyson, Stephen Hawking, Richard Leakey and others on his roster of third culture intellectuals, a group he also calls “new public intellectuals”. These are experts in science and technology who take their cases directly to citizen-consumers through their popular writing.

10. Challenge for Third Culture Intellectuals

This group needs to be distinguished from false pronouncers who are often technophobic. They tend to be very critical without necessarily being very informed. Scientific and technical information also comes from those critics whose expertise may be limited and whose agenda seems political in nature or merely attempts to capture publicity. Two especially pertinent illustrations should be sufficient: Mander and Rifkin.

Gerry Mander, a new age anti-industrialist, criticizes nanotechnology for its anti-spirituality in a book reminiscing about Amerindian value systems. He criticizes nanotechnologists by describing them as a group of thinkers who have no historical appreciation of the horrors of technological progress (Mander 1991).

There is, in the whole nanotechnology movement, no political understanding, no spiritual understanding and no feeling for nature outside the human realm. But the real problem is not in their vision or their intent. It is in their world-view – the same techno utopian world view that has already come close to destroying the planet. These people have in fact already left the planet. (Dowie 1988, pp. 148-149)

The other critic worth mentioning is Jeremy Rifkin. He has taken on biotechnologists, ecologists, and meat eaters in some of his books. An avowed techno-heretic, he has his own Washington, D.C., foundation. His views on nanotechnology are equally pessimistic.

The idea that we will be able to redesign the material of this planet to suit the anthropocentric caprices of a generation of scientists and technicians without doing harm to the delicate fabric that has developed over a billion years is beyond hubris. (Dowie 1988, p. 149)

As a rule, this group of critics engages in mudslinging and appeals to fear to attract attention. Unable to accommodate ideas other than their own, they attempt to discredit scientific claims by deferring to some greater power. For example, Mander defers to some cosmic spirituality and Rifkin uses anthropocentrism. It would be exceedingly unfortunate if citizen-consumers were forced to accommodate these technophobic and dystopian claims rather than scientific ones.

11. The Media Recedes from the Public Sphere

Traditionally, citizen-consumers have learned about science and technology through an interpretive medium, a college of scientific journalism. Though many journalists lay claim to membership, very few carry the experience, credentials, or both.

A major criticism of them is that science journalists simply lack zeal. Fuller argues “except in cases of scientific misbehavior sufficiently grave to worry Congress, journalists will often print watered down or mystified versions of a scientist’s own press release, which ends up only increasing the public confidence in science without increasing its comprehension” (Fuller 1993, p. 234).

Journalists are not only underzealous, but their publishers are also underconcerned about accurate reportage. Citing Burnham, Fuller reports “the supermarket tabloids [remain] the public’s primary source of information about the latest developments in science” (Fuller, 1993, p. 236, Burnham 1988). Journalists and publishers are driven by market considerations, selling copy. Though their motives may not be universally impeachable and suspect, they hardly advance the interest of accurately informing citizen-consumers.

While some journalists make a genuine effort to accurately report scientific claims, fighting for column space they must give their editors what they can sell. For example, when coverage is given to science, the sensational is often accentuated. Too often many scientific claims are reported before definitive burdens and standards of proof are met (cold fusion, for instance). Highly impatient readers tend to blame inconclusive results on bad science rather than premature reporting and outrageous overclaims.

Not only do science journalists devalue the time frame between theorizing and verification, but they also present issues in “winner-take-all contexts that turn on some crucial fact or event” (Fuller 1993, p. 235), promoting an overly simplistic model of causation. Furthermore, science journalists do not appreciate proof obligations associated with scientific claim making. “Moreover, the more provocative the theory under dispute, the more likely journalists will champion it, which often serves to shift the burden of proof onto the opponents...” (Fuller 1993, p. 235).

Finally, trying to balance their reporting, reporters tend to solicit respondents from a local college. These experts express opinions on claims about which they are often unprepared to make truly informed comments. This often leads to attacks on credibility, sometimes personality assaults, which leave readers with a view of scientific discourse as a schoolyard brawl.

12. Third Culture Intellectuals Enter the Public Sphere

The result: the majority of those writing in an attempt to bridge Snow’s “two cultures” and to communicate with a scientifically unsophisticated audience write articles with flash, sparkle, pizzazz, but weak on information and insight. In response, third culture intellectuals have begun to avoid the science media altogether.

Traditional intellectual media played a vertical game: journalists wrote up and professors wrote down. This is an activity referred to as popularization. Today third-culture thinkers avoid the middleman [sic] and write their own books, much to the consternation of those people with a vested interest in preserving the status quo. Some scientists have seen that the best way to present their deepest and more serious thoughts to their most sophisticated colleagues is to express these thoughts in a manner that is accessible to the general intelligent reading public (Brockman 1992, p. 16).

Third culture intellectuals have begun to avail their writing to the more general readers markets. Luckily for them, readers have begun demanding more science related literature. There has emerged a thriving demand for their works. According to W. Daniel Hills, “People no longer have a view of the future stretching out even through their own lifetimes, much less through the lifetimes of their children. They realize that things are moving so fast that you can’t really imagine the life your child is going to lead. That’s never been true before, and it’s clear the cause of that change and that discontinuity is science, somehow” (Brockman 1995, p. 26). Much like von Neumann, Vinge, Eder, and Ross’ view of the singularity, the citizen-consumers recognize a compelling need to learn to survive, and “one way to do it is to read books by scientists” (Brockman 1995, p. 26).

The new public intellectuals are motivated to publish directly to citizen-consumers for two additional reasons.

First, they are often interdisciplinarians. Their fields of theorizing and reasoning are insufficiently distinct. Their ideas and claims “don’t fit within the neat structures of their internal disciplines. Many of the scientists who write popular books do so because there are certain kinds of ideas that have absolutely no way of getting published within the scientific community” (Brockman 1995, p. 26). Their work seems outside a publication’s usual fare – partially pertinent but not wholly so. Drexler made a very similar complaint regarding his own research.

The second reason: scientists have begun to understand that consensus building and outright support for their interests and fields are necessary co-requisites to their theories and findings in order to procure and sustain third party interest and backing for their research agenda.

Because science exists in a dialectical relationship within the broader society and culture, scientists must justify their pursuits to the political leaders and other persons who control essential resources (Moyer 1992, p. 8).

Popular support can move government as well as create and sustain demand for industrial products and services. Third culture scientists are marketing their ideas directly to citizen-consumers engendering support to help secure patronage on many different levels: public interest groups, foundations, university and college administrators, government agencies, and policy makers. Science has its lobbyists and third culture scientists contribute in their own way toward popularization of their projects. Brockman’s observations are particularly true regarding nanotechnology.

13. Preliminary Observations: Communication about Nanotechnology

Teaching science is no small feat. Witness the popularity of more subjective or softer disciplines at America’s colleges and universities. There is a simple reason why America has lagged in science and mathematics education: for most of us, it’s difficult. Nevertheless, nanotech evangelists need to package this new technology in a language that most citizen-consumers can try to comprehend.

Drexler joined the ranks of third culture scientists by speaking directly to the public. He and his colleagues still remain a predominant source of information on nanotechnology for the general public. Hence, my primary criticism focuses on Drexler and The Foresight Institute (FI).

14. Case Study: Criticism of Foresight Institute Communication

FI’s goal involves developing and supporting public consensus. “[T]oday, only the smallest fraction of the world’s population is aware of the coming juggernaut, or even slightly prepared to cope with the kind of changes that it will bring in its wake” (Merkle 1993, p. 15). Merkle continued: “it just hasn’t sunk in. The possibilities of rocketry didn’t sink in to the good citizens of England until they found themselves on the receiving side of a barrage of V2’s. The idea that washing your hands might be advantageous didn’t sink into the medical profession until almost the turn of the century, despite the fact that Ignaz Semmelweis demonstrated its value quite clearly in 1848” (Merkle 1993, p. 15).

We are slow to catch on. Applied nanotechnology “will change both the world in which we live and the assumptions we live by” (Merkle 1993, p. 15). Hence, FI’s goals must include both educating citizen-consumers and empowering them with a sufficient understanding to develop and sustain a consensus, which will lead to informed and wise decision-making by the governmental and corporate barons of our technocratic state.

While they have had some triumphs, FI has not been very successful to date. Fault lies in many hands, some are personal, and some are systemic or organizational.

FI and its people remain diligent and persistent. Being outspoken about a speculative technology is also daunting. Weaker men and women would have backed off years ago. Despite some nasty personal attacks and ridicule, they continue to make their case known. The following criticisms are wholly constructive in intent. They are observations made by an outsider who greatly respects FI and its people.

15. Specific Concerns

First, access to FI material is difficult. Drexler's *Engines of Creation* can be found in many libraries and bookstores, *Unbounding the Future* is in bookstores, *Nanosystems* can be ordered from its publisher and it is slowly making it to university library shelves. While all three books are available from FI, FI's publications are less available. Initially, FB (*Foresight Background*) and FU (*Foresight Update*) were mostly unavailable except to a select group of members. Today, FU can be downloaded from the Rutgers archive of sci.nanotech and FI's web page.

Though FI attempts to disseminate information, they have closed down some conduits of information flow. Anecdotal support is found in a FU where in response to a request by a high school student for information on nanotechnology which he could use in interscholastic debates, FI answered: "We have prepared a package of materials for high school debaters." Furthermore, they responded, "[d]ue to the large number of debates (*sic*), we ask that a \$4 donation accompany each request".

Though filling requests for information can be costly, it is imperative that information be circulated as freely and completely as possible. Creating barriers as simple and seemingly minor as a fee are counterproductive. In addition, to design a kit which provides only selective material is unnecessarily patronizing. This is especially problematical when we begin to understand that "[t]hese debaters, young men and women, will be tomorrow's leaders". If we keep these young people fully informed "when they design remedies for some of the problems confronting society in the 21st century, nanotechnology will, at least, receive a serious and fair discursive treatment" (Berube 1990, p. 6). The solution demands a more open market for information on nanotechnology, which may require more aggressive fundraising and grant solicitation and less discrimination.

Second, access to FI concepts is difficult. There are two reasons: First, what is nanotechnology? Less than two-thirds of the respondents to the MAST study could agree on a definition of nanotechnology; the remainder of the respondents in the project could not agree on the definition of one of the most important key terms of the survey (MAST 1989, p. 94). A recent bibliometric study demonstrated a similar dissonance (Porter & Cunningham 1995, pp. 12-15).

The prefix nano means a measurement of size. It appears when we approach sub-micron sizes.

Consider how the prefix has been used. For example, "[t]wo new companies making fine-grained materials are Nanophase Technologies and Nanodyne. Longevity magazine carried ads for NANO shampoo and NANO conditioner, containing a derivative of the anti-baldness agent minoxidil" (Drexler 1993, p. 9). A company, which markets medical diagnostics and biopharmaceutical arrays, is called Nanogen. It is attempting to combine molecular genetic, microelectronics and nanotechnology in product design ("Nanogen..." 1994, n.p.). Nanometrics, a decade old Silicon Valley company manufacturing semiconductor metrology equipment, "has nothing to do with molecular nanotechnology" (May 1995). Two pharmaceutical biotechnology firms, Vertex (VRTX) and Agouron (AGPH) are traded on NASDAQ and both claim they are developing pharmaceutical compounds atom-by-

atom (Conover, 1995). Gryphon Services claims to be on the verge of marketing “nanocellular” products, a synthesis of large, complex multifunctional molecules for a new generation of vaccine and gene therapy (“Gryphon Services...” 1996). On the other hand, Nanothinc (Foremski 1994b, p. 8) is about to base its whole business on the embryonic nanotechnology market (Smith 1994, p. C5) with products, services, and divisions like Nanotainment, a product and consulting division, and Nanoventures, an investment service.

The root word ‘technology’ describes everything from a flint axe to a 2 GHz processor. “Nanotechnology in the broader sense of nanoscale technology covers a diverse collection of activities, with varying relevance to this goal” (Smith 1994, p. C5). As Timothy May posted, “most uses of nano don’t have anything to do with molecular nanotechnology” (May 1995).

Confusion over terminology has led to substantial communication difficulties. For example, in the U.S. the term nanotechnology is beginning to be used by those doing submicron semiconductor work of all sorts. This makes it difficult to discern the goals and drives researchers to use the longer and more complex terms molecular nanotechnology and molecular manufacturing. (Peterson 1992b, p. 399)

Furthermore, this problem is aggravated by two additional observations. First, “truth be told, there was never any love lost between the micro and nano factions of the miniaturization fraternity” (Regis 1995, p. 237). Secondly, micromachinery may be irrelevant to mecha-nosynthesis nanotechnology.

One of the problems Drexler has confronted is simply one of naming and definition. He testified that “[n]anotechnology has become a buzzword, but if it is often used to describe incremental improvements in existing semiconductor technologies, although of great value in their own right, they are of surprisingly little relevance to molecular nanotechnology” (Drexler 1992, p. 21). Drexler referenced those tiny machines, which are featured occasionally in some of our newsweeklies. He concluded that as nanotechnology, “[m]icromachine research, often confused with nanotechnology in the popular press, is even less relevant” (Drexler 1992, p. 21). Merkle characterizes the misappropriation of the term ‘nanotechnology’ as a “turf war”. He explained:

“Nanotechnology” is a term, which has an aura of excitement and great promise. Much of this aura was created by Drexler’s adoption of the term and its association with molecular manufacturing. As a consequence, many researchers wish to adopt a definition of “nanotechnology” which includes their own work. An unfortunate consequence of this is that the unqualified term “nanotechnology” has come to mean very little. (Merkle 1996)

The confusion over the nanotechnology label is further confounding because “[t]his degree of overlap between nanolithography and micromachines, on the one hand, and molecular nanotechnology, on the other hand, appears to be remarkably slight, even though those subjects have commonly been confused in the popular press” (Drexler 1992, p. 30). Add that the product of both processes might very well be indistinguishable. A nanoscale machine whether chiseled to size or built from the atom up remains a nanoscale machine.

Nanotechnology means different things to different people. To Eric Drexler it is an extraordinary vision of machines as small as molecules making things an atom at a time. To many others, it is a more prosaic, though still impressive vision of electronic circuits scaled down from the size of a micron, to that of a nanometer, a thousand times smaller still (“Doty” 1993, p. 89).

Taneguchi and Drexler use the word “nanotechnology” differently and when writers link together citations from papers, articles and books, they often commit the so-called term shift fallacy whereby meaning becomes obfuscated because descriptions of unlike things

labeled the same are inaccurately juxtaposed. No wonder time frames for the arrival of assemblers and nanotechnology are so variable.

Does nanotechnology now exist? Has the revolution arrived? If so, then the nanotechnology revolution seems to be a dud. Where are the molecular machines? Where are the desktop manufacturing systems? Where are the nanocomputers, the cell repair machines, and the era of abundance? Few in the newly mustered army of nanotechnology researchers aim at such goals. It would seem that there [has] been a profound miscalculation – unless, that is, there has been a more prosaic modification in the use of words. (“Dotty” 1993, p. 89)

Drexler exhibits much of the frustration of the experienced wordsmith and image-maker. Any public relations acolyte would grant two truisms: (1) make certain you are accurately describing what you are pushing, and (2) it is easier to create an image than to recreate it.

Drexler discusses dry ‘bottom-up’ molecular mechanosynthesis nanotechnology manufacturing. Unfortunately, this term is seriously confusing. Drexler finds this term and others like it “bulky and awkward enough to retain a distinct meaning” (“Dotty” 1993, p. 89). He understands that by reducing it to the single word ‘nanotechnology’ it would feed the term shift fallacy, which is plaguing much non-technical discussion of this field. Drexler fields as many questions about definitions as about feasibility, and he readily admits that naming and labeling is an enormous difficulty when trying to generate consensus.

Consider this illustration. The nanotechnology that yields the magnet particles described in *Science News* (Pennisi 1992, p. 20) works by oxidizing ions that have been loaded into an ion exchange resin used commercially in water softeners. This is, literally, nanotechnology because the resulting iron oxide particles are only 2 to 10 nanometers across, containing mere thousands of atoms. Of course, along this line of argument, producing cigarette smoke would also be nanotechnology (Drexler 1993, p. 9).

It’s not all bad news. It may be somewhat correct to claim that awkward descriptions might discourage term shifting. Nevertheless, as it is universally true that the more one speaks and writes the more likely one is to contradict oneself, so it is exceedingly difficult to erase the misunderstanding fostered by Drexler and FI’s earlier work in the late eighties.

So where’s the good news? The good news is that the confusion “is a sign of progress. Researchers in chemistry, molecular biology, material sciences, and so forth, have worked at the nanoscale for many years; the advent of a new, unified perspective, and with it an understanding of longer-term goals for the field” (Drexler 1993, p. 9). If FI sees itself as a macro-organization umbrellaing the field of nanotechnology, then Drexler’s save is legitimate. On other hand, if its purpose is to foster understanding and develop public and technical consensus, the use of the vague term ‘nanotechnology’ to describe molecular nanotechnology based on mechanosynthesis is self-defeating and confusing.

A second major problem with access: nanotechnology is still steeped in technobabble. This has implications on the two levels of scientists and engineers, and of the citizen-consumers or the public world.

Ostman made an interesting observation in 1994. “Lack of awareness even amongst the technical community is still probably the greatest impediment toward a more robust pursuit of nanotech development” (Ostman 1994, p. 558). Drexler and the FI are trying to keep some of the scientific and technical community informed with their conferences and Web Enhancement Project. These efforts are laudable but much remains to be done.

The challenge is further compounded by the interdisciplinary nature of nanotechnology. This demands the special rhetoric that Steve Fuller dubbed interpenetrative. He argues that a knowledge policy reaching across disciplines must address the new epistemic standards created to make interdisciplinary exchanges meaningful. Fuller complains interdisciplinary discourses usually “mutate without replacing some already existing fields. Thus,

they merely amplify, not resolve, the level of babble in the academy” (Fuller 1993, p. 40). He further grumbled that pluralists are not the answer either.

Given the exigencies of our epistemic situation, pluralists hardly help matters by magnanimously asserting that anyone can enter the epistemic arena who is willing to abide by a few procedural rules of argument that enable rival perspectives to remain intact and mutually respectful at the end of the day. (Fuller 1993, p. 40)

Fuller asserts that the separate disciplines retain much, if not most, of the language and ideas which help define their uniqueness such that interdisciplinary communication is seriously challenged. Prestige and stature considerations catalyze a defensive epistemic, which appears cooperative yet stymies interchange by forcing any depthful and layered exchange to use the babble specific to the fields being addressed.

Finally, dominant discussants emerge either because they arrived early or because they involve better rhetors. They may, intentionally or unintentionally, establish a vocabulary, grammar, rules of argument, even tools of conviviality, which prevent newcomers from making their message known. Even if expressed, it seldom is likely to become the center of attention unless it is remarkable prescient and insightful.

The public world is challenged as well. Babble on this level convinces the public or the citizen-consumer that the scientific community has little intention to communicate with them.

Technobabble is a pervasive phenomenon in debates over science and engineering. Nanotechnology is not immune from technobabble, and it may be an unfortunate and an inescapable problem. For example, when *FU* reports advances that may be significant in terms of nanotechnology research and development, it is forced to use the terminology of science. This is especially true since Jeffrey Soreff took over the “Recent trends” column in *FU*. It is apparent that Russell Mills and Soreff, the current writer, addressed very different audiences. This alphabet soup of acronyms makes communication between science and the layperson more difficult. Though on some levels, it might make communication between scientists easier.

Drexler and Peterson wrote: “[i]f our future will include nanotechnology, it would be useful to understand what it can do, so that we can make sensible plans for our families, careers, companies and society” (Drexler, Peterson & Pergamit 1990, p. 38). Unfortunately, *FI* and others don’t seem to fully appreciate the importance of popularization. Referencing Burnham, Drexler and Peterson summarized the problem nicely. “Today, the culture of sciences takes a dim view of popularization. If you can write in plain English, this taken as evidence that you can’t do math, and vice versa” (Drexler, Peterson & Pergamit, 1990, p. 36, Burnham 1988).

James Dinkelacker provided me with a vivid illustration of this problem. Criticizing a very early draft of this manuscript, he made the following comment.

To those of us who are faced with the challenge of actually communicating this information, instead of the luxury of communicating about it, professional language is a necessity. Some ideas can only be expressed pragmatically in equation form; and if a person doesn’t understand the basics of a sp³ carbon bond, or he [isn’t] familiar with *kt* as a concept, it would take tens (if not hundreds) of hours to bring him/her up to speed. Why penalize the many thousands who took their chemistry courses in high school, and did their homework? I reject the notion that either you or I, with our advanced degrees, can truly judge what is “accessible” to the lay public. (Dinkelacker 1991, n.p.)

The tenor of his remarks suggested that there is an expertise barrier, which might be impenetrable to the public. Though I doubt that he embraced the apparent tenor of his remarks, this insipid form of technoelitism must be rejected.

The reality is that technology has created a huge gap between the techno-literates and the techno-illiterates, between those who can ride the technological wave to financial awards and those who must remain outside its direct influence. This reality flies in the face of society's ideals of equal voices, equal opportunity, equal influence, and equal access. While the reality-ideality split has always existed, the advent of high-tech instrumentation has accelerated the pace of dislocation. (Hey 1991, p. 51)

This reality-ideality split will be substantially aggravated especially during the early transition period of a nanotech civilization. In order to enable techno-illiterates participation in that culture, we must begin to prepare them. Peterson seems to understand the germ of this potential problem.

Educating the public is very important. Eventually, there are going to be political issues that arise. They haven't arisen yet, but they're inevitable, and to have those decisions made correctly – or at least have them not made incorrectly – you need an educated public, and we're nowhere near there yet. (Peterson 1992a, p. 12)

In response, Drexler and FI have made some attempts to simplify many of the concepts associated with nanotechnology. Drexler's greatest achievement might have been *Engines of Creation*. As I wrote in 1990, "*Engines* was readable by everyone and only misunderstandable by those who refused to open their minds.... More important, its explicative style reads as easily as fiction" (Berube 1990, p. 6). This very quality may account for the fact that nanotechnology has become the subject of much current science fiction. This is understandable because any new idea is bound to solicit unexpected conjecture.

However, the third major problem associated with access to FI concepts is not a function of how others have conjectured about nanotechnology, but rather how Drexler and FI have conjectured about it themselves. Traditionally, science and technology rhetoric includes occasional attempts to explain using imagery of all sorts. Straining to familiarize a deep scientific observation or discovery, rhetors attempt to use popular terminology. Most often the audience gets carnival facts, banal awareness, storybook imagery, military simile, and sports references (Montgomery 1989, p. 68). Metaphors are complex language devices and poorly wielded by inexperienced communicators. The rhetors of nanotechnology end up receiving a failing grade for effort and product.

For example, Drexler and FI's efforts to oversimplify nanotechnology have led to similes which function to trivialize nanotechnology and stoke the ovens of pseudo-scientific conjecture. Here are a few illustrations: Drexler referred to the unlikely uncontrolled replication scenario as "gray goo". Hapgood and others picked up the phrase and used it as a central focus for their journalism: rich in fantasy and poor in fact. Even Congress' OTA report includes a reference to the "gray goo" metaphor (OTA 1991, p. 20).

Also, in his 1989 OMNI interview Drexler discussed the "cabinet beast", that is, a machine from which you could slice nanotechnologically fabricated meats (Drexler 1989b). This image enabled the interviewer to ask: "Doesn't the so-called meat machine enable you to shovel in some straw and dirt and have a steak pop out?" Rudy Rucker describes a tongue-in-cheek dialogue.

"You done building that roast beef out of dirt yet, Bob?"

"Ten molecules down, to the twenty-sixth power to go." (Rucker 1993, p. 95)

Here's another. In an early *Foresight Background*, Drexler used a simile as he tried to define the difference between a bacterium with an *Engines*-style nanomachine. It is "like confusing a rat with a radio-controlled model car" (Drexler undated, p. 3). Not very elucidating.

Though this imagery may seem innocuous, it stokes ridicule. Nanotechnology is sufficiently astounding without attaching images like those mentioned above. Reporting on the

1992 nanotechnology conference, Mike Langberg wrote that “proponents of nanotechnology are making such grandiose claims that the Palo Alto meeting sometimes appeared at risk of sliding into science fiction”. He tells an anecdote about Minsky’s luncheon speech. Rhapsodizing on nanotechnology and its creative applications, Minsky “looked at the audience and paused. ‘I don’t want to go on like that, because I’ll scare the financial people away’” (Landberg 1993, p. B7).

Practices like these make FI concepts more difficult to assess. The solution may involve reducing techno-babble and simultaneously reducing fantastic similes.

A fourth major difficulty: access to FI ideas is difficult. This is primarily because FI has failed to endorse any evaluative matrix by which complex nanotechnological issues may be analyzed, if not resolved.

Again, there are two challenges: communicating among scientists and engineers and communicating with the public. Without a common solution to both these problems, the challenges must be met with different tactics.

First, there is the challenge of communication among scientists and engineers. The MAST survey in 1989 included experts from many disciplines: “biological sciences; mechanical, electrical, and chemical engineering; pharmacology; computer sciences and artificial intelligence; robotics; and others.” ‘Others’ was a broad grouping and included a list of researchers who might impact on the future of molecular nanotechnology. They were involved in:

- Macromolecular design and folding
- Self-assembly methods
- Catalysis (inorganic, enzyme and other)
- Dendrimers, fullerenes, and other novel chemical structures
- Bioenergetics, nanobatteries, and ultrasound driven chemistry
- Semiconductor-organic/biological interfaces
- Miniaturization and massive parallelism of SFM
- Molecular modeling tools (Nelson & Shipbaugh 1995, p. xi).

MAST assumed these disciplines as likely to “draw on and effect” discoveries involving molecular and atomic scale technologies (MAST 1989, p. 1). A concern expressed in the MAST report was “the difficulty encountered by researchers in the various fields in finding out about relevant discoveries in other fields” (MAST 1989, p. 1). In other words, chemists need an easier way to learn what protein engineering is up to.

To FI’s credit, it has done an excellent job of networking interested researchers across many fields. We are near to reaching the point where anyone with an interest can find out who is doing what in the field of nanotechnology. Vocabulary and conceptual barriers will slowly fall until only the researchers unwilling to make the effort will be incognizant of developments in another field impacting their own research agenda.

Second: communicating between technologists and citizen-consumers remains a challenge. Since nanotechnology seems to affect everyone to some degree, and since deciding what is desirable should not be left to the scientists and engineers exclusively, we need to reach out to a large base for support and input. This seems especially true when the vanguard might be consortia of governments and industries rather than a single state, national or even transnational corporate organization. What we need is new organizational thinking to help generate events which can then be tested in simulations.

16. Some Concluding Remarks

Unless an affirmative effort is made to incorporate citizen-consumers into the decision-making process, the reality-ideality split will worsen. What too many of us sometimes for-

get is that absent extensive efforts to educate the citizen-consumer, pseudo-technoliterates will people the ranks of both techno-utopians and technophobes. A failure to speak to the citizen-consumers risks fueling pervasive popular misunderstanding. Such misunderstanding could, in turn, produce formidable resistance as pseudo-technoliterates become prominent and ridicule nanotechnology.

People listen to Mander, Rifkin and even Limbaugh. In turn, their works become rallying points for technophobic dissent.

On the other hand, if those who understand nanotechnology educate the citizen-consumers, they may be able to mitigate many of the effects outlined above. Dinkelacker modified his earlier comments to me a few months later.

Advances in molecular research are accelerating, and thorough control over the structure of matter appears to be imminent. Clearly, it's vitally important for everyone to be aware of the potentials of these oncoming technologies. It is only through communication and education that the public and technical communities can become knowledgeable such that they are prepared to make informed decisions. (Dinkelacker, 1992b)

In the same letter, he offered an additional goal of the FI as "working to communicate with people about the prospects of nanotechnology and molecular manufacturing so that society can be bettered prepared" (Dinkelacker 1992b). The most significant by-product might be an army of enlightened citizen-consumers who embrace rather than ignore or reject the nanotech civilization. Indeed, Milbrath has suggested, "[o]ne of the best ways to work for planetary policies is to try to help people all over the world develop an understanding that these are questions that require consensus" (Milbrath 1992b, p. 316).

This is a massive project, as is my scholarship on the subject. While much of it is dedicated to a careful study of Drexler and the Foresight Institute, it also includes the rhetoric of policymakers, national laboratories, university NanoCenters, private corporations, and venture capitalists. A fuller account therefore must go beyond this article (Berube 2005).

Notes

¹ http://www2.ncsu.edu/ncsu/univ_relations/crisis.html.

² Prolescience characterizes the philosophy that "knowledge production should proceed only insofar as public involvement is possible" (Fuller 1993, p. xviii). Plebiscience involves the public only when adverse consequences are likely and then it involves only the directly impacted community. Fuller views prolescience "as an implicit challenge to many of the elitist assumptions of plebiscience" (Fuller 1993, p. xviii). Prolescience is characteristic of hyperdemocracy which is defined by a far greater emphasis on initiative and referendum, that is, two vehicles of change which even our elitist founding fathers considered sufficiently worthwhile to incorporate into our governing charters.

³ Scientists can account for their behavior and research agenda. "It may be inconvenient for scientists to make sense of their activities to a larger audience, but they are not precluded from doing so mainly because of the work they do" (Fuller 1993, p. 283). Scientists are sufficiently competent to compose grand proposals to fund their research agenda. Oftentimes, grant non-scientists make allocations. As such, scientists have become sufficiently adept at answering all questions, scientific and otherwise. They testify before Congress, are interviewed on morning talks shows, and even do book tours.

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Nanomedicine and Space: Discursive Orders of Mediating Innovations

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Abstract. This paper examines from the perspective of discourse analysis the rhetoric of negotiation in the area of nanomedicine and compares it to the debate on genetic engineering. The following questions will be raised: what kind of symbolic space is generated by the negotiations and what role does this space play in determining the possibilities for communication regarding future nanotechnological innovations? For example, which position does the vision of the nanobot inhabit in the discourses of negotiation? Does the nanobot represent a discursive interface between the concepts of technological miniaturization and hybridization of nature and technology?

Introduction¹

Institutions designed to support and negotiate new technologies present nanotechnology as the quintessential future technology of the 21st century. If we turn to the rhetoric used to negotiate the innovative potential of nanotechnological procedures in medicine, we happen upon the following strategy of discourse: nanotechnological developments in medicine are placed in a continuum with microtechnological innovations in minimal-invasive surgery. That means that developments in nanomedicine are negotiated like progressive miniaturizations and specifications of technical instruments in surgery.

To describe the requirements of *microsystems technology*, the joint internet presentation of the *German Federal Ministry for Education and Research* (BMBF) and the *Association of German Engineers* (VDI) uses the example of neurosurgery as follows:

What is microsystems technology? It is as if you are standing outside the front door wanting to sew a button on a duvet in the bedroom by inserting tweezers through the keyhole. In addition, imagine the rooms full of furniture, around which you have to maneuver the tweezers. And be careful not to knock anything over!

The presentation continues that the difficulties arising on such “journeys through man’s inner world” are not only “a topic in media visions” of the future. They are also “the starting point for current real problems in the development of new technologies”. All solutions “to improve existing instruments, ranging from active endoscopes to models of autonomous mini-robots, which not only can observe and measure but also perform surgery” rely on “miniaturization and built-in intelligence”, that is, “they depend on microsystems technology” (VDI/VDE/IT 2004).²

The German Ministry of Research assigns microsystems technology great significance for the future and notes its relevance for a very wide range of technological fields like communications technology, automotive technology, building services engineering, environmental technology as well as biomedical technology. In addition, the report continues, microsystems technology is important due to its character as a cross-sectional technology, since it unites the findings from a multitude of manufacturing and process technolo-

gies with information technology and bio-technology (BMBF 2000, pp. 16-29). The VDI expects that in the future a radical, innovative thrust will come from *nanotechnology* – that is, from a nanosystems technology that is expected to exceed by far all innovative developments from microsystems technology. Only through nanotechnology has it become possible to access a “scale [...] 1000 times smaller than the building elements in the micrometer sphere”. This new dimension has become accessible “both by application of physical instruments and procedures and by further diminution of current microsystems as well as by using structures in animated and non-animated nature as models for the self-organizing construction of matter” (VDI-Nanotechnologie 2004).

According to these descriptions, nanotechnology is not only a matter of reducing the size of microtechnology. Aside from the emphasis placed on continuous ‘reduction’, we also find that a second aspect is emphasized, which is supposed to be specific in comparison to microsystems technology, namely the ‘self-organizing construction of matter’. Giving prominence to this characteristic allows nanotechnology to be differentiated from the tradition of continuous microtechnological miniaturization. Thereby a break is marked. Nanotechnology is expected to place this mark in the sense of a ‘radical’ innovation within the incremental developments of medical technologies.

Presentations describing the specific characteristics of nanotechnology – as they are found in less recent specialist literature and textbooks – differentiate between two approaches: first there is a physical, technically oriented *top-down approach* that involves molding, carving and fabricating small structures ‘from the top down’. This approach aims at defining small structures down to the atomic scale (0.1 nm). Next to that is a chemical, bio-molecular-oriented *bottom-up* approach that manipulates molecular and atomic components to build up structures ‘from below’ to arrive at the nanometric scale (Köhler 2001, pp. 1-14). In contrast, presentations in more recent literature and textbooks, place emphasis on the *hybridization* of the top-down and bottom-up approaches (that is, on combining the concepts of technological miniaturization with the self-organizing construction of matter). Today, according to a current textbook on nanotechnology, “nanosystems technology’s” crucial potential lies in combining these two approaches – the technical miniaturization of existing microtechnology and the bio-molecular creation of nanostructures. According to that textbook, microsystems technology has focused until now on the top-down approach, but

the dominant position of classical physical principles is being overcome by nanotech’s arrival at atomic and molecular dimensions. Physical and chemical aspects [are becoming] equally significant factors of influence in the production and implementation of nanotechnological structures. [...] Because nature [is] not only a role model [...] for the construction of large molecules, but also makes technically interesting tools available, [...] bio-chemistry and molecular biology have taken up an important position in nanotechnology. (Köhler 2001, p. 2)

The VDI projects that by “using natural processes of self-organization” the difference between technical instruments and bio-molecular processes will be cancelled out (VDI-Nanotechnologie 2004).

In these examples of negotiation, a dual rhetoric is evident. Talk of the *miniaturization* of micro-technical instruments is one of the discursive strategies. Opposed to this is the talk of a *hybridization* of nature and technology, that is, of physical-technical instruments and chemical-bio-molecular processes. In the following sections it will be asked whether the simultaneity of these two discourses is also suggestive of their equal status in negotiating innovations. Which forms of rhetoric are applied specifically to the negotiation of nanotechnological innovations in medicine? I propose the thesis that in the presentations of nanomedical innovations, talk of hybridization is largely excluded.

1. Theoretical Approaches

In older technology debates – for example, in the debate on genetic engineering – the constitutive significance of discourses of negotiation became obvious for scientific and technological developments as well as for their socio-cultural implementation. Discourses of negotiation take place between politics, science, business, the media and the general public. They open up a symbolic *space of possibilities*. Inside the boundaries of this space it becomes possible to articulate and communicate technological – including nanotechnological – innovations. In this discursive space, plausibility and evidence are produced, which determine the way an innovation is accepted and implemented (Lösch 2001, pp. 34-38). In the following case studies, the rhetoric of negotiation in the debate on genetic engineering will be compared to the rhetoric of negotiation of nanomedical innovations. The studies are informed by the following theoretical approaches:

In the first place, I will be looking at the empirical field from the perspective of discourse analysis. This approach is oriented toward Michel Foucault's concept of discourse (Foucault 1972, Lösch *et al.* 2001). My objects of study are regularities and similarities in statements of varying origin – for instance, statements taken from the context of research, business and the mass media. I will investigate the common orders of the statements articulated in the processes of communication concerning nanomedical innovations conducted between the spheres of research, business and the media.³

Since this inquiry is concerned with processes of communication that produce meaning for that which is the novelty of nanotechnology, it is necessary to incorporate innovation theories such as are discussed in the area of sociology of science and technology (for example, Bijker 1995, Brown *et al.* 2000, Dierkes *et al.* 1996). The question regarding the possibility of the new has always been and continues to be raised in the areas of philosophy, in the social sciences and in cultural studies (for example, Groys 1999, Blumenberg 1996). With hindsight we can often describe the implementation of a new technology as an innovation, as a sort of recombination of 'old', tried and trusted elements, or as the transfer of concepts from one discursive context to a new context (for example, from the scientific arena to popular culture and vice versa; see Maasen *et al.* 1995, Schulz-Schaeffer 2002, Morgan *et al.* 1999). From the perspective of the sociology of knowledge, meaning for the 'new' and thus 'foreign' is produced by recourse to trusted forms of representation. This meaning arises through the reciprocal communication processes between various actors, discourses, or systems. Metaphors and images play a decisive role in the mediation and negotiation of innovations. They serve as the media of communication (for example, Bono 1990, Martin 1982, Heintz *et al.* 2001): that which is new and unfamiliar becomes communicable through the re-combination of culturally habituated concepts of nature and technology, of space and time in the representations that are used in the mediation and negotiation process.

For negotiation of innovations in the medical world, space-related metaphors (like trips through the body or body cartographies) appear to be central. They are referring to the boundaries between internal/external world, between body/environment or micro-/macrocosm. These boundaries themselves are culturally assumed to be obvious. Linking up to trusted perceptions of space seems to be an important condition for meaningfully negotiating innovations or for producing sociotechnical evidence in the medical arena (see, for example, Jones 2000, Orland 2003, Gilbert *et al.* 1996).⁴ Regardless of this connection to trusted concepts, metaphorical and visual representations of nanomedicine can lead to a transformation of the perceptions of nature and technology that are typically for medical discourses. Visual images – for example, of so-called 'nanobots' – irritate the habituated perceptions of spaces within the body and of body boundaries whenever, for example, medical instruments are portrayed as spaceships within the body.

According to Bruno Latour's model of a two-fold "constitution of modernity", practices of separation ("cleaning") bring about the transformations that make it possible to both connect and break with the 'old' when negotiating innovations ("translation"; Latour 1995, pp. 22-67). An example of such a practice of cleaning is the rhetorical differentiation between the physical, technological top-down approach and the chemical, bio-molecular bottom-up approach. In the debates on genetic engineering at the end of the 1980s, to name a further example, the differentiation between genome analysis that 'discovers' nature and genetic engineering that 'constructs' nature played the dominant role. For political and judicial assessments as well as for the social implementation of new technologies in medicine, it is decisive whether these technologies are portrayed as a means of intervention in nature (in terms of medical diagnosis and therapy) or as a technological construction of nature (in terms of engineering designs). But it appears to be impossible to communicate new technologies in medicine as hybrids of nature and technology.

2. The Simultaneity of two Discursive Orders

From the viewpoint of discourse analysis, the two rhetorics of negotiating nanotechnological innovations are based on two simultaneous orders of discourse which served as the foundation of previous technology debates in the 20th century. Talk of nanotechnology as 'miniaturization' can be assigned to the discursive order of the progressive mechanization of human and non-human nature. For this order of discourse, the semantic dichotomy between nature and technology (that is, between the natural and the artificial) is seminal. Talk of the 'self-organizing construction of matter' through nanotechnology can be assigned to a discursive order of hybridization of nature and technology. This order of discourse is based on the semantics of dissolving the difference between technological intervention and biological evolution.⁵

However, their simultaneity does not imply that both orders of discourse are of equal status within the rhetoric of negotiating innovations. Instead, I will demonstrate in the following that the process of negotiating nanotechnological innovations in medicine is dominated by talk of miniaturization (that is, by the discursive order based on the separation of nature and technology). Only when nanomedical innovations are portrayed as a miniaturization of minimally invasive surgical procedures does it become possible to couple the technological discovery with familiar representations and modes of perceiving medicine. Intervening in inner bodily spaces using technical tools is among the most important images in the field of surgery.

The production of evidence for the 'new' requires, however, not only a link to already existent, familiar elements, but also the transformation of these elements in order to differentiate between 'old' and 'new'. This would be the appropriate point of entry for talk of 'the self-organizing construction of matter'. When negotiating nanomedical innovations, however, this discourse seems to remain in the background.

3. Orders of Discourse in the Debates on Genetic Engineering

In the debates on genetic engineering – more precisely, in the debates concerning human genetics – an order of discourse distinguishing nature from technology has prevailed over a discursive order of hybridization (Lösch 2001, pp. 81-161). From the viewpoint of the hybridization discourse, genetic engineering functions just like nature. In the debates on the political, judicial and social regulations of biotechnological applications in human medicine, a difference is made between 'genetic nature' and 'genetic technology'.⁶ A distinction is made between techniques based on 'knowledge' of nature and others that construct na-

ture. For example, in the debates on the prospects and risks involved in the Human Genome Project of the European Union, genetic analysis and genetic diagnostics were assessed as fundamentally different from the biotechnological interventions employed in gene therapy. Biotechnological interventions were then divided into two types: those carrying out therapeutic repairs on humans, and those using technology to shape a person's nature prior to his or her birth. Corresponding to this distinction, therapeutic interventions like somatic gene therapy were judged much differently than, for example, so-called germ line therapy. Today, adult stem-cell research is evaluated differently than research on so-called embryonic stem cells (Lösch 2001, pp. 155-161, 233-236).

As viewed from the perspective of discourse analysis, a long-term criterion of assessment is provided by the distinction between diagnostic analysis or therapeutic repair of a 'gene's nature', on the one hand, and the construction of a 'gene's nature' by applying the principles of engineering, on the other.

Space-related metaphors play a decisive role in such substantiated differentiation (Lösch 2003). During the process of negotiating biotechnological innovations, the portrayal of the Human Genome Project as a cartographic procedure was given the main function of endowing meaning (for example, Haraway 1997, Kay 2000). The cartographic descriptions support the dichotomy between knowledge or repair of 'genomic nature' on the one hand, and fundamental technological construction of 'genomic nature' on the other hand. In research programs, medical advice pamphlets, or news reports, images that directly relate the maps of the laboratory to familiar territorial maps have often been used to negotiate the meaning of genome analysis.

A German pamphlet with information on human genetics portrayed the goal of the genome project as making a complex book of very detailed maps of the human genome. It created evidence for this by comparing territorial maps with gene maps, a world map with a cell, a national map with a chromosome, a city map with a genetically mapped DNA segment, the map of a city district with a physically mapped DNA sequence, and a building's room number with a specific part of a DNA sequence. All the maps appear as partial representations of the human genetic landscape, and the comparison allows the genome project's results to resemble a world atlas (for example, Schmidtke 1997, p. 256). The comparison of laboratory maps with maps of the earth's surface allows for the negotiation of the genome project as a continuous, increasingly detailed process of exploration of natural landscapes and ever smaller regions within the human body. What is ultimately found is a specific section of an isolated DNA sequence that has the appearance of describing the location of a specific gene (see Lösch 2003, p. 10).⁷

Gene technologies that do not allow for the cartography metaphor are differentiated and assessed according to the nature-technology dichotomy, thereby excluding the notion of the hybridization of nature and technology. Somatic gene therapy thus appears like a medical means of doing repair-work at a specific site on a genome. Germ line therapies would fully re-design the cartographically recorded 'nature of man' from the bottom up. They would therefore appear like the opposite of cartographic exploration, namely as if they could construct nature on the basis of engineering principles.

4. Nanotechnological Miniaturization

In the negotiation of nanotechnological developments in medicine, the rhetoric of miniaturization dominates. As in the debates on biotechnology, this rhetoric rests on the nature-technology dichotomy. The essential medium for the production of evidence appears to be images of long-term future visions of nanomedicine in the form of so-called nanobots. Whenever, for instance, the news media, investment brochures, or specialist medical journals feature reports discussing the opportunities and risks associated with nanomedical de-

developments, existing innovations (for instance, nano carrier systems or drug delivery technology) are often portrayed as “partial solutions” along the way to developing “self-sufficient” and “intelligent” surgical systems, that is, nanobots (for example, Jordan 2001, pp. 1074-1077; Morris 2001; Haas 2003, p. 28). As a current investment brochure regarding nanotechnology concedes, the application of “self-sufficient” nanobots capable of working in the blood vessels or of nanobots capable of “independently” adjusting to their assignments still belongs to the realm of science fiction; but the vision itself nonetheless has a great significance in that it indicates the direction in which nanotechnological development in medicine will take (Beckmann *et al.* 2002, pp. 65-66).

At first glance the overall impression is that nanotechnology merely conveys visions [...], for instance, the ‘nanorobots’ or other endovascular *devices* especially for applications in medicine [...] but they appear more concrete when you look more closely and concentrate on the partial solutions and production approaches, which are already being implemented, *e.g.*, using the nanoparticles and nano carrier systems. (Jordan 2001, p. 1080)

In his contribution to the specialist medical journal *Der Onkologe* the biologist and physician Andreas Jordan reports about recent successes in treating brain tumors using ultra-small supermagnetic iron oxides (USPIO) and an external alternating magnetic field. Accompanying the text is an illustration of a nanobot maneuvering itself to locate and destroy the body’s cancer cells using laser beams (Jordan 2004, p. 1074). The picture, which is located in the “Nanomedicine Art Gallery” on the homepage of the US-American *Foresight Institute* in Palo Alto, CA, is captioned as a futuristic vision of a nano carrier system (Freitas 2004). News articles also feature fictional pictures of nanobots. An example may be found in the newspaper *Frankfurter Rundschau*, where a journalist reports on the success achieved with nanoparticles in cancer therapy. The article includes an illustration of a nanobot removing debris from the arteries (Haas 2003, p. 28).

As much as the nanobots in specialist journals differ from those appearing in the newspapers, all these visions portray the nanobot as a technological instrument in the body’s inner regions. In Jordan’s article, for example, the nanobot resembles a space ship and in the *Frankfurter Rundschau* the nanobot looks like an excavator and industrial-size vacuum cleaner. Both hardly resemble surgical instruments, but by means of their form they indicate the dichotomy between natural space and the intervening instrument. Through such visual representations nanomedicine is negotiated and mediated as a process of miniaturization and refinement of technical instruments with which surgical interventions in the body become possible. The use of these technologies is metaphorically described as a “journey into the nanoworld” or as a “dive down into the human body” (for example, Krägenow 2002, pp. 164-165). In line with this discursive order of negotiation, future nano-systems appear as mere miniaturizations of microsystems such as the recently developed microtechnological capsule endoscope. This endoscope is a sort of “video pill”. Equipped with a tiny monitor, it is expected to enable a more extensive examination of the intestinal tract of patients (for example, Krägenow 2002, pp. 164-165; CNN 2000; Wired 2000). According to this rhetoric, then, nano systems would mean a miniaturization of the video pill, so that in the future they could be sent not only through the intestinal tract but also through the blood vessels.

In the debates on genetic engineering, genetic cartography served as the main metaphorical description to suggest a form of ever more detailed knowledge of natural landscapes. Likewise, nanomedicine is represented as an ever more precise intervention in ever tinier spaces within the human body using ever smaller technical instruments. This is the prevailing order of discourse when negotiating the medical significance of nanotechnology.

It cannot be claimed that talk of the ‘self-organizing construction of matter’ has the same status.

5. Nanotechnological Hybridization

In some publications that are comparable to those portraying the nanobot as a long-term vision for a continuous miniaturization of microsystems, the original idea of the nanobot is attributed to the visions of Eric Drexler, one of nanotechnology’s founding fathers (for example, Haas 2003, p. 29; Malinowski *et al.* 2001). When viewed from the perspective of discourse analysis, the ‘figure’ of the nanobot is doubled: the nanobot, which is portrayed as a miniature version of a surgical instrument, is being extended by the concept of the nanobot as self-organizing material.

In *Engines of Creation* (1982) and *Nanosystems* (1992) the “nanotech pope” Eric Drexler is said to have envisioned building small systems – so-called assemblers – directly at the atomic level. These systems would subsequently be able to self-replicate and create other materials or machines by combining atoms. The image is that of an assembler being built or building itself on a level at which physical, technological processes coincide with chemical, bio-molecular processes. The assembler is expected to function like nature, that is, to have the ability to organize itself and to self-replicate (for example, Beckmann *et al.* 2002, pp. 27-30; Jordan 2001, pp. 1073-1074; Haas 2003, p. 29).

This second nanobot concept can be classified as belonging to the discursive order of a hybridization of nature and technology. This concept does not, however, seem compatible with the body concepts currently dominant in medicine, thereby making it unsuitable for the negotiation and mediation of innovations. The nanobot visions attributed to Drexler are thus considered to be completely unrealistic. Realistic research and technology development should be carefully differentiated from them (for example, Haas 2003, p. 29; Beckmann *et al.* 2002, pp. 15-30; Meißner 2000; Pantle 2000). This act of differentiation must be viewed as a ‘cleaning’ strategy, considering the fact that similar statements made in other places are structured according to the discursive order of hybridization. These might concern the nanotechnological production of materials that are acceptable to the body.

To mention an example, we may look at the reports on the development by NASA researchers of a self-growing band-aid. The band-aid consists of nanostructures that replicate themselves on the model of nature (for example, Hörrlein 2003, Pfaff 2003). The replication of nanostructures seems to function according to the principle of self-developing assemblers. When considered with respect to their principles of function, NASA’s externally applied band-aids can hardly be distinguished from nanobots that correspond to the second conception, namely nanobots that are expected to be used on accident victims with “heavy inner bleeding” in order to support the body’s own system of wound contraction or – once they have located a wound from *within* – to “incorporate themselves like a plug” (Beckmann *et al.* 2002, p. 67).

These and similar possibilities for representing nature-technology hybrids continue to be excluded from the future-oriented process of negotiating innovations in the area of nanomedicine.

6. Conclusion

In section 1, I delineated theoretical approaches for a discourse analysis of the dynamics of metaphors and images in processes of negotiating innovations. Viewed from this perspective, sociotechnical evidence for the ‘new’ can only be produced through linkage to familiar notions – either by recombining elements of knowledge or by transferring concepts. For

this it is necessary to assume that these combinations and transferals are founded upon orders of discourse and semantics that dominate perception in the respective areas of science or technology. In the area of nanomedicine it has been shown that processes of negotiating innovations are organized along the lines of a semantic distinction between nature and technology or body and environment, which corresponds to culturally habituated, space-related bodily perceptions.

Images that present nanotechnological innovations in medicine as the progressive miniaturization of technical instruments for the reconnaissance and repair of very small spaces in the body, seem to dominate in the negotiation of innovations because they are able to connect with familiar perceptions in modern medicine (especially in surgery) and thereby produce evidence. Even today, medicine is understood to consist in the diagnosis and therapy of a naturally existing entity and hardly as a new construction according to the bottom-up approach of basic engineering. Here, the nanotechnological top-down perspective functions as a rhetorical figure. If we look comparatively at how innovations are negotiated in other areas of microsystems technology and nanotechnology, such as in materials technology or the auto industry, we might assume that here, too, an order of discourse that differentiates between nature and technology should dominate. As it turns out, however, the rhetoric of the bottom-up approach here appears to be producing the sociotechnical evidence. The obvious choice, then, in this case, is to connect this semantically to the tradition of basic engineering in construction work. When negotiating innovations in medicine as well as in the engineering sciences, the discursive order of the hybridization of nature and technology (for example, of the self-organizing construction of matter) is never central. Hybrids are emphasized only when nanotechnology is to be distinguished as a special or 'radical' innovation from the innovations in microsystems technology.

This first analysis of discursive orders in the negotiation of innovations has primarily indicated the points of connection with old and familiar forms of representation and the culturally habituated ways of perceiving. In order to investigate more completely the symbolic space of possibilities in which nanotechnological innovations become able to be articulated and communicated, the question must be raised as to whether the perspectival representations of technological innovations on various levels of negotiation – for instance, among research institutes, business firms and the mass media – result in a modified semantics of representation. Should we expect the portrayal of innovative nanotechnology to be modified by the integration of discursive orders from other technological fields? Do cross-sectional technologies like nanotechnology enable or even demand a hybridization and a recoding of transmitted, culturally habituated, medical and surgical as well as engineering concepts of nature and technology? At which points in the combination of various concepts and discursive orders can we observe 'discursive innovations'?

Notes

¹ This paper is based on preliminary studies and first results of a project sponsored by the *German Research Foundation* (DFG). The project's title is "Spaces of Biomedical Microsystems Technology. A Case Study in the Sociology of Knowledge on the Negotiation and Mediation of Technological Innovations". The project and this paper are based on empirical material that consists mostly of German-language publications. My claim that the rhetoric of negotiation plays a significant role in the creation of a space that allows for the communication about nanotechnology in international publications is supported by preliminary work in the field of science and technology studies (for example, Fogelberg & Glimell 2003).

² The quotes from German sources have been translated by A. Heede.

³ Inner-scientific forms of knowledge, procedure and communication – typical subjects of current social studies of science and of sociological laboratory studies – will not be examined in this project. Here, the objects of examination are interdiscursive interfaces or hybrid platforms of reciprocal communication among the arenas of the research lab, business and the mass media.

- ⁴ According to the historian of technology David Gugerli, “sociotechnical evidence” is generated from the specific combination of visualization techniques, pictures, and culturally cemented rules of attention in medicine (Gugerli 1999).
- ⁵ The ‘classic’ nature-technology dichotomy of the first order of discourse frequently functioned in modern history since the 19th century as a strategy of discourse for political and societal assessments of technological developments. These developments made the differentiation between naturalness and artificiality appear questionable in the wake of the Industrial Revolution (see, for example, Latour 1995; Foucault 1970). The second discursive order established itself in the middle of the 20th century with the rise of cybernetics, systems theory and information technology. This order of discourse is also found in certain debates on genetic engineering or concerning the immune system and bionics (for example, Haraway 1991; Hayles 1999).
- ⁶ This differentiation is not obvious. In the labs devoted to genetic engineering, unlike in the political sphere, such a differentiation does not exist. With “genetic engineering the central ‘technological’ entities, the tools of manipulation of a molecular-biological undertaking, even molecular tools themselves, [...] are qualitatively no longer distinguishable from the processes with which they interfere. The scissors and needles, with which genes are cut and spliced, as well as the carrier used to transport the genes, are themselves macromolecules“ (Rheinberger 1997, p. 275).
- ⁷ In the laboratory, cartographic methods cannot be equated with making a world atlas. The maps in the lab serve as instruments which, when overlapped, enable investigation into such relationships as those between genetic characteristics on a chromosome and the molecular biological information of DNA sequences. Here the maps do not represent an enlargement in scale; rather, they represent maps with varying functions (see Lösch 2003).

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Shrinking the Ecological Footprint with NanoTechnoScience?

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Abstract. Nanotalk has provoked expectations just as high as fears: On the one hand NanoTechnoScience is expected to solve problems in almost every area of our daily lives; on the other hand there serious objections are being raised against the promises of a “brave new world”. Nanorhetorics and nanovisions, the fictitious and factitious, the seemingly rational and irrational in this debate coalesce with peculiar sharpness in the “environmental argument”. Here, in turn, the ambiguous concept of sustainability is important. The variety of meanings of this concept, its pluralistic use and at the same time problematic and attractive character is discussed with respect to nanodiscourse. The concept of the ecological footprint will be used to show the inconsistencies in the nanodebate. The discussion ends up noting that the concept of sustainability may at least be conceived to serve as a sort of information campaign or boundary concept that allows the debate of issues like growth and environment in the nanodiscourse. As such it could eventually help to place the whole debate in a more political and less ethical or economical context and to prevent the “nanotechnification” of nature and society.

Introduction

Talking about the future potential of “Nano” seems to be no less than proclaiming the next Industrial Revolution. Both supporters and critics of NanoTechnoScience alike agree that the new TechnoScience¹ will radically change all areas of life and concern all branches of industry: medical and pharmaceutical systems, agricultural and food production, transportation as well as building trade, and last but not least the military. In January 2003 a prediction was published, saying that “(b)y 2005, Atomtech will attract more interest (and controversy) than biotech. By 2010, Atomtechnologies will be the determining factor to profitability in virtually every sector of industrial economies. By 2015, the controllers of Atomtech will be the ruling force in the world economy.”²

Looking a bit closer at this nanotalk, one might suspect that it fits perfectly into the sustainability discourse on revisiting the boundaries between science and society, nature and culture, as well as respecting the limitations of natural resources and the scarcity of environmental goods. As Roald Hoffmann, Nobel Laureate in Chemistry, pointed out already in 1981: “Nanotechnology is the way of ingeniously controlling the building of small and large structures, ... it is the way of the future, a way of precise, controlled building, with *environmental benignness* built in by design.”³ Nano promises to eradicate poverty by providing material goods (of course pollution free) to all the world’s people, cure diseases, even reverse global warming, and finally solve the energy crisis. This meets quite well the general objectives of the sustainability discourse represented (for example) in the just emerging discipline of “Sustainability Science” that claims “to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes with the ecological and social characteristics of Science”.⁴

On the other hand, one can clearly find properties of conventional economic development: nano, techno and science as a dream team of the classical model of economic growth and prosperity as it is criticized by most of the economic conceptions inspired by the principle of sustainability. It seems that the investment community has decided that nanotechnology is “the next big thing”; business investment in nanotechnology start-ups is on the rise.⁵ This is well documented by the following numbers: U.S. venture capital investment has grown from a modest 100 million dollars per annum in 1999 to 780 million in 2001 and was expected to pass 1 billion in 2003. Of the 710 million dollars in funding for the US NNI (National Nanotechnology Initiative) in 2003, less than 500,000 (that is 0.1%) is devoted to the study of environmental impact.⁶

The pros and cons in the debate and the ambitious forecasts, above all, echo the arguments of the biotechnology-debate of the early 1980s. In the following I will focus on a rhetorical phenomenon in nanodiscourse and bring it together with a certain concept developed in the context of the sustainability debate, namely that of the “ecological footprint”. The phenomenon is the seeming ease with which nanotalk embraces the concept of sustainability – e.g. in the promise “to reverse global warming and to resolve the energy crisis”. This will be discussed not with respect to the consequences for nanotechnoscience but rather to the concept of sustainability.

1. Ambiguity of the Concept of Sustainability

The use of “sustainability” is quite malleable in respect to the problems and challenges of such concepts. It is used in innumerable contexts and with various meanings without taking into consideration differences due to language as in the German “Nachhaltigkeit” or the French “développement durable”. One of the early critics commented already in 1987 – the same year when the famous Brundtland-report *Our common future* was published: “The balance between fruitful ambiguity and outright contradiction is a delicate one, and ultimately the idea of sustainable development could not bear the weight of competing interpretations.”⁷ In spite of such skeptical objections, the idea of sustainability experienced an outstanding success story, and nowadays it is well known and established in society and, of course, science.

Why, then, should we not acknowledge this as a victory for environmentalists? Because it is – as the environmental philosopher Dale Jamieson stresses – just the surface.⁸ In reality it reflects the lack of interest in further environmental protections by postindustrial nations and it represents the colonization of the sustainability discourse by economists. Consequently, disciplines such as ‘ecological economy’ could grow up in the 1990s.⁹

The ambiguities described go back to the earliest English use of “sustain” and its cognates. One family of meanings is related to the idea of sustenance; a second one centers on maintaining something in existence and leads naturally to a focus on preservation. The former pushes in the direction of “meeting the needs of the present”, while the latter leans towards concern for the interests of the future. This semantic ambiguity forms the background to the whole discourse on sustainability. Another important and certainly more visible feature structuring the discourse is the distinction of human versus natural capital. Based on this distinction are the two probably most important conceptions of sustainability which have been developed over the last decade. Strong sustainability asserts that what should be preserved is “natural capital”, while weak sustainability is centered on well-being and makes no essential reference to environmental goods. Both conceptions have their problems.¹⁰ Furthermore, it is important to note that between the meanings of sustainability in professional discourse and in everyday understanding is a remarkably wide gap. What at least the majority of these meanings share is an anthropocentric outlook. While strong sustainability is very complex and technical, weak sustainability refers to simple and grand

ideas, which can be characterized in short as follows: sustainability is a good thing; it is about human survival and the avoidance of ecological disaster. According to this, the values most evident among the arguments advanced for sustainability are justice, well-being, and the value of nature “in its own right”.

Most authors participating in nanodiscourse refer by and large to those simple and grand ideas, that is, to the colloquial use of the term “sustainability”. In the following I will analyze some excerpts from various texts, stemming from fairly distant contexts.

2. The Setting: NanoTechnoScience and the Environment

The influential brochure *Nanotechnology: Shaping the World Atom by Atom* was published in 1999 by the U.S. National Science and Technology Council (NSTC) and worked out by the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), chaired by M.C. Roco. Under the slightly threatening title *Nanotechnologists project that their work will leave no stone unturned*, several aspects of everyday life are listed that will be subject to change. The aspects concerning the environment are the *Smokeless Industry* and *But, wait, there's more!*¹¹ The projected “smokeless industry” promises that nanotechnological bottom-up manufacturing “should require less material and pollute less”. Engineers are believed to be able to embed life-like functions into materials, finally resulting in self-maintaining materials. “Even concrete will get smart enough to internally detect signs of weakness and life-like enough to respond by, say, releasing chemicals that combat corrosive conditions. In effect, the constructed world itself would become sensitive to damaging conditions and automatically take corrective or evasive action”. In other words: the nano-constructed bottom-up world would be more sustainable than the traditionally constructed bottom-down world ever could be. This takes up exactly the vision of the “environmental benignness built in by design” already raised by Roald Hoffmann in 1981.

Interestingly, the environmental argument does not occur at all in the plea for “the small world” in the nano-founding paper by Feynman, which dates back another 20 years to 1959. His promises for the projected technoscience clearly point out the possible economic applications and particularly the intellectual adventure: “What are the possibilities of small but movable machines? They may or may not be useful, but they surely would be fun to make. How many times when you are working on something frustratingly tiny like your wife's wrist watch, have you said to yourself, ‘If I could only train an ant to do this!’ What I would like to suggest is the possibility of training an ant to train a mite to do this.”¹² It would certainly be interesting – especially with respect to the assumptions and consequences of technology assessment and the shaping of technology – to figure out in detail at which time the environmental argument entered nanodiscourse and how this was linked to the emerging sustainability debate of the 1980s.

The surprises under the heading *But wait there's more* of the NSTC-brochure come in a list of further techniques to improve techniques in the field of “green business” that are partly existing already. These include molecular layer-by-layer crystal growth to make new generations of more efficient solar cells and selective membranes that can fish out specific toxic or valuable particles from industrial waste. Even more ambitious (and of course fictitious) are scenarios envisioning nanotechnoscience as the “only hope” for preventing natural catastrophes resulting from earthquakes, climate change, or asteroid collisions. “To survive a giant plume of volcanic dust in the atmosphere, for example, we could unleash ‘sky bots’ that would consume dust particles as feedstock and self-replicate into the trillions.”¹³ Other more moderate and apparently more realistic positions lean obviously towards the sustainability discourse. Lester Milbrath from the State University of New York claims for example: “Nanotechnologies have the potential to produce consumer goods with much lower throughput of materials and much less production of waste, thus reducing carbon

dioxide build up and reducing global warming. They also have the potential to reduce waste, converting it to natural materials which do not threaten life.”¹⁴ Environmentalists object to the general claim of nanoproduction requiring less material and polluting less. Even if this is true, there may be counteractive effects in the more costly process engineering. Even more serious objections are raised against the speculations to “seed” the oceans to better absorb pollutants or “seed” the stratosphere to patch up holes in the ozone layer. These hold that the implications of such experimentation are unknown, “but profoundly troubling”. These seeding scenarios have raised the most persistent environmental fear concerning nanotechnology that are discussed under the heading “grey and green goo”. There is a huge and heated debate behind this, but the most important point here is that it is argued that industry might see nanotechnology just as a means to “medicate” environmental problems, rather than confront the underlying problems that are over-consumption and waste – these obviously important objections also draw upon the sustainability concept.¹⁵

The inconsistencies in the nanodebate concerning the meaning of sustainability are surfacing in the confrontation of different social and political groups. But the suspicion that sustainability and environmental discourse may be of merely strategic use – and the malleability of the sustainability concept invites us to do so – can be strengthened even further by quoting the NSTC-brochure again. Reflecting on the viability of nanotechnology’s promises it proposes the following: “consider the claim that nanobiology will enable people to live longer, healthier lives” and “longer average lifetimes will mean more people on earth” – but “how many more people can the Earth sustain?” Translated into arguments of the sustainability discourse, the NSTC-brochure begins with the well-being argument, seeks justification with the justice-argument and ends up conflicting with nature in its own right. The longevity-dilemma is in the end due to a problem with the sustainability concept itself. Both, the interest in human well-being and the conservation of nature are central to the sustainability discourse and correspond to the distinction between human and natural capital. Their different evaluations mark the difference between the two conceptions of weak and strong sustainability. The claims made in the nanodebate are mostly much more demanding than suggested by weak sustainability. Rhetorically, at least, it is more oriented to strong sustainability and will be discussed here under the heading “shrinking the ecological footprint”. But before going into the details of the footprint, I would like to insert a note. The example from the brochure that led to the general dilemma of sustainability is a fictitious dilemma; according to the Greenpeace report published in July 2003, only a small part of the world population will benefit from the nano-world (predicted are 8.6% by 2025) – and they are the least likely to suffer the effects of the overpopulation problem.¹⁶

3. Tracing the Ecological Footprint

The Ecological Footprint is defined as “the land (and water) area that would be required to support a defined human population and material standard indefinitely”.¹⁷ The concept has not just been inspired but refers directly to the ecological concept of “Carrying Capacity”¹⁸ that is based, overall, on economic assumptions. In general it seeks to express the continuing material dependence of human beings on nature. But the concept’s most important critical implication is that limits to growth are invisible to static monetary analyses, because monetary expansion itself is not bound by physical limits. The authors point out that “The ecological perspective ... challenges (the) money-based view. Clearly the physical consumption of natural income by one person pre-empts any other person from using those same income flows.” Now, what Mathis Wackernagel and William Rees propose is to translate the total of social and economic activities carried out by the people of a city or single persons into land areas – of course, the ecologically productive land areas. They have developed a sophisticated system to calculate the footprint of cities, newspapers, cars, and

so on. The footprint of a typical North American measures 98000 m², an average Canadian leaves one of 78000 m², and a European has a footprint of about 48000 m².¹⁹

The strength of the concept is surely its ability to communicate that humanity is materially dependent on nature, and that nature's productive capacity is limited. Why not represent the environmental nano-promises and visions in terms of the ecological footprint? From a sustainability perspective, this could certainly contribute to the shift of social consciousness and to the development of suitable policy responses.

At the same time, this cannot deflect the critical objections that were raised even against the concept of strong sustainability. It may be true that the invention of "natural capital" enhances the reference to environmental goods, but it does not escape the economic notion in the concept. Instead, it incorporates the natural world into economic thought. The idea of natural capital implicitly involves the idea of human transformation and use; thus it is quite difficult to distinguish natural from human capital. Renewable resources, for example wood or drinking water, are not given to us by brute nature. Nature produces trees; humans act on trees in such a way so as to utilize the wood. What turns water into drinking water is that it is fit for humans to drink. Another important question to be raised is what exactly it means to maintain natural capital or "ecologically productive land". While ecologists can agree that a terrestrial ecosystem can be productive, most of them would object against the notion of ecologically productive land: Of course, the ecosystem *high mountains* is productive in an ecological sense, but it is not according to Wackernagel and Rees.

There seems to be little hope for the ability of the concept of sustainability to structure nanodiscourse. At most it could serve as a sort of information campaign or boundary concept that allows the debate of issues like growth and environment. As such, it could provoke us to reassess our notions of quality of life and environment and eventually to help us place the debate in a more political and less ethical or economical context.

Though I discussed in a rather critical sense nanorhetoric and nanovisions, I do not want to claim that visions are *per se* something bad or have to be avoided. On the contrary, I think it is most important to develop a richer set of positive visions regarding the proper human relationship to nature. But – as the environmental philosopher Dale Jamieson points out, "(t)hese visions must go beyond the bloodless futures of scientific forecasters".²⁰ I agree with Jamieson when he points to the necessity of simple and compelling stories that show us how to participate practically in creating the future in our daily lives. What we need is a discourse that permits deeper discussion of aesthetic, religious, cultural, political, and moral values; hopefully preventing the "nanotechnification" of nature and society.

Notes

¹ I am using the term in the sense of Haraway 1997.

² ETC 2003, p. 43. The "etcetera-group" is talking of "atomtech" instead of "nanotech" to point out the political connotations of the technology.

³ NSTC-report 1999, p. 4 (emphasis added).

⁴ Kates *et al.* 2001.

⁵ Arnall (ed.) 2003, p. 32.

⁶ Arnall (ed.) 2003, p. 40.

⁷ Redclift in Jamieson 1998, p. 184.

⁸ Jamieson 1998, p. 184.

⁹ One of the first and most prominent publications in the field is the book *Ecological Economics: The Science and Management of Sustainability*, edited by Robert Costanza in 1991 (Columbia University Press).

¹⁰ See extended discussions in Hinterberger, Luks & Schmidt-Bleek 1997 and Holland 2002.

¹¹ NSTC-report 1999, p. 8.

¹² Feynman 1960, p. 26.

¹³ NSTC-report 1999, p. 8.

- ¹⁴ The Ecologist 2003, p. 38.
¹⁵ ETC 2003, p. 30.
¹⁶ "Those who participate in the nano revolution stand to become very wealthy. Those who do not may find it increasingly difficult to afford the technological wonders that it engenders" (NSTC/CT 2001).
¹⁷ Wackernagel *et al.* 1996, p. 11.
¹⁸ For more details see in Höhler 2004 the comparison of different concepts that rely on the idea of the carrying capacity.
¹⁹ Schomberg 2002, p. 21; the European research program FP6 lists under priority 6 and 7 "Research mapping our footprint on national, regional and global scale to increase eco-efficiency".
²⁰ Jamieson 1998, p. 191.

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Dissolution of the Nature-Technology Dichotomy? Perspectives from an Everyday Understanding of Nature on Nanotechnology

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Abstract: The topic of this contribution is the tension between the everyday dichotomy of nature and technology and the nanotechnological understanding of the world. It is essential to nanotechnology that nature and technology not be categorically opposed as the man-made and the non-man-made, but rather regarded as parts of a structurally identical whole. After the introduction, I will address three points: In a brief first section I will formulate a few questions and a thesis about the nanotechnological developments that can be expected to come. In the main section I will assess four aspects of everyday understanding of nature and technology that are used to legitimate nanotechnology. Finally I will discuss whether an everyday understanding of nature can be conceived as a critical authority with respect to the nanotechnology program.

Introduction

In everyday life, the dichotomy of nature and technology continues to play a significant role. That is to say, there is a clear distinction among the objects encountered in private life between, on the one hand, things that arise essentially of their own accord and undergo change irrespective of human intervention and, on the other hand, things produced by craftsmanship or by industry. Still, this traditional distinction has been rendered partially problematic by the increasing technological transformation of everyday life (cf. Schiemann 1997, 2001, and 2005).

Everyday understanding of nature and technology takes as its point of reference the objects perceived with the senses. Plants and animals serve as exemplars of natural objects, while objects owing their form to human influence are exemplary technical objects. This distinction goes back to the ancient Greeks. Its paradigmatic formulation occurs in Aristotle's *Physics*, where Aristotle counts as natural whatever has "in itself a source of change and continuity" (Aristoteles 1987, chap. II.1, line 192b13-4). This criterion has remained applicable up until now because of a cross-cultural structural difference in the everyday modes of appearance of things that are produced and things that are not.

But the appeal to sense perception also sets a limit to the applicability of the everyday distinction between nature and technology. The distinction runs into trouble as soon as technological processes become partially concealed from the senses. It is already difficult to distinguish between a self-moving nature and technological processes driven by mechanisms like electric motors that are not immediately visible to the senses.

I would like to assume that there are multiple understandings of nature in everyday life. Nature could be identified with the material of which all objects consist, or with the

world untouched by culture. While the distinction between nature and technology is central to these understandings of nature in everyday life, in other areas of experience the distinction carries much less weight. I consider nanotechnology to be one of these areas. It is essential to nanotechnology that nature and technology not be categorically opposed as the man-made and the non-man-made, but rather regarded as parts of a structurally identical whole. Laws of nature hold within technology, and there are no laws in technology that are incompatible with the laws of nature. Natural phenomena are investigated through technological experiments and made fruitful for technology. But, above all, the nano-world lies beyond the reach of the senses and thus of everyday experience. Macroscopic characteristics produced by nanotechnology elude everyday classification unless some visible element betrays their origin. Nanotechnologically produced macroscopic self-movement would undermine or dissolve the everyday distinction between nature and technology.

The topic of my contribution is the tension between the everyday dichotomy of nature and technology and the nanotechnological understanding of the world.

I will address three separate points:

In a brief first section I will formulate a few questions and a thesis about the nanotechnological developments that can be expected to come.

In the main section I will assess four aspects of everyday understanding of nature and technology that are used to legitimate nanotechnology.

Finally I will discuss whether an everyday understanding of nature can be conceived as a critical authority with respect to the nanotechnology program.

1. Novel Relation with Nature?

I will begin with the developments that we can expect from nanotechnology. Since nanotechnology is application-oriented, one of its goals is the introduction of its products into everyday life. This is especially true of the planned applications for medical therapy. In other areas, envisioned nanotechnological developments – like improved or new material qualities – will find their way more or less directly into everyday life. We may expect, for example, nanotechnological means of building ultra-light vehicles or of increasing the capacity to store information electronically. Moreover, there are countless developments that will make innovations easier not in everyday life but in industrial production. Main points here include “bottom-up manufacturing” – which refers to changes in the means of production that do not affect the end product – and nanotechnological control of chemical reactions that are already applied today.

Will the planned nanotechnological artifacts, insofar as they are applied in everyday life, enter into some novel relation with nature, understood in the Aristotelian sense? Will they dissolve the dichotomy of nature and technology, thereby ushering in a new conception of nature? In response to these questions I would like to formulate a thesis that does justice to the fact that the everyday distinction is based on visible differences whereas nanotechnological objects do not appear to the senses. *The thesis is that the everyday criterion of natural self-movement will not necessarily be dissolved by applications of nanotechnology. Indeed, it could prove to be immune to them.*

This may well be valid for nanotechnological innovations that are limited to improving qualities of technological objects already applied in everyday life – for example, nanotechnological improvement of the media used to store information electronically. From the perspective of everyday life, the technological processes responsible for this improvement would be a matter of irrelevance. On the other hand, the traditional distinction would be dissolved if nature no longer appeared to the senses as that which is not produced by humans, if living objects no longer arose from natural growth, or if nature could no longer even be distinguished from nanotechnological artifacts.

2. Nanotechnology and the public

With that I come to my second point: an assessment of the everyday content of arguments intended to legitimate nanotechnology. The example I will discuss is the brochure “Shaping the World Atom by Atom”, published under the direction of the US National Science and Technology Council (National Science and Technology Council 1999). The brochure seeks to justify state financing of nanotechnology to a broader public.

Since one of the goals of nanotechnology is the introduction of its products into everyday life, everyday life is also an important court of its legitimacy. Moreover, considerations of everyday life play a decisive role in the formation of public opinion. Since state funding of technology is largely dependant on public opinion, the presentation of nanotechnology is decisively framed in terms of an everyday understanding of nature and technology.

In the brochure “Shaping the World Atom by Atom” the nature/technology distinction is framed in this way, so that its extension overlaps with that of the respective everyday distinction. I mark this overlap as a *first point* of contact between the brochure and everyday life. Like our everyday understanding, the brochure conceives technology as the man-made and nature as the non-man-made. By virtue of its human origin, technology remains qualitatively distinct. The relationship between nature and technology finds its clearest expression in the image of nature being sensibly organized by human hands, as in the brochure’s representation of nanotechnologically produced letters. In the first picture of this representation one sees disorganized atoms, which are then technologically manipulated step by step until they come to form the IBM logo.

The point of the brochure, however, is not its similarity to everyday understanding, but its difference. It tries to shock the reader by contradicting what one takes for granted and weakening the dichotomy of nature and technology.

Thus nature itself is presented as engineering. It is suggested that nanotechnology is not uniquely human, but in fact occurs also in nature. This changed concept of technology fits in the context of a technologized understanding of nature. Although they are not produced by humans, the natural nano-processes discussed in the brochure resemble human technology and serve human purposes. According to the brochure, nature’s untouched forms and visible outgrowths conceal a universal atomic principle of construction. At the beginning of the brochure, we are told what would remain of a person broken down into his or her chemical components. We learn that nature builds from this worthless lump of material a living being that can even think and dream. So the human being appears to be composed mechanically out of simple parts. Complex phenomena that cannot be derived from the properties of their components remain unexplained, processes between system and environment remain unmentioned.

With these questionable simplifications, the brochure conceives nature only insofar as it is useful for humans and their technology. Seen from this perspective, nature assumes the character of a machine: Rotation in organic cells is compared to the rotation of a fan; the description of photosynthesis is intended to remind the reader of a device for producing domestic solar energy.

I’m not going to assess the appropriateness of such analogies. I merely want to demonstrate that they form a *second point* of contact with the everyday understanding of nature and technology. They apply elements of the everyday understanding of technology to natural processes that are inaccessible to sense perception. It’s worth mentioning that Aristotle made use of a similar analogy to explain the invisible processes involved in procreation. He compared procreation to the work of a carpenter. According to Aristotle, just as in procreation the passive material provided by the woman is shaped by the active form from the man,

in carpentry the passive wood is shaped by the active creative force of the carpenter (Aristoteles 1860, chap. I 21, line 729b14 et seq.).

But the modern form of this analogy is different from the ancient form in that it devalues everyday life. From the perspective of everyday life, objects perceived with the senses constitute a privileged human world. But by assuming a homogeneous structure of the real world and the universality of natural laws, nanotechnology contests the privileged status of this middle dimension of everyday life.

This devaluation of a particular area of experience goes hand in hand with elevating the human. On this view, nature should be rebuilt from the ground up, atom by atom, only to fulfill human needs. The brochure names no natural phenomena that have a value independent of human interests.

Support for the notion that only a completely artificial world is truly human can also be drawn from everyday understanding. Non-human phenomena have gradually lost their significance in the everyday life of cities since ancient times. Plants and animals have taken on the dispensable function of decoration. Technology is regarded positively in the modern everyday life that it created. This constitutes *a third point* of contact between efforts to justify nanotechnology and everyday understanding of nature and technology.

Finally, an assumption made in the presentation of the National Science and Technology Council is that the further development of nanotechnology will realize the present plans of a future world that will be a better one. The influences that nanotechnological innovation can have on the human mind are not taken into consideration here. This idea, too, echoes certain everyday notions. Everyday understanding conceives the human mind as an autonomous agent that uses technology to achieve the goals it sets for itself.

In summary, there are *four aspects* of everyday understanding that are invoked to legitimate nanotechnology:

First: The conceptual uniformity between the nature/technology distinction made in the brochure and the corresponding everyday distinction, *i.e.* technology as the man-made and nature as the non-man-made.

Second: The analogy between everyday technological devices and natural processes at the nano-level.

Third: The positive attitude towards technological innovations of the World.

Forth: The independence of mind from technology.

Surprisingly, nanotechnology can be thus legitimated on the basis of an everyday understanding of technology without denying its conceptually distinct understanding of technology. To repeat, nanotechnology assumes no categorical opposition of nature and technology. Nanotechnology has no problem conceiving nature on the model of technology. There is a long tradition which is in line with the report's choice to take everyday technological devices as models. The seamless comparison of processes at different orders of magnitude demonstrates that nanotechnology – in contrast to everyday understanding – does not favor one dimension over the others.

3. Leaving no Stone Unturned?

It seems that proponents of nanotechnology utilize everyday notions of technology in their efforts to legitimate nanotechnology. If this is correct, then the question arises whether an everyday understanding of nature can nevertheless be conceived as a critical authority with respect to the nanotechnology program. With this question I come to the third aspect of my discussion of the relationship between everyday life and nanotechnology.

The nanotechnology program is predicated on instrumental reasoning that banks on technology as a solution to problems. But it is doubtful that the solution of everyday problems – especially those arising in developing countries – requires technological innovation.

It is true that developing countries are in need of technological improvements, but what they need even more is fair participation in the technology we already have.

Nanotechnology is supposed to re-shape the world in a fundamental way. To quote from the report "Shaping the World Atom by Atom", "Nanotechnology advocates say their field will leave no stone unturned." But this goal is a long way off. To stick with this image, nanotechnology has managed to turn just a few stones so far. In terms of everyday life, turning a few stones is not comparable to building a house, not to mention the emergence of complex organic creatures.

Unlike technology, everyday life assumes – rightly, I think – that organic creatures have their own dynamics. Whereas organisms have a right to life that cannot be violated without justification, everyday technological devices – like computers, television, sources of light – can be turned off at will. In everyday life we concede to technological processes only dynamics – uncontrollable by everyday means and hidden from the lay observer – that can be ended or reversed at any time.

But the same is true of everyday attitudes towards natural processes. It is expected that there should always be protection from the elements and certainly from natural disasters. Illnesses should not occur at all, we feel; and when they do, they should be immediately eliminated. This stance towards nature calls into question the critical competence of everyday understanding with respect to technology.

Itself essentially an artificial world, everyday life may express only qualified doubt about the supposed need to improve nature. As a local world it does not offer a sufficient foundation alone to pass judgment on nanotechnology's claim to universality and the human responsibility stemming from it.

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The End of Pure Science: Science Policy from Bayh-Dole to the NNI

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Abstract. The science policy of the United States federal government has undergone a series of changes in emphasis since the Second World War. Most of the debate about what federal science policy should be, has focused on two questions – what is the role of science and technology in national security and what is the role of science and technology in economic growth. This paper details the shift from military to economic motives for American science from 1980 through the turn of the century. While this shift was caused in part by the end of the Cold War, the economic challenges of the late 1970s and early 1980s first laid the ground for a new kind of federal involvement in scientific research as an economic engine. This new economically driven science policy has culminated in the National Nanotechnology Initiative of 2000.

Introduction

In 1995, Charles Vest, President of MIT, claimed that, “We are in a period of fundamental reconsideration of US science and technology policy. The end of the Cold War, the changing nature of US economic competitiveness, and the increasing direct involvement of Congress in science policy have led to a lack of stability in goals and philosophy. The roles of government, industry, and academia are being examined in a fundamental way.” (MIT 1995, p. 2) From practitioners like Vest to policy scholars like Lewis Branscomb to politicians like Bill Clinton it is common to find claims that science and technology policy today is rather different from the science and technology policy of the Cold War. But exactly what is the nature of this difference? Just as importantly, when and why did key underlying assumptions about the government’s role in science and technology change? Determining when these changes began to occur and the particular historical circumstances of the changes promises to help answer the question of why changes began to occur. This paper is a historical examination of these changes – focusing in large part what problems policy makers saw in federally-sponsored science and technology research, and how they expected individual policies to address those issues. Still, while individual pieces of legislation were crafted to meet particular concerns, the sum total of changes between the late 1970s and the present suggest that some broadly defined sea-change has occurred – the change Vest referred to in his quotation above.

Nanotechnology emerges exactly in this reconsidered moment of science and technology policy, and some would argue that it rises to prominence in part because of this new regime. Nanotechnology policy has become a centerpiece of science and technology policy at the turn of the 21st century. Arguments about whether nanotechnology constitutes a new way of doing and thinking about science must, therefore, consider the role the government has come to play in scientific and technological research as a result of the changing governmental attitude toward research beginning in the 1980s. Perhaps more so in the case of nanotechnology than in any other area of scientific research, government policy has played

a role in the formation of the field. At least from the current vantage point, the changing motives and aims of US federal science and technology policy beginning in the 1980s appear to culminate in Bill Clinton's National Nanotechnology Initiative of 2000. Consequently, it is important to examine the history of federal science policy to understand the policy environment in which nanotechnology has developed.

1. The Complexity of Science and Technology Policy in the United States

It is tempting to focus largely on how science and technology projects have been funded in order to determine the government's goals. However, doing so often results in overlooking the early phases of change. In many instances, structural and institutional changes precede new funding. These social changes are designed within particular historical contexts to address specific issues, even though in many cases there are unintended consequences. Context matters to the construction of policy, because it defines a 'room for maneuver,' or a limited array of choices that are feasible given the political, economic, and social context of the moment.¹ A policy environment is formed when many different policies, created in different contexts to solve different problems come together in contingent ways. Seeing trends in science and technology policy requires looking at the changing environment, that is, the interaction between many different kinds of policies designed to do different and occasionally contradictory work.

As many policy analysts have pointed out, there exists no institutional or agency structure for science and technology policy – policies, for this reason, lack a single, overriding vision.² In 1993, Lewis Branscomb wrote, "U.S. S&T policy is largely uncodified; it must be deduced by observation of the laws, organization of government, and the actions of government managers and agencies. That policy is continuously in flux and it is unclear what direction the de facto policy will take in the next decade" (Branscomb 1993, p. 4). Daniel Sarewitz describes US science and technology policy as "Balkanized" and claims that the lack of a centralized science and technology policy is one reason that studies of changing funding levels and allocation plans take center stage in policy studies (Sarewitz, 2003, p. 2). Recently, Sarewitz wrote, "It is not only axiomatic but also true that federal science policy is largely played out as federal science budget policy" (*ibid.*, p. 1). But in the period of the 1980s and the 1990s studying budget allocations to determine the importance and direction of science and technology policy is not particularly productive because federal R&D funding has remained so stable. As a result, small changes in allocations are examined in detail for their hidden meanings. However, if the full array of policy shifts, and not just funding, are taken into account and placed in their historical perspective, a dynamic picture of science and technology policy arises. The striking aspect of this fully dimensional picture is that it shows how the political notion of what science and technology were expected to do for the nation was, in fact, changing. I will argue here that structural, educational, regulatory, and particularly legal changes in the 1980s set the stage for changes in how money has been allocated in the 1990s, giving a much clearer picture of what has happened to the place of science and technology in US federal government.

2. From Cold War Science and Technology to Technoscience for Global Competitiveness

The socio-economic problems that the new policies of the 1980s and 90s were designed to address first begin to appear in the mid-1960s and early 1970s. Traditional American industry, which obviously played an important role in the overall health of the US economy, began to see itself as under assault from competitors, both foreign ones from East Asia and

West Germany, and domestic challengers from new industries like information technology (Buderi 2002, p. 247). One of the failings of American industry was seen as its inability to apply expensive ‘basic’ research – research that was often derided for being interesting, but irrelevant.³ To some extent this was an unfair characterization, but this point of view fueled efforts to remake both federal science and technology policy and the corporate reorganization of R&D in the 1980s. The primary concern of policy makers was how to measure, assess, and increase the productivity of research, especially that which was federally funded.⁴ How could American scientific research, seen as one of the nation’s great resources, help the American economy, which in the 1970s was in a period of rising prices but stagnant growth?

As a result of looking to science and technology to end economic malaise, government interests in sponsored R&D shifted from so-called basic science, justified by military needs to a new paradigm of directed research, justified by economic needs. In the 1950s and 60s science and technology policy was guided by the ‘pipeline’ model of the relationship of science to technology championed by Vannevar Bush (Branscomb 1993, p. 9-10). In this scheme, federally funded basic science would provide the new knowledge that underpinned new technological developments. Government spending needed to focus on basic, non-targeted research because this kind of scientific work was both fundamental and less attractive to the private sector. This linear picture was attacked by the 1966 Project Hindsight report. This study, sponsored by the Department of Defense, claimed that ‘pure’ science contributed little to the actual development of new weapons systems. On the heels of Hindsight, policy makers asked whether it made sense to claim a linear relationship for basic research and civilian technologies, if undirected scientific research contributed little to sophisticated defense technology? As a result, basic, un-directed research was under a continuing assault throughout the 1970s. As economic circumstances worsened after 1973, policy makers wanted to demand more economic bang for their research buck. American scientific research had to be part of the solution; American scientific superiority needed to translate into economic performance. But to do so, the role of the federal government had to change, and these changes took over a decade to put into place. However, by the end of 1980s the new regime was more or less in place, and only an aggressive rhetoric justifying federal spending on science in economic terms had yet to come. The arrival and success of this language in the 1990s is obvious from simply reading the titles of science and technology policy documents from the past decade: “Technology for America’s Economic Growth” (1993), “Science in the National Interest” (1994), the Advanced Technology Program’s “Prosperity through Innovation” (1999), “The National Nanotechnology Initiative: Leading to the Next Industrial Revolution” (2000), and more.

Several questions remain about how this new regime came into being, and to answer these requires a more detailed look at the policies that, piece by piece, came to constitute the new science and technology policy. For the most part, these new pieces of legislation focused on the issue of technology transfer – of getting more economic productivity out of the research that was already being performed. Policy makers could not see why, given the quality of American science, it was not generating the kind of technological innovation apparent in America’s economic challengers, like Japan and West Germany. As a result, the focus of much federal science and technology policy in the 1980s was on problems in the movement and translation of knowledge from the lab through development onto the market.⁵ The public-private partnerships that resulted, constructed largely during the Reagan administration, were an acceptable conservative alternative to greater government involvement in industry (Hart 1998, p. 228).

3. Science and Technology Policy in the 1980s

Two pieces of legislation were passed in the waning days of the Carter administration that set the stage for the sea-change in science and technology policy evident in the 1980s and 90s. The lesser-known of the two was actually passed first; the Stevenson-Wydler Technology Innovation Act passed into law on October 21, 1980. Stevenson-Wydler was an act to promote technology transfer, particularly from federally supported research performed in universities and federal laboratories to the private sector for commercial development. To do this, Stevenson-Wydler set up a Technology Administration (hereafter, TA) in the Department of Commerce, where efforts to bring new technologies into American industry would be studied and sponsored. The TA would include the already existent National Bureau of Standards (the government's first physical science laboratory, established in the late 19th century) and a new Office of Technology Policy. Stevenson-Wydler also empowered the TA to create organizations to study innovation and the relationships between technologies and their economic and industrial impacts, with an eye toward world trade and international competitiveness. Stevenson-Wydler represented the federal government's recognition that technology was an important determinant of economic progress and one that could not be left solely to the private sector. The federal government needed more than just military technology policy; civilian technologies also required guidance. This new attitude naturally had predecessors (*e.g.*, the OTA), but coming out of the economic stagflation of the late 1970s, it was also an acknowledgement that old *laissez-faire* attitudes, at least with regard to technology and industry, had failed to perpetuate the growth rates of the 1950s and early 60s. But the Stevenson-Wydler Act was quickly overshadowed by the next piece of science policy, which also aimed at moving federally sponsored research into the commercial sector.

On December 12, 1980, the Patent and Trademark Law Amendments Act became law. This bill, commonly known as the Bayh-Dole Act, because it was initially introduced by Robert Dole and Birch Bayh, was a more direct attempt to transfer knowledge from universities and federal laboratories to commercial applications. Prior to Bayh-Dole, research funded publicly could be patented, but the licenses were not exclusive unless a waiver could be obtained. Research that was publicly funded was publicly available. As a result, there was a considerable disincentive for private concerns to purchase licenses to university-performed research, since they could not be assured that a competitor would not beat them to market with a similar product. In addition, different funding agencies had different rules about patenting and licensing inventions produced with federal funding. This created an extraordinarily complex set of laws under which universities had to operate; as a result, only a small number of research universities engaged in patenting. Bayh-Dole changed this environment by creating a common set of patenting and licensing rules for all government-sponsored research and development (with the notable exception of classified research). Under Bayh-Dole, the government retained non-exclusive rights to patents developed with public funds, but universities could grant exclusive licenses to commercial interests. The framers of the policy imagined that Bayh-Dole would create an incentive system to facilitate technology transfer from university labs to the market. Like the Stevenson-Wydler Act, Bayh-Dole itself did nothing to fund research; instead it constituted a legal change that made university-industry collaboration much more feasible and attractive. David Mowery, who has studied the effects of Bayh-Dole at some length, has also pointed out that Bayh-Dole made nothing legal that was previously illegal – instead, it rationalized patenting rules across multiple agencies (Mowery 2002, p. 265).

Critical assessment of the Bayh-Dole Act has been mixed, but from a statistical point of view, the number of patents granted to university-performed research has exploded, as has the number of universities involved in patenting activity. The Association of University

Technology Managers reports that the number of patents granted to universities has increased from 500 in FY1980 to 3272 in 2000, with 3606 new licenses granted in FY2000 (AUTM 2000, p. 30). At the same time, membership in the AUTM has grown from 200 to 2,000 (COGR 1999, p. 3). But measuring Bayh-Dole's impact in other ways is more complicated and yields a more nuanced picture of the Act's success (Mowery 2002, pp. 263-5). Furthermore, there have been unintended consequences to Bayh-Dole. These include debates over the price of drugs developed from federally-sponsored research; disputes between collaborating institutions over intellectual property rights; and tense discussions about the unintended consequences of changes in universities' financial structures (Hardy 2002, pp. 10-12). Mowery and Ziedonis also note that the bulk of the products patented by universities for licensing are in the biotechnology/pharmaceutical/medical technology sphere, and the causes for the explosive development of this sector lie outside Bayh-Dole (Mowery & Ziedonis 2002, p. 415).

Several bills following Stevenson-Wydler and Bayh-Dole in the 1980s continued the Carter administration's emphasis on lubricating the process of technology transfer. During the first Reagan administration, the 1984 National Cooperative Research Act broke down more legal barriers in the commercial use of research findings by softening antitrust legislation. Prior to this change, independent firms that collaborated on any scientific or technical research could be charged with violating anticompetitive standards of corporate behavior. This act established a rule of reason for evaluating cooperative research undertakings and their potential antitrust implications.⁶

Stevenson-Wydler was amended in 1986 by the Federal Technology Transfer Act (FTTA). This law largely affected government-owned and -operated laboratories (so-called GOGOs). Lab employees were now allowed to share in the royalties their inventions generated, and their performance evaluations would consider their roles in technology transfer. GOGOs were, in fact, required to actively seek commercial uses for the research they undertook – scientists were to be the ambassadors and salespeople for their research. The FTTA also allowed GOGOs to create cooperative research and development agreements (CRADAs) with other agencies, universities, as well as private sector companies.⁷ One of the more visible effects of FTTA has been the proliferation of mission-specific research centers, often located on university campuses.

In 1988 the Omnibus Trade and Competitiveness Act (OTCA) took the government's attention to technology transfer even further, by modifying the structure of National Bureau of Standards to spearhead technology transfer, and renaming it the National Institute for Standards and Technology (NIST). The Department of Education was also authorized to set up centers for training in technology transfer. Generally, however, the aims of the OTCA were directed at the private sector, by creating greater incentives for commercial cooperation in seeking out and sharing in federally sponsored research. Along these lines, the OTCA created the Advanced Technologies Program (ATP) in NIST as a structure to aid commercial interests in moving new cutting edge technologies from the laboratory to the production line. Projects in the ATP are jointly funded by government and private corporations.⁸ On a smaller scale, the OTCA facilitated royalty payments to non-government employees of federal laboratories – creating innovation incentives on the individual level.

The FTTA was further buttressed in 1989 by the National Competitive Technology Transfer Act, which established technology transfer as one of the *primary* missions of the federal laboratories, including the nuclear weapons laboratories. This act also allowed the creation of CRADAs between government-owned, contractor-operated laboratories (GOCOs). In addition, the products of CRADAs could also be protected from disclosure by this legislation – making these agreements even more attractive to the private sector. The result of this array of policies in the 1980s was to change the mission of scientific and technologi-

cal research in the federal government, moving from a relatively laissez-faire stance to first facilitating technology transfer, then eventually requiring it as a chief research objective.

4. Science and Technology Policy in the 1990s

The end of the Cold War in 1990 accelerated changes that the policy shifts of the 1980s had already begun. Most importantly, the ending of the Cold War fundamentally altered the common military justification for supporting a wide range of science and technology research projects. Yet, as we have seen, another justification was already in place, even before the demise of military necessity – an economic necessity focused on global competitiveness. Naturally, this newly important justification would affect the kinds of science seen to deserve federal support.⁹ In an effort to ease the transition from a largely military to a generally civilian basis for scientific and technological research and development, George Bush Sr. created the President's Council of Advisors on Science and Technology (PCAST) in 1990. However, even with a more serious and better organized conduit for advice from non-governmental research practitioners, the transition from a focus on military technology to an integrated vision of military and civilian technology promised to be, and has proven to be, complicated. Writing in 1993, Lewis Branscomb even claimed that the US manufacturing economy consisted of two cultures – military and civilian. According to Branscomb, government institutions were more in touch with military innovation than with civilian (Branscomb 1993, p. 13). Branscomb then argued that US technology policy faced three challenges in the post-Cold War world: First, to recognize “that defense priorities will no longer dominate the U.S. federal government's technology policy”; second, to create a “publicly supported technology base, supporting industry's capability to create technologies for all three areas [military, commercial, and environmental] of national need”; third, to emphasize the “diffusion of technical skills and knowledge”, since “economic performance in a competitive world economy rests primarily on how well the society uses the existing base of technology, skills, and scientific understanding” (*ibid.*, p. 16). These issues represented the foci of science and technology efforts during the 1990s, and were principally shepherded by the Clinton-Gore administration, who shared these priorities.

In the first month of the Clinton presidency, Bill Clinton introduced his technology policy initiative called “Technology for America's Economic Growth”. This document outlined the Clinton administration's commitment to the new model of economically justified science:

Since World War II, the federal government's de facto technology policy has consisted of support for basic science and mission-oriented R&D – largely defense technology. Compared to Japan and our other competitors, support for commercial technology has been minimal in the U.S. Instead the U.S. government has relied on its investments in defense and space to trickle down to civilian industry. Although that approach to commercial technology may have made sense in an earlier era, when U.S. firms dominated world markets, it is no longer adequate. The nation urgently needs improved strategies for government/industry cooperation in support of industrial technology. [...] This new policy will result in significantly more federal R&D resources going to (pre-competitive) projects of commercial relevance. It will also result in federal programs that go beyond R&D, where appropriate, to promote the broad application of new technology and know-how. (Clinton 1993, p. 8)

The paper then lays out the 6 particular areas where new initiatives would be made: extending the research tax credit; investing in a national information superhighway; advanced manufacturing technology; the next generation of automobiles; technology for education and training; and investment in energy-efficient federal buildings (Clinton 1993, p. 24).

Clinton also emphasized the need to redirect federal research funding from 59% toward military aims to an equal split between civilian and military objectives.

Clinton's commitment to the economic goals for scientific research was extended in 1994 with his science policy statement "Science in the National Interest". This was the first executive statement on science since Carter's in 1979. Ironically, Clinton cast back to Vannevar Bush's famous 1945 policy recommendation, *Science the Endless Frontier*, for inspiration, echoing Bush's emphasis on the need for government support of scientific training.¹⁰ But Clinton's policy was fundamentally different from Bush's in many ways, since Clinton's policies would increase government involvement in and control of scientific research, a position Bush fought against. Similar in structure to his 1993 statement on technology policy, Clinton's 1994 science policy pointed toward 5 specific goals: "maintaining leadership across the frontiers of scientific knowledge"; "enhancing connections between fundamental research and national goals"; "stimulate partnerships that promote investments in fundamental science and engineering and effective use of physical, human, and financial resources"; "produce the finest scientists and engineers for the 21st century"; "raise the scientific and technological literacy of all Americans". Vice-President Gore described the White House's view of science and technology as "more like an ecosystem than a production line. Technology is the engine of economic growth; science fuels technology's engine."¹¹ To accomplish this wide variety of initiatives, Clinton set up a new cabinet-level group, the National Science and Technology Council (NSTC), to help coordinate research policy across numerous agencies. The NSTC would work in concert with Clinton's new PCAST.¹² Clearly, by the second term of Clinton's presidency, science and technology policy had successfully moved from the Cold War mentality of military needs to a global economy paradigm of economic justification. Still, in the slow economy of the first half of the 1990s many of Clinton's promises fell victim to budgetary concerns. In this sense, Clinton's policies played a more important role in changing attitudes about what government intervention in science and technology was supposed to accomplish than in actually accomplishing these goals.

5. Nanotechnology Initiatives

Nanotechnology policy initiatives began to appear near the beginning of Clinton's second term, initially coming through the Advanced Technology Program of NIST.¹³ The ATP made nearly \$57 million in grants to nanotechnology projects prior to the year 2000, with an equal amount of matching funds guaranteed by the private sector.¹⁴ However, by the end of the decade, the National Science Foundation, Department of Defense, and Department of Energy had taken the lead in funding nanotechnology projects. But the most important development in nanotechnology policy was not its funding within agencies; it was its migration outside standard funding avenues into the position of being the jewel in the crown of Clinton's science and technology policy. This process took several years, building on the developing imperative that science and technology needed to be managed for the economic health of the nation.

The visibility of nanotechnology in science policy took an important step in 1998 when the National Science and Technology Council established the Interagency Working Group on Nanotechnology (IWGN). The IWGN was a small group of practitioners who could explain and advocate for nanotechnology. The IWGN funded workshops on nanotechnology, many of which were focused on forecasting the future. This emphasis on what could be was enormously helpful in selling nanotechnology to the NSTC and the President – the 1999 publication *Nanostructure Science and Technology: A Worldwide Study* contains a chart of 5 nanotechnology areas showing both their present and potential impacts. While reports of the IWGN are highly technical, they still contain numerous po-

litically useful statements. For example, “Nanostructure science and technology is a broad and interdisciplinary area of research and development that has been growing explosively worldwide in the past few years. It has the potential for revolutionizing the ways in which materials are produced and products are created” (Siegel *et al.* 1999, p. xvii). Through the workshops the IWGN created a draft plan for a national nanotechnology initiative. PCAST responded to the draft in November of 1999, and a nanotechnology panel, headed by Charles Vest, endorsed the 5-year initiative suggested by the IWGN. The PCAST statement was far less technical than the IWGN report and championed the potential, long-term economic benefits of a commitment to nanotechnology. However, dealing with long-term consequences and benefits was more challenging in the paradigm of economic justification. Statements had to be carefully constructed to emphasize the considerable economic payoffs of such research, while also justifying government action by showing that the work to be supported contained disincentives for industry – but these disincentives were based on a dynamic of time and risk and not on serious doubts about the efficacy of the research. PCAST constructed the following statement with an eye to these concerns:

Most foreseeable applications are still 10 or 20 years away from a commercially significant market; however, industry generally invests only in developing cost-competitive products in the 3 to 5 year timeframe. It is difficult for industry management to justify to their shareholders the large investments in long-term, fundamental research needed to make nanotechnology-based products possible. [...] There is a clear need for Federal support at this time. [...] we strongly believe that the United States must lead in this area to ensure economic and national security leadership. (PCAST 1999b, p. 3)

In a letter to the President accompanying the review quoted above, PCAST urged Clinton to “make the NNI a top priority” (PCAST 1999a, p. 1). This letter also makes the strongest claim for the economic importance of nanotechnology, arguing, “We believe that nanotechnology will have a profound impact on our economy and society in the early 21st century, perhaps comparable to that of information technology or of cellular, genetic, and molecular biology” (*ibid.*, p. 2). Similar support came from Neal Lane, the President’s science advisor, who rated nanotechnology one of the government’s 11 R&D priorities. The National Nanotechnology Initiative officially came into existence in the spring of 2000, and was first funded for fiscal year 2001, beginning in the summer of 2000. Clinton’s budget request for the NNI in its first year included a doubling of the federal investment in nanotechnology, for a total of \$497 million to be spread across 6 agencies (NSF, NASA, NIH, and the Departments of Defense, Energy, and Commerce).¹⁵ In the Congressional responses to Clinton’s request, the economic justification for the nanotechnology bill proved to be compelling. Senator Evan Bayh said,

Research in nanotechnology is extremely important to future rates of innovation in the country. Innovation is the key to our comparative advantage in the global economy, yet federal investment in the physical sciences that help drive innovation – math, chemistry, geology, physics, and chemical, mechanical, and electrical engineering – are all declining, as are the number of college and advanced degrees in these areas. [...] It is vitally important that we increase our investment in the physical sciences, including nanotechnology, if we are to see increases in productivity and incomes in the years ahead. (quoted in Leath 2000, p. 2)

From these statements about the NNI it is clear it fits into the regime of science justified by its role in global economic competitiveness.

6. Effects of the New Regime of Science and Technology Policy

In his 2000 book *Real Science*, John Ziman argues for the emergence of a new way of doing science. His model of Post-Academic science develops along a parallel timeline to the policy changes and changes in the U.S. federal government's vision of science, which I have described here. Although Ziman grants the importance of science policy, he writes very little about science policy and its role in the scientific culture that he details. When Ziman does focus on government-science interactions, he is interested in the effects of the 'soft-money' system and the competition for grants, but this is rarely related to what policy-makers thought they were accomplishing when funding protocols were changed. In this sense, Ziman largely ignores the details of the effect of policy on science, although he does admit "the emergence of science and technology policy as a major factor in the transition to a new regime for science" (Ziman 2000, p. 75).¹⁶

Ziman claims that a new regime of science began to emerge in the 1960s; many of these changes were evident by the end of the 1970s. There was no single underlying cause for the emergence of this new culture. Rather, a series of changes, both inside of and external to the scientific enterprise, occurred which in sum net a socio-cultural shift. This new regime had several distinct qualities.¹⁷ First of all, there was a change in the social arrangement of work. In the Post-Academic regime, work is collective and trans-disciplinary (*ibid.*, p. 69). Teams of scientists and technicians are not arranged by discipline – the kinds of problems they work on require specialists from numerous fields. This fundamentally challenges the social structure of scientific work.

Second, this new regime has to work in a steady-state of funding. Science is no longer an expanding activity. R&D, as a percentage of national income, hovers around 2-3%. Whereas during the Cold War there had been an escalation of funding (in the US this occurred after Sputnik), in the world of Post-Academic science, there is no assumption of overall increase in the size of the research enterprise. This promises to amplify the language already central to science policy about the productivity of research. However, while the overall size of the research landscape is not expected to expand, allocations will shift and explosive growth in particular sectors will occur (*ibid.*, p. 71).

These changes in allocation are driven by a new stress on the utility of the science – Ziman's third criterion. Research is targeted at recognizable practical problems – regardless of their field of the research (*ibid.*, p. 72). Commercial evaluations of discoveries precede and become more important than scientific validation (*ibid.*, p. 74). The new emphasis on utility also makes scientists accountable to institutions outside the scientific community – from businesses to government overseers. It also has explicitly ethical consequences – if science is done with applications in sight, then scientists can no longer remain neutral about the potential uses of their work.

Taken in concert, the changes described by Ziman yield a picture of science that obscures traditional distinctions between basic and applied work.¹⁸ Because science is valued chiefly for its applicability in the Post-Academic regime, even research with extremely long term goals is cast as having potential for use (*ibid.*, p. 173). Furthermore the history of science is rife with cases of science performed without an eye to application, which has subsequently become enormously important economically. These cases often give support to research which seems to have little direct application. Like my earlier argument about the economic justification for research, what is important to see about Ziman's claims about the basic/applied distinction, is that it represents a cultural shift in how science is perceived and discussed. Science may be important to scientists for exposing fundamental knowledge about the world, but it is important to politicians and the public for generating products and jobs. In reality, there is no reason not to claim that science does all three, but the latter two justify public spending in a more concrete, and frankly, popular way than the first. The pic-

ture of science that Ziman paints in *Real Science* is summed up in the sentence, “Science is being pressed into service as the driving force in a national R&D system, a wealth-creating technoscientific motor for the whole economy” (*ibid.*, p. 73). From both this statement and from his general description, it is quite clear that Ziman’s Post-Academic mode of science agrees quite well with the science for global competitiveness model espoused by policy makers in the 1990s.

7. Nanotechnology as a Moment in Science

If we accept Charles Vest’s and others’ claims that science and technology policy in the 1990s shows a visible shift in both function and rhetoric and John Ziman’s and others’ claims that science is being done differently, we arrive at a coherent picture of a new regime in science. Both of these dimensions revolve around claims that the economics of science is changing. But there are two perspectives on the economics of science: the input of both public and private funds necessary to support science; and the potential economic impact generated by the products of scientific research. These two aspects are linked by science policy – both governmental and corporate – which uses the products of science to justify and allocate the funds to actually perform scientific and technological R&D.

Given the coherence of the politics, economics, and culture of science in this new regime, would it be fair to characterize the emergence of nanotechnology as a crystallizing moment in science? While it may be too early to tell, examining the context of science, politics, economy, and culture into which nanotechnology was introduced in the 1990s seems like a fruitful avenue for investigation. Cultural historians of science often seek historical episodes where changes in actual scientific practices can be related to socio-economic, political, and cultural contexts. Peter Dear explains that the cultural history of science often operates by showing “people doing things that look somewhat unexpected – or, crucially, can be *presented* as looking odd – and makes sense of their behavior by appropriate contextualization: finding out what made particular behaviors or ways of doing things look normal” (Dear 1995, p. 151, emphasis in the original). Often these works look at the emergence of new disciplines and fields of inquiry and show how these developments happened in light of particular circumstances outside of the science itself.¹⁹ The emergence, and particularly the hype, of nanotechnology and the government’s attention to it are just such a case of an odd-looking event that can be made to look expected through attention to its political and economic context. Nanotechnology, in particular, seems to require, or at least benefits from, such a multidimensional explanation.

These cultural arguments are not to claim that nanotechnology would not have developed without this particular environment. However, it is to claim that because of the socio-economic environment of the 1990s, nanotechnology has developed in a particular way.²⁰ Embracing this type of contingency helps to explain the positioning of nanotechnology as the jewel in the crown of current publicly supported science. Nanotechnology is a nearly perfect fit for what both companies and the government expect from science. It also conforms to the new Post-Academic regime within science, so that the development of the field is less stymied by the challenges it presents to traditional modes of doing science – *e.g.*, transdisciplinarity, focus towards applications, ties to proprietary industrial research, blurring of science and engineering.²¹ Nanotechnology corresponds to the current regime of science so well because it grew up in this regime – no crippling modification of it had to occur, as happened in particle physics after the budget axe fell on the superconducting supercollider.

Nanotechnology hardly represents the end of pure science as I provocatively titled this paper. However, it does stand as an exemplar for a new relationship between science, politics, and economy, where seeking the fundamental truths lacks political punch. With an

eye to history, it is worth restating the origin of the rhetoric of pure science. The ultimate statement in support of an elevation of pure science is Henry Rowland's 1883 "Plea for Pure Science" Address given to the AAAS. Rowland complained that,

it is not an uncommon thing, especially in the American newspapers, to have the applications of science confounded with pure science; and some obscure American who steals the ideas of some great mind of the past, and enriches himself by the application of the same to domestic uses, is often lauded above the great originator of the idea, who might have worked out hundreds of such applications, had his mind possessed the necessary element of vulgarity. (Rowland 1901, p. 594)

As David Hounshell points out in his investigation of "Edison and the Pure Science Ideal in 19th Century America", Rowland was reacting to Edison, who had aggravated Rowland and other academic scientists a decade before by using the press to publicize his science, behavior Rowland considered inappropriate for a scientist (Hounshell 1980, p. 613). Furthermore, Rowland was also upset with his scientific colleagues for their adulation of Edison and their championing of him as a scientist – Rowland believed that credit should be going to the academic physicists. Rowland wanted to distinguish his own work in the laboratory from Edison's inventions and industrial laboratory, and to do so he attempted to hold them up to a higher moral standard. Making money off scientific research was, as David Hounshell puts it, "vulgar, opportunistic, and even cutthroat, and had somehow been confused with the work of pure science" (*ibid.*, p. 616). Of course, as Hounshell points out, this was ironic, since it was Edison's inventions that fueled public support for science. Apparently, science justified by industrial transformation sold as well at the turn of the 20th century as it does at the turn of the 21st. But Rowland's own credentials were themselves conflicted, with a civil engineering degree from Rensselaer Polytechnic Institute, and a short stint as a railroad surveyor. Furthermore, his employer, the Johns Hopkins University, did not shy away from close industry-academy relationships. The Rowland-Edison debate demonstrates once more the complexity of the pure-applied divide, even at one of its most crystallized moments.

In *The Landscape of History*, his recent apologia for history, Cold War historian John Lewis Gaddis tackles the difficult problem of whether history gives us any insight into the future. While it would be folly to claim that it does so in a narrow fortune-telling sense, Gaddis also points out that "we know the future only by the past we project onto it. History is, in this sense, all we have" (Gaddis 2002, p. 3). But then in explaining why this approach might be useful, Gaddis explains that history depends on the recognition of patterns, "the realization that something is 'like' something else" (*ibid.*, p. 2). Seeing the recurrence of the debate between Rowland and Edison over the nature of real science bears Gaddis out. Edison's tactics, for all of Rowland's attacks won out – therefore, his are the lessons to bear in mind. Edison's science produced what he said it would – lights, among other things, and the public cared. Nanotechnology promises to be many things, but in the current environment of policy, it is best to be an economic engine. Still, it is even smarter to claim to be tomorrow's engine, since this provides protection from immediate demands for productivity.

Notes

- ¹ The notion of room for maneuver ("Handlungsspielraum") as I use it here is best developed in Knut Borchardt's study of German economic policy during the interwar crisis (Borchardt).
- ² Since 1980, there have been many legislative and executive attempts to pull together all of the various agencies and institutions involved in science and technology policy. Several of these attempts will be detailed in this paper. Still, no one body has gained overriding control over all scientific and technological affairs.

- ³ This was clearly not the only problem in the US economy of the late 1970s, and no policy maker from the period argued it was. However, the notion that science was an untapped resource was a common sentiment and there was hope that a number of the major problems plaguing the economy had technological fixes (e.g., the oil crisis, the quality crisis in manufacturing, productivity).
- ⁴ The notion of research productivity fits into a nearly obsessive concern with productivity in general. This issue was ubiquitous in industrial policy during the 1960s and 70s. However, the notion of research productivity posed special problems in how to relate money spent on research to long-term economic goals.
- ⁵ In *Forged Consensus*, David Hart sees the renewed economic emphasis on technological innovation in the 1980s as part of a new, explicitly civilian industrial policy, advanced as an alternative to “Reaganomics” (see Hart 1998, p. 227).
- ⁶ The Rule of Reason requires that both harmful and beneficial effects of the cooperative effort be examined. Antitrust proceedings will begin only if the analysis shows that the potential harm outpaces the benefits to the industry and market.
- ⁷ Despite the orientation of these policies, it is important to realize that private-public research partnerships predate this legislation by at least a century – perhaps much longer than that. Universities and private companies were doing collaborative research in the 19th century in the US and in Europe. There are countless incidences of other private public research partnerships before the 1980s (such as DuPont’s work with Oak Ridge during the Manhattan Project). However, FTTA looked to encourage these partnerships with a renewed vigor. For earlier examples of private-public research partnerships, see Nathan Rosenberg & David Mowery’s *Paths of Innovation*.
- ⁸ Nanotechnology projects have been a part of the ATP from its inception.
- ⁹ Nowhere in this paper do I want to imply that an economic justification for science and technology was a new idea in the 1990s – clearly it is one of the oldest justifications. However, I do argue that, in the 1990s, the economic justification of science became much more direct and public. Furthermore, my argument here is about *perceptions* of what science could and should be doing, not some objective, philosophical claim about what science was “really” about. I also am wary of claiming (naively) that there are clear distinctions in the kinds of science supportable by the new regime of science for economic benefit. In fact, claiming that a particular body of research would play an important economic role was often a rhetorical choice more than an issue of what was happening in the lab. Still, there were real effects to what kind of work scientists chose to do.
- ¹⁰ However, Clinton specifically points out differences between his vision and Bush’s, claiming to “acknowledge an intimate relationship between basic research, applied research, and technology, appreciate that progress in any one depends on advances in the others and indeed recognize that it is often misleading to label a particular activity as belonging uniquely to one category” (Clinton 1994, p. 5).
- ¹¹ This quote is notable for the directness with which it addresses the economic motives for science. Still, it is a peculiar claim. Although Gore refers to an ecosystem, the engine analogy seems linear in the Vannevar Bush sense. This seems to point out the complicated project of justifying non-targeted research in terms of economic goals.
- ¹² PCAST is a non-governmental advisory group that does not require Congressional approval – therefore it operates at a less formal level than the cabinet. Each President must set up and renew the existence of this group – it is not a standing committee. As a result, each administration can rename the organization (calling it variously a council or committee) and then claim to set the group up as though it were new. On the other hand, the NSTC is a standing committee made up of cabinet members with responsibility in science and technology policy matters. These conflicting arrangements add to the multidimensional complexity of US Science and Technology policy.
- ¹³ NIST claims that it made nanotechnology grants as early as 1991, however the bulk of funds have been paid out closer to the end of the decade.
- ¹⁴ ATP has made another \$85.5 million in grants since 2000, an amount that has been matched by industry, as is the guiding principle of the ATP.
- ¹⁵ \$464 Million was actually allocated. Additional agencies have since joined the NNI: EPA, Justice, Transportation, Agriculture, State, Treasury, CIA, and the NRC.
- ¹⁶ Ziman’s reference to the “emergence” of science policy in the Post-Academic regime is troubling, since it implies there was no science policy prior to the 1960s. However, I think he’s trying to emphasize the real partisan political work that science policy does once it moves into the realm of economic justification. Science policy as politics is what emerges, not just science policy. When science was justified militarily, or in the Bush paradigm when it was never directly justified, science policy remained non-partisan and out of the political spotlight.
- ¹⁷ One of the places to quibble with Ziman’s model, and Ziman admits this, is in the comparison of the new Post-Academic model with the older Academic one. Ziman makes a number of generalizations about how science works in the pre-1960 period that many historians of science would disagree with. In his defense, whenever an aggregate model like his is constructed, one of the consequences is to lose touch with the ac-

- tual details of any of the case studies. It is only natural that the model of Academic science (and Post-Academic science, too) doesn't exactly map onto any real example. However to dismiss his model because of these quibbles invites "throwing the baby out with the bathwater".
- ¹⁸ There is a massive historical and philosophical literature about this distinction, which has always been slippery. Many works focus on the labels of "pure" and "applied" as rhetorical tools and as normative rather than accurately descriptive labels. It is in this sense, as well, that Ziman uses the terms. I will discuss this distinction further in the conclusion to this paper.
- ¹⁹ The best recent example is Galison 2003.
- ²⁰ John Gaddis explains, "while context does not directly cause what happens, it can certainly determine consequences" (Gaddis 2002, p. 97).
- ²¹ Of course, I do not imply that nanotechnology alone has these attributes; these are the characteristics Ziman claims for Post-Academic science that cover a much broader array of sciences. But without a new acceptance of these qualities and new social structures for science, these attributes would be disincentives and handicaps.

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Grand Visions and Lilliput Politics: Staging the Exploration of the ‘Endless Frontier’

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Abstract. The paper outlines a sociological analysis of politics and rhetorics accompanying the genesis of nanotechnology as the latest research policy priority. It gives an account of certain traits and events linked to the NNI initiative, being conceived of as ‘gatekeeping activities’ in relation to its emerging societal agenda. Further, it demonstrates how these become permeated by the self-replication controversy. In an attempt to situate the present appropriation of ‘nano’ also in a wider transformation, the paper proceeds by taking stock of the changing science-society relations. It reviews in passing some of the current debates on the new mode of knowledge production and the heralding of a ‘scientific citizenship’.

1. Navigating the ‘Spaces between’

“As ‘the Hermes of modern scholarships’ (*i.e.* a prominent interpreter of mediation, translation and multiplicity), the French philosopher Michel Serres has made the quest for connections between science and the humanities his lifelong mission.”¹ There is in his understanding nothing like a smooth ‘interface’ between those two domains of human knowledge. There is sometimes communication, but also non-communication and static. Pursuing this, Serres has set himself the task of exploring landscapes which are rough, variable, baffling; where there are interesting ‘spaces between’. The rough and unruly conditions of the North-West Passage here provide the key metaphor: “Between the hard sciences and the so-called human sciences the passage resembles a jagged shore, sprinkled with ice, and variable” (Serres 1981).

At the present stage of technoscience, sociologists, philosophers, ethicists and historians of science are to an increasing extent invited to set up or accompany expeditions heading towards those rough waters where nature and culture intersect. This can be traced back to a widened political recognition of the importance to open ‘Pandora’s Box of Science and Technology’ before its stream of inventions is released to transform society on a full-scale. As an example for the broad-based demonstration of a new prospective policy, one could think here of the political mobilization in recent years for investigation and control of the nanoscale.

Whereas uncertainty, irregularities, and unexpected fractures permeate Serres’ North-West Passage, the nano policies now launched by politicians, civil servants and other stakeholders are fueled by visions of smoothness and reliable navigation to safely steer clear of obstacles. The architects of current initiatives confidently declare that this time we will avoid future frictions, controversies and outbursts of public mistrust of science (such as

those experienced by geneticists or nuclear scientists) by “making everything right from the start”.

Serres’ metaphor may serve, I suggest, as a useful antidote to the current public and media appropriation of ‘nano’. Although playing down roughness and glossing over unruly conditions may be inherent features of the political naiveté accommodating contemporary ‘hypes’ around emerging technologies, they should not be allowed too much leeway when it comes to the scholarly accounts of the intersections between the sciences and the humanities. No matter how very desirable smooth interfaces sometimes may appear, it remains the critical task of social scientists to recognize the existence and implications of ‘the spaces between’.

From here, the paper proceeds as follows. As a first destination, some of the politics and rhetorics accompanying the genesis of the American National Nanotechnology Initiative (NNI) will be visited. This will therefore be about ‘bringing nano in’, or – echoing Coffin and King’s smashing hit back in 1962 – about the invention of ‘the Roco-motion’.² The next destination is the specific outgrowth of the NNI where the so-called ‘societal implications’ of ‘nano’ are to be looked into further. I am going to ask how this came about in the first place, but will also raise the more impertinent but still largely open question what kind of activities will be judged as appropriate in that realm, or: who will be allowed in there? In doing that, I will describe in some detail certain ‘gatekeeping activities’ that are safeguarding this new policy, including an attempt to reconstruct the key controversy underpinning this micropolitics.

Next there will be a short tour through some of the current debate on the science-society relation, by some referred to as the changing ‘mode of knowledge production’. Certain social science constructs such as ‘the public understanding of science’ and ‘scientific citizenship’ will be introduced in an attempt to situate the present appropriation of ‘nano’ in a wider socio-political transformation. I finish this part by elaborating a bit the idea that for contemporary technoscience the so-called ‘context of *implication*’ is becoming as important as the ‘context of *application*’. That offer links back to Serres, while also serving as a bridge to my sketch of things to consider when setting out to ‘discover the nanoscale’.

2. Bringing ‘Nano’ in (the Invention of ‘the Roco-motion’)

“We offer next to nothing”, reads the text on a poster facing those who enter the spacious hall of the new Nanoelectronics Centre at Chalmers Institute of Technology in Göteborg, housing one of the most advanced laboratories for nanometer-based research in Europe. That makes a good joke of course, a witty reference to the fact that just about everything in this minutely vibration-protected building, is under a spell of processes taking place at a scale 80000 times smaller than the width of a human hair. Also, anyone familiar with the recent flood of nano rhetorics can read the irony of that poster, since what indeed is being offered in this current outbreak of ‘techno-babble’ comes much closer to ‘next to everything’ than ‘next to nothing’.

The stunning political success of the NNI has been embedded in rhetorics zigzagging between ‘the glorious past’ and ‘the unique opportunity of today’. In the extensive material gathered during a series of workshops, there are references to legends like Vannevar Bush and his famous manifesto from the 1940s (Bush 1945), and to academic champions like Richard Feynman. But above all, it is humankind’s present predicament which is said to require extraordinary action and commitment. Almost like a mantra, phrases are repeated such as “We are in an Age of Transitions, when we must move forward if we are not to fall behind”. One here walks down a well-known road by claiming modern societies’ dependence on scientists’ authoritative knowledge to sustain its citizens’ welfare. Beyond that, one also embraces the idea that at certain points in history – such as this one – scientists have to

shoulder our common fate by grappling with risks: “At times, scientists should take great intellectual risks, exploring unusual and even unreasonable ideas, because the scientific method for testing theories empirically can ultimately distinguish the good ideas from the bad ones” (Roco 2001).

The grandiose scope of the NNI was from its outset manifested as nine ‘Grand Challenges’, wrapped in ‘airy’ and clearly under-socialized technological visions. Certainly this is no new phenomenon in conjunction with science policy. One could think of it as a necessary playing to the gallery, instrumental in drawing public attention to a new candidate for the policy top of the charts. In this case, however, instead of moderating the hype once the money was there, one escalated it. In December 2001, NNI-general Roco with the help of experts gathered for a workshop, to further inflate his *bella donna*. As the building blocks for all sciences are to be found at the nanoscale, one could, those experts claimed, by pulling down the barriers between the major provinces of contemporary science, accomplish radical improvements in human life. By chance, these provinces coincided with the four invogue areas *nano-bio-info-cogno*. Instead of four potent provinces there now came forth a fully irresistible NBIC empire. Only shortly after its public launch as the new ‘endless frontier’ then, ‘nano’ was recast as merely the precursor for the ultimate ‘endless-ness’ of the scientific endeavor (Roco & Bainbridge 2002).

The ‘NBIC’-vision at once is making all scientific progress up to now look rather pale in comparison. ‘Lilliput Politics’ is clearly ‘Grand Politics’, and vice versa. There is simply no limit to what utopian qualities the synergistic combination of the NBIC provinces can add to the yet so imperfect world, to how truly powerfully they will be able to energize one another:

Entirely new categories of materials, devices and systems for use in manufacturing, construction, transportation, medicine, emerging technologies, and scientific research [...] engineered biological processes to manufacture valuable new materials [...] a union of nanotechnology, biotechnology and computer science may be able to create “bio-nano processors” for programming complex biological pathways on a chip that mimic cellular processes. Virtual reality and augmented reality computer technology will allow scientists to visualize the cell from inside, and to see exactly what they are doing as they manipulate individual protein molecules and cellular nanostructures. [...] a ubiquitous network that collects and offers diverse kinds of information in multiple modalities, every-where and instantly at any moment. (Roco & Bainbridge, 2002, p. 10)

Mastering molecular matters then, becomes a matter of empowering ourselves to be able to do whatever we can think of wanting to do. The alchemists after all got it right, only they didn’t have the Dream Team we now have; a team saluted with a slogan by one of the participants of the NBIC workshop:

If the *Cognitive Scientists* can think it
the *Nano people* can build it
the *Bio people* can implement it, and
the *IT people* can monitor and control it. (Roco & Bainbridge, 2002, p. 11)

In a study of the remarkable biotechnology advance of the 1990s, Herbert Gottweis applies what he refers to as ‘a poststructural analysis of policymaking and policy texts’. Traditionally, policy has been regarded within the frame of a realist epistemology which views policymaking as a struggle between rational actors, or as determined by institutional structures. By contrast, Gottweis puts forward an understanding of it as essentially constituted by narratives, which rhetorically stand for the interests of various groups in policymaking. Hence, in making objects governable, policy narratives draw their language from ‘political metanarratives’ such as modernization or international competition (Gottweis 1998).

Gottweis further proposed that science policy constructed from such rhetorical resources is successful only to the extent that it operates by also incorporating conflicting ideas as forms of legitimate difference. If it fails in doing so, public concerns developing into counter-narratives threaten to undermine the stability of policy decisions. Gottweis further claims that scientific language itself is metaphoric, symbolic and even poetic, and that it can be exploited as such. Symbolic objects like the gene, which are made only more multivalent as a result of their ‘governability’, thus participate in the process of surplus value production. This bears a close resemblance to the ideas on ‘genetic fetishism’ by science historian Donna Haraway: a relationship between human and nonhuman actors in a scientific network becomes mistaken for an unambiguous and ‘corporeal’ truth about ‘life itself’ (Haraway 1997, pp. 141-148).

A similar framing could, I argue, become of interest also for our attempts to approach the ongoing public reception and exploitation of ‘the nanoscale’. How will ‘governability’ be produced in this field? What potent ‘symbolic objects’ could there be within nanoscience that are ready to become enrolled in metanarratives, and is there anything like a ‘molecular fetishism’ analogous to Haraway’s genetic fetishism? And, in a more self-critical vein: to what extent and in what capacities can one expect social scientists to take part, and become co-opted by, a flourishing trade of nano narratives and nano counternarratives?

3. Making Nano ‘Bene’: The Societal Implications Thrust Area (SITA)

In addition to the ‘Grand Challenges’, NNI was composed of the ‘Fundamental Research’, ‘Centres and Networks of Excellence’, and ‘Research Infrastructure’ subprograms, and then also of the much more novel funding construct “Societal Implications and Workforce Education and Training” (NNI 2000a, pp. 11-13). 5-6% of the total NNI budget was allocated for this NSF-based construction of an annex to the nano skyscraper that was being built. Why did this extension of the standard policy toolbox come about in the first place?

Well, there has been no mystery or hush-hush whatsoever concerning that. The annex is there because of the determination of the NNI strategists not to repeat the mistakes of others. Neither are there any doubts about who those “others” are. They are the geneticists, being thought of as a troop of scientists badly suffering the consequences of failing to prepare for the societal reception of their research. The physical sciences have, as Eitzkowitz has expressed the motives of the skyscraper constructors, “a need to find a way to emulate the success of the life sciences while avoiding the ethical and social problems that have emerged as genetically modified organisms hit the market” (Eitzkowitz 2001). When a committee two years ago was given the assignment to assess the initial phase of NNI, the fifth subprogram was pointed out as an indispensable component of NNI (NRC 2002). It was at the same time relabeled as ‘the societal implications thrust arena’, or ‘SITA’.³

The first two years of SITA activities (starting in September 2000) produced rather disparate and ad-hoc attempts to grasp the social problematic. Rather than develop social science informed approaches, the initial workshops invited any participant not suffering from too much self-criticism to fill the vacant construct ‘societal implications’ with any non-technical issue or more or less mundane management problem they could come up with. Those in charge of the SITA site were either committed not to bring mainstream social science into play, or did not know how to do so systematically.

Were it not for the later inclusion of certain solid academic initiatives such as ‘NIRT’⁴, one could have ended up as manufacturers of some wishy-washy SITA-styled copies of the real thing – of ‘Social Science Light-products’, if you like. Or, employing a more nano-tuned metaphor: by coating the skyscraper with thin layers of societal, ethical and cultural concerns, one seemed to side with the macro-political calculation that it will acquire new properties and come out as more socially robust. As long as certain rules-of-

conduct were obeyed, and as long as those obeying them were people in possession of the proper credentials (academic, industrial, or political ones), any statement even if only remotely related to ‘societal implications’ was embraced as good as any other.

However, the conditional clause is important to notice here. The first few years of SITA exercises were in many ways open-minded and transparent, but in parallel some ‘gatekeeping’ also took place. Setting themselves the task of investigating the genesis of a new policy frontier of technoscience, philosophers, historians and social scientists have a specific obligation to further reflect upon gatekeeping activities. After all, by establishing and guarding the rules of access and authorization, such activities set the tone of how to frame the social here: at the point when the scientific nano community crosses the threshold of ‘bringing visibility to the invisible’, what can become voiced and made publicly and politically visible in the first place?

4. Gatekeeping at the Lowest (10^{-9}) Level (a Prolonged Social Drama)

In 2002 at a joint EU/NSF workshop in Italy, the American sociologist Mark Suchman initiated a discussion about the relation of nanotechnology to what he called ‘governance regimes’ which are defined as “the laws, rules and norms by which society manages interdependence and vulnerability” (Suchman 2002). Is there reason to believe, he asked, that this emerging technology poses any radical challenges to those regimes as we know them?

To come to grips with this, Suchman suggested one should first distinguish between issues concerning nano-materials and issues concerning nano-machinery, defined as follows:

Nanomaterials arise from the manipulation of the nano-scale structure of macro-scale substances. It could for *e.g.* be wear-resistant polymers for tires, super-hard ceramics for drill bits, or ultra-fine membranes for filters. Nanotechnology is here primarily linked to chemical engineering and materials science.

Nano-machines concern technologies of constructing nano-scale devices for operation in macro-scale environments; *e.g.* ultra-small in-vivo medical devices, miniaturized surveillance systems, or lilliputian mining and manufacturing equipment. This links nanotechnology to mechanical engineering and robotics.

Suchman argued that the enhanced performance of nano-materials does not in itself pose unprecedented challenges to society. Their potential is not a new phenomenon as mankind has developed many other transformative compounds, from glass to gasoline to plastic. Although nanomaterials may in some respects become revolutionary, they will still be “revolutionary in relatively familiar ways” (Suchman 2002, p. 96). Policy issues will arise from the performance of particular products, not from the inherent nature of nanotechnology per se. Case-by-case planning will represent a sufficient response. Applications are not likely to arrive any more simultaneously than those of, *e.g.*, semiconductors, synthetic polymers, or wireless telecommunications.

By contrast, when it comes to nano-machinery, Suchman’s standpoint was that it threatens to confront society with policy issues which are as unprecedented as they are profound; it opens up “a genuinely new frontier”. There are, he declared (by paraphrasing Feynman), “very few sheriffs at the bottom, to keep that room safe and productive” (Suchman 2002, p. 97). As currently envisioned, nano-machines would possess at least three distinctive properties each of which would generate novel issues of responsibility and control:

Invisibility: nano-machines would be among the first complex constructions intentionally engineered to accomplish human purposes at a microscopic level, and their

introduction into the technological armory would dramatically increase the potential for orchestrated covert activities;

Micro-locomotion: (the ability to move through and within macroscopically solid matter): free ranging nano-machines will radically challenge our traditional understandings of macro-boundaries and barriers; fences, walls and even human skin are largely open space, at the nano-scale;

Self-replication: as difficult as it may be to realize as of yet, self-replication will be a common attribute for any nanotech production passing market conditions, thus becoming socially significant; it poses profound challenges to human foresight and control, since without a carefully designed ready 'off switch', a population of self-replicating nano-machines could grow exponentially. (Suchman 2002, p. 97)

When introducing the proceedings published from this workshop, this line of thought was reviewed by the founder of the Roco-motion himself. After quoting the three traits of nano-machinery depicted as reasons for a deeper concern, the NSF official refuted Suchman by establishing:

None of this exists. Literature reports new theoretically possible lifeforms, autonomous and self-replicating, but this is only science fiction. [...] Moreover, the three above-mentioned characteristics refer to carbon-based chemistry, being e.g. relevant to viruses and studied under genomics. Thus, nanotechnology tools and approaches may be adopted, but substantially these aspects stay outside the development of nanotechnology as we intend it. (Roco 2002, p. 23)

This, in my eyes, reads like a rather remarkable piece of polemics. Maybe it is just a slip of the pen, or a bad day at work. It anyhow seems rather strange stating that 'none of this exists', when two of the three characteristics referred to are obviously inherent in the very definition of 'nano', and the third (self-replication), as pointed out by Feynman already, simply is a 'must' if nano is going to carry any significance for full-scale production. If you assure us it does not exist, some 80% or so of the grandiose NNI rhetorics vanish as well; and Roco would have to resign as the reigning nano policy champion, confessing he was never anything else but a (civil servant) top salesman of good old materials science and electronics, jazzed-up a bit.

According to my bluntly 'psychologizing' interpretation of this episode, a third person entered Roco's mind when he was faced with the word 'self-replication' in Suchman's paper, namely an 'enfant terrible' who was not wanted there – Bill Joy. Just a few months before the very first 'SITA' meeting, Joy had published an article launching a major attack on current technological development for being hazardous and way ahead of our ability to safely control the things we innovate. He specifically pointed out the risks of atom-sized self-replicating nano-machines ('nanobots'), and argued for a general moratorium (Joy 2000).

Bill Joy touched a sore spot, of course, and did so right on the eve of something big. In principle though, his unexpected attack offered the best of opportunities to test the NNI guidelines for 'how to cope with public reactions' that were outlined in the program declarations. They prescribed that one should adopt an open, liberal and rational attitude; something like 'no bans and no blinders, instead: include, listen, analyze and learn'. But that was not exactly how Joy's ideas in fact were dealt with during SITA's opening workshop.

Hence, several of its participants devoted the larger share of their presentations to the refutation of all the major elements of Joy's dystopian analysis. Attracting the greatest attention perhaps, Nobel Laureate in nano chemistry Richard Smalley used most of his time to outline his 'fat and sticky fingers rebuttal' of nanotechnology's alleged risks (see below).⁵ Throughout the conference Joy came to serve as something of a joke, really, although quite an annoying one. I heard no one trying to analyze *why* it was that he had come up

with such a hair-raiser. After all, being a respected expert himself, Joy was not exactly the madcap or nerd type of guy.

There seem to have been two programs operating in parallel here. One prescribes ‘listen emphatically to everybody’, and try to grasp the wider context and motives explaining a person’s views – that is, the official SITA rule-of-conduct. Then there is a second *unauthorized* program saying that it is sometimes okay to skip that empathy a bit, and go straight to the arguments, and if you don’t fancy them, please feel free to smash them into pieces. Actually, an informal authorization was given to this approach during that first workshop, when one participant to the obvious liking of many of the present SITA colonists frankly stated: “The rub in exploring the borderlands is finding that balance between being open-minded enough to accept radical new ideas, but not so open-minded that your brains fall out!”

I suggest that Roco when again reading about ‘self-replicating’ somehow recalled this event, that he became ‘Joy-phobic’ and did not manage to keep up the broad-minded approach when commenting upon Suchman’s in fact not so very provocative piece.⁶ If that really was part of a general strategy (or instinct, for that matter) by the NNI coordinator to nip in the bud any radical anxiety associated with nano technology, then ‘reality’ has not been particularly nice to him ever since he slammed shut that door.

First, it was reopened by Pat Mooney at a prestigious conference on ‘Sustainability in a Global Perspective’ in Stockholm. The head of the ETC group unleashed a storm of radical nano critique, in relation to which Suchman (and even Joy) stands out merely as a subtle breeze.⁷ Next, the American science fiction and screenwriter Michael Crichton served the same purpose by publishing his novel *Prey* (Crichton 2002); and then in 2003, believe it or not, Prince Charles ended centuries of absence and brought royalty back into the business of science politics through his ‘Grey Goo Alarm’.⁸ So there certainly seem to be many more Joy-boys ‘out there’; apparently risking their brains to fall out...

With all due respect for the knowledge and dedication of these people (including, of course, His Royal Highness), they are still not representing the front-line in this combat. As suggested already, Roco’s harsh rebuttal of Suchman seemed to be modeled after Smalley’s treatment of Joy two years earlier. Although Joy at that time was the official target, it is hard to escape the conclusion that Smalley, when claiming that self-replication was impossible because nature itself does not provide enough room at the nanoscale for the plethora of ‘fingers’ that this would require, was also addressing someone who argued something very similar 41 years earlier – the legendary physicist Richard Feynman.

There is a slight problem here, namely that two highly prominent scientists in making a similar inquiry whether replicating things at the nanoscale is feasible or not, arrived at exactly the opposite conclusion. Indeed, Feynman’s speech and paper in 1959 was called ‘There is plenty of room at the bottom’ (Feynman 1959). Why is that a problem? Surely it is not forbidden nor uncommon that one Nobel laureate rebuts another; in fact, having done so convincingly on some important issue, is often exactly why he or she is awarded the prize.

The problem is a different one. It concerns the overall legitimation for the current level of government spending on nanoresearch. Before this boom there were already innovative areas within, *e.g.*, materials science and microelectronics with the potential to produce nanoscale knowledge advancing the engineering project. Still, there can be no doubt that ‘the Feynman legacy’ – with its key thesis of the feasibility of human-controlled molecular assembling – provided the basis upon which extensive public promotion of nanotechnology was erected. To corroborate this, there were several references to the Feynman thesis in the public announcement of the NNI by former president Clinton in 2000, as well as in the bulky documentation (much of it written or commissioned by Roco) accompanying its initiation.

This of course does not impose any obligation on Smalley to be loyal. Notwithstanding his position as one of the major beneficiaries of the program, he could as a 'free academic' still choose to call into question the legacy of the field's intellectual founding father. But, there is here another component, perhaps causing a problem for Smalley. Hence, to judge from his public statements on the self-replication thesis from 1999-2003, there seems to be a certain lack of consistency in his arguments. Appearing before the US Senate in 1999, and more recently in a talk before a White House Council (Smalley 2003), he endorsed the Feynman thesis from 1959. On various occasions apart from the one cited above he refuted it quite energetically.

To no surprise for those monitoring nanotechnology also long before Clinton lent it public fame, there is one person, in particular, who has been carefully monitoring Smalley's positions on this issue. This someone is not an observer like anyone else, but a key player, in fact the third link in the front-line of this controversy: K. Eric Drexler. He is the person who can lay claim to having first drawn attention to Feynman's radical molecular manufacturing vision by publishing *Engines of Creation* in 1986. Smalley has, of course, been fully aware of Drexler's position as the prime spokesperson for the grandiose potential of nanotechnology. After having 'rehearsed' his lines by taking on Joy at that SITA opening workshop, he directly addressed Drexler and the Feynman thesis which "has inspired the nanotechnologists everywhere" in the following year in a widely read journal (Smalley 2001).

According to Smalley, for self-replication to take place at the nanoscale, the small assemblers (also 'nano-machines', 'manipulators', 'nanobots') which are to perform that task must have 'many tiny fingers' – to be precise, one per moving atom. With all the manipulators needed to have complete precision in and control over the chemistry, assembling 'atom-by-atom' as it were, these tiny fingers amount to such a great number that there isn't enough room in the nanometer-size region to accommodate them. Self-replication is simply impossible in our world, he concluded, adding: "To put every atom in its place – the vision articulated by some nanotechnologists – would require magic fingers."

In an open letter to Smalley in 2003, Drexler rebutted this argument. He denied that the assemblers proposed by himself and others during two decades of work on molecular manufacturing have or need those 'Smalley fingers' (Drexler 2003a, p. 1). Accordingly, all the problems with 'fat fingers' and 'sticky fingers' dwelled upon in Smalley's argumentation are of no relevance whatsoever. Not only does Drexler here accuse his critic for repeatedly having "publicly misrepresented my work"; he also constructs a 'straw man', one which he then goes on to attack.

Recently, Drexler essentially repeated this rebuttal of Smalley. This time, however, he devoted more space to demonstrate that not only has he been misrepresented, but also Feynman and his famous 1959 thesis (labeled 'the original nanotechnology vision' in an NNI promotional brochure from 1999). Feynman, he emphasized, never assumed or talked of any need to "separately grab and guide many neighboring atoms simultaneously" (Drexler 2003b). His thesis hence cannot be affected by any Smalley fingers. In response to the Nobel laureate chemist's denial of Feynman's core claim ("There's plenty of room at the bottom.' But there's not *that* much room." [Smalley 2001]), Drexler insisted: "The Feynman thesis stands."

Drexler also elaborated on the 'pattern of ambiguity or inconstancy' in Smalley's public appearances; the one I cited above. By comparing excerpts from several speeches and relating those to the different contexts within which they were given, Drexler seeks to demonstrate the variability in Smalley's positions regarding the original nanotechnology thesis, accusing him of engaging in 'promotional rhetoric' (Drexler 2003b, p. 6). Further, he ascribes the worry for a backlash as the motive for this engagement, quoting his combat-

ant: “we should not let this fuzzy-minded nightmare dream scare us away from nanotechnology” (Smalley 2000, p. 116).

The price that Smalley has to pay to extinguish this nightmare – namely to proclaim Feynman’s thesis false – is not only unacceptable for Drexler (to him, this thesis *is* nanotechnology). He also finds the very idea of trying to calm public fears misguided and dangerous. Ever since reintroducing Feynman’s vision in 1986, he has maintained that molecular manufacturing based on the nanomachinery of living systems is “a technology of unprecedented power” and always associated with “commensurate dangers and opportunities” (e.g., Drexler 2003b, p. 2). Both should be addressed. Nanoreplicators are feasible, thus their control is a most legitimate concern. Drexler finishes off his rally by charging that Smalley is getting himself into deep water:

Continued attempts to calm public fears by denying the feasibility of molecular manufacturing and nanoreplicators would inevitably fail, placing the entire field calling itself ‘nanotechnology’ at risk of a destructive backlash. (Drexler 2003b, p. 8)

I have no intention to intervene in this controversy “itself”, *i.e.*, by taking a position myself on whether self-replication is feasible or not. I lack the natural science background needed, and I lack the motive for doing so, as this is an outline of the *social* framing of the problem. Things are a little different when it comes to Drexler’s second point, Smalley’s alleged inconstancy. It is true that my illiteracy could also play a part here by impairing my ability to judge whether the positions taken are as incompatible as Drexler claims. On the other hand, those speeches address ‘the public’ which include me as a layperson in relation to natural science. So, here my view at least should count. This view is also informed in the sense that I have studied the documents fairly close; and I have already indicated that inconsistency is also my ‘verdict’.

As regards Drexler’s third point, namely how to act in relation to public worries on science-related risks, I can lay claims of having some expertise, since my academic field (Science and Technology Studies – STS) represents quite some work on that. In the light of those findings, I would argue that Drexler’s message to Smalley is very much ‘on track’. His point that public concerns cannot be suppressed by denying any rational reason for them is empirically well-founded. Anyone following the ‘infected’ debates related to bioscience during the last decade could confirm this. Smalley’s standpoint on how to kill off fuzzy-minded nightmares appears out-of-date. By contrast, Drexler practiced deliberate forms of knowledge production long before they became ‘politically correct’: along with his appropriation of Feynman’s legacy in the mid 80ies, he founded the Foresight Institute to organize workshops, chat groups, newsletters, etc, focusing on the wider societal, political and ethical implications of nano technology (including dystopian ones such as uncontrollable ‘nanobots’).

Bringing this section to a conclusion, I will recapitulate the controversy not so much in the idealistic or pure terms in which scientists tend to represent themselves, but instead as the staging of what anthropologists sometimes call ‘a social drama’. It all started when Smalley, after having smashed Joy’s appeal into pieces, decided to also take on Drexler, and indirectly Feynman himself. As these two were already symbolically present during his attack on Joy, one could say in favor of Smalley that it was ‘intellectually honest’ of him not to stop his rebuttal short of the real targets. And he did what he had decided to do with great force.

Consider for example the metaphorical language he mobilized, the one involving ‘fat and sticky fingers’ (those which Drexler with contempt refers to as ‘the Smalley fingers’). That language vigorously conveys the message that there is a true drama taking place at the very core of nature. My God! – it’s just everywhere around us, in the inner realms of every element of our physical world. Although we cannot actually see them, there are here lots

and lots of fingers, unruly and adhesive fingers which constantly stick fast to each other, creating a muddle of everything. Not only do the atoms and molecules inhabiting that chaos get captured by heaps of entangled tiny fingers. They at the same time ensnare those humans who by their scientific imagination inhabit this place: the famous Feynman and Drexler, his controversial disciple of our days. It threatens to suffocate not only them, but at once also their vision of a giant leap forward for one of mankind's proudest creations: engineering.⁹

As dramatic and powerful as this may seem, critical questions whether Smalley created something of a mess for himself pop up. First, he has come out in public as having contradicted himself, on a point fundamental for the nano mobilization policy to which he has been committed for the last few years. Secondly, I suggest that he might have missed a good opportunity here. If the major motive behind his engagement has been his worry that significant obstacles might be imposed on the nanoscience community, then, instead of getting a public controversy going, Smalley could have been more efficient by approaching Drexler as a potential ally; 'politically', although not scientifically.

The catch here is that although Drexler and Joy make bedfellows when it comes to their belief in self-replication as a real possibility, they certainly do not when it comes to the implication of that. Whereas the latter argued for a moratorium, Drexler has for many years advocated full speed ahead, both when it comes to developing the technology *and* when it comes to scrutinizing the ugly sides of molecular self-assembly. He represents a third position here, different from Smalley's siding with the traditional (default) option to sweep uncomfortable stuff under the carpet, and from Bill Joy's 'agonistic' advice to force scientists to put on the brakes.

As Smalley staged the social drama, this third option was 'sacrificed' for the sake of a public scientific controversy, perhaps right at the point when it was most called for. No doubt he stands more than a fair chance of coming out as the winner of the rally; if not for the superiority of his scientific arguments, but because of the great suspicion that his antagonist has encountered from the science community long before this particular drama already (Fogelberg & Glimell 2003). However, the choice in this case may not be between winning and losing, but between victory and a Pyrrhic victory. 'Gatekeeping', then, may sound like a straightforward activity, but, apparently, it may soon turn into a rather tricky business; no matter whether those practicing it are clever civil servants or people rewarded the most prestigious of scientific prizes.

5. The Changing Mode of Knowledge Production

Reflections on the present formation of nanotechnology policy can be usefully situated, I suggest, in the vivid research on the changing 'science and public relationship'. What I have brought to attention so far stems exclusively from American events, but the ideas below are mainly of European origin. They are part of a general debate rather than specifically related to how nano policies evolve in Europe (an account of which is outside the scope of this paper). Nonetheless, the connection between this section and the former ones may not be that far off. Already joint EU/NSF workshops have been arranged, catalyzing perhaps the advent of a 'euro-roco-motion'. What now follows could therefore be read as an act of stocktaking preparing for the encounter of that hybrid with European political traditions.¹⁰

A recurrent claim in the current debate is that we are witnessing the emergence of a new mode of knowledge production. Science and society are understood to be accelerating towards each other rendering conventional ways of analyzing them in isolation from one another irrelevant. The distance between science and society collapses into their mutual embrace and varying depths of entanglement (Elam & Bertilsson 2003). This new intimacy

has been described as, *e.g.*, evolving practices of ‘*contextualized knowledge production*’ (Gibbons et al 1994), an all-inclusive engagement in ‘*collective experiment*’ (Callon 1999), or the defining predicament for ‘*post-normal science*’ (Ravetz 1999). Broader participation means that controversy is just as likely as consensus to come along with innovation. As science helps expand the scale and scope of innovation processes in society, so it helps expand the scale and scope also for potential disagreement. By adding new ingredients to collective experiment, “science does not promise to put an end to politics, it only serves to *enlarge politics further*” (Latour 1998).

The European Union appears to be a governmental context particularly well disposed to the forging of a new ‘social contract’ between science and society. The construction of active forms of ‘*scientific citizenship*’ in support of knowledge-based communities is now gaining recognition as of vital importance for the European project. It can be described as the idea that citizens should not just be generally informed about science, but also actively engaged in the process of scientific and technological change (Irwin 2001). The current interest in scientific citizenship has arisen as the commitment to the ‘Enlightenment model’ of science and society relations has declined. That model postulated that the only scientific citizens are the scientists themselves. For science to produce proper scientific knowledge, it must live in a ‘free state’ or republic, disentangling and purifying itself in a domain apart from the rest of society; a cosmology mirrored as “science is the goose that lays the golden egg, but only under suitably autonomous circumstances” (Elam & Bertilsson 2003).

Also in line with the Enlightenment model, it is only natural that communication between science and society is one-way. First, scientists develop new matters of fact, then others in command of suitable scientific training disseminate these facts to society, without society being given the opportunity to talk back to science. As the lines of communication between science and society are now subject to radical reconstruction, that regime can be seen to give way to a range of alternatives for the future ‘democratic governance’ of science.

This shift is usually seen as synonymous with the development of the Public Understanding of Science (PUS) movement, establishing itself some ten years ago. Innovations which should have found a place in society as a matter of course were seen as being blocked by ignorant and irrational patterns of resistance. The solution to this stalemate was to focus on ‘science literacy’. PUS was to engage in a missionary work into the everyday lives of ordinary citizens enabling them to gradually acquire an enlarged, but still restricted, scientific citizenship.

In recent years, the PUS movement has become more prepared to take seriously a lack of public confidence in science and technology. From fighting public ignorance and resistance, it is gradually rededicating itself to the task of securing public *consent* for the carrying out of radical new science-based combinations. PUS also increasingly is associated with deliberative modes of democracy originating out of the work of Jürgen Habermas and John Rawls:

The ideals of equality between scientists and non-scientists and of informed public debate as the preconditions for forging socially sustainable public policies need to be translated into new processes of deliberative democracy. (Durant 1999, p. 317)

Deliberative democracy is here viewed as a science-friendly model of democracy; one which scientists can embrace not only because it helps make science more democratic, but also because it helps make democracy more scientific. However, the suspicion has also been voiced that by producing ‘better’ citizens through experiments that value rationality, deliberative democracy is a politics played out on the scientists’ home turf. It can be accused of promoting a vision of innovations without real adversaries. This speaks against the cultural logic of democratic politics. It abstracts ‘the political’ out of politics, implying that

conflicts can be reduced to a competition of interests that can be harmonized through rational argumentation (Mouffe 2000). A strong reliance on deliberative fora to the exclusion of other forms of political expression in the construction of virtuous scientific citizens, may prove counter-productive in the long run. Tools of deliberation will be turned into tools of hegemony, not of rationality.

In a similar vein, Sheila Jasanoff has recently discussed the dedication of producing consent in relation to risks (Jasanoff 2002). She notices that even in the adversarial US environment, there has been an eagerness for processes such as consensus conferences to foster cooperation among disparate parties – ‘Getting to yes’ has become a paramount goal. But as uncertainties mount and as science impinges upon the most intimate, even sacred, aspects of human life, it is no longer wise to assume that societies will or should always agree upon the instruments of governance. Jasanoff argues that, instead, a diversity of approaches can acknowledge that within modernity’s complex socio-technical formations, safety comes from the heterogeneity of our accommodations with risk. Rather than seeking consensus, it may be more fruitful for authorities to learn how to foster ‘informed dissent’ about risk among knowledgeable publics.

According to Jasanoff, much of the analytical ingenuity of science policy has been directed toward devising predictive methods like risk assessment, cost-benefit analysis or climate modeling. For her, these represent ‘*technologies of hubris*’, achieving their power through claims of objectivity and by systematically overstating what is known about risks while downplaying uncertainty and conflict. There is instead a need for ‘*technologies of humility*’, capable of incorporating unforeseen consequences, plural viewpoints and mutual learning.

Another strand of thinking that bears a relation to Jasanoff’s argument is Michel Gibbons’ discussion about the distinction between ‘context of application’ (c-o-a) and ‘context of implication’ (c-o-i) (Gibbons 1999, Nowotny *et al.* 2001). ‘Contextualization’, he claims, is at the core of what ‘rethinking science’ is all about; denoting an endeavor that must embrace the planned or predictable applications of scientific research as well as its unknown implications. Thus, if science is to secure a new social contract with society and produce the *socially robust knowledge* which will be required, it must take it upon itself to become fully familiar with the larger ‘c-o-i’ surrounding every major program of science-based innovation. To try to take into account the ‘c-o-i’ of a research area is, Gibbons emphasizes, something very different from coming to terms with its immediate ‘c-o-a’. It typically demands a much more thorough ‘reflexivity’, going far beyond a ‘forward look’ or a ‘technology foresight’ exercise.

Neither Gibbons nor Jasanoff is particularly helpful in guiding us how to actually ‘address the unknown’. Perhaps Gottweis’ method of looking deeper into the narratives and rhetorical resources mobilized in science policymaking here could be of some help for moving from applications to implications. To exemplify, while the so far dominant application orientation of technology assessment has mobilized metanarratives focusing on constructs like prosperity and progress, one could imagine a turn towards contexts of implication to evoke alternative narratives and counternarratives exploring phenomena such as viability and accountability.

Our need for thoroughly reflective practices is of course no news for any ‘true humanist’. It is just that so very little of it has been channeled in the direction of science and technology. Is that really about to change now? Are Gibbons and others in the contemporary debate sensing a significant historical shift, when claiming that contexts-of-implication is what counts from now on? If only some of that would become the case, I imagine that Serres – although fully aware of the difficulties involved – would be pleased after devoting so much effort to prepare for navigating the roaring waters of the North-West Passage. One might also recall here C.P. Snow and his well-known manifesto on the ‘the two cultures’ (Snow 1963). In my reading, and reframing it in Gibbons’ terms, the gap

(Snow 1963). In my reading, and reframing it in Gibbons' terms, the gap depicted by Snow reflected his deep concern over how a 'c-o-a focus' of modern science and technology was about to establish a hegemony, excluding crucial human experiences and values from the agenda. The envisioned 'c-o-i turn' could bring these back to the fore. So Snow would be pleased, too.

Or would he not? Could it be that the current appeal for 'c-o-i' does *not* represent a radical rethinking of the role of science in our society, after all, but that it prescribes instead a way to *preserve* the contextualization of science merely in the limited terms of 'applications'? Is it perhaps in line with what Gottweis talked of, namely the incorporation of conflicting ideas as forms of legitimate difference – in other words, developing 'c-o-i' analyses in terms determined by the old 'c-o-a establishment'? Without surrendering to cynicism, social scientists have to be open also to this possibility; remaining essentially skeptical or methodologically agnostic when investigating the motives of new policies and practices.

6. Rounding-off: Discovering the Nanoscale while Constructing it

Adding the last piece to this nano mosaic, I will expand a bit my last commentary on the role of the social scientist. Again I will draw on a typology put forward by Mark Suchman, this time categorizing four policy agendas or ambitions for social studies of nanotechnology:

The most modest agenda is simply *observation*, carefully tracking the emerging field and cataloging its impacts, without necessarily intervening to divert its course. Somewhat more actively, social science might facilitate *communication*, allowing nanoscience researchers to explain technical capabilities and limitations to the general public and, equally importantly, allowing the general public to explain social needs and concerns to the research community. Building on both observation and communication, social science might also assist in *remediation*, helping to control and repair any undesirable side-effects of the nanotechnology enterprise before they become too severe. Finally, and most ambitiously, sound social research might actually encourage creative *restructuring*, taking advantage of the sweeping novelty of nanotechnology in order to envision new social institutions – laboratories, disciplines, firms, markets, professions, and states – that would be more flexible, open and egalitarian than the old regimes that they would replace. (Suchman 2002, p. 99)

As Suchman himself underlines, these agendas are interrelated, and accordingly the boundaries between them could easily become blurred. Although the model holds the first two agendas to be 'modest' ones, whereas the last two are more 'ambitious', this is not necessarily how they always come out. Being affiliated with the constructivist science studies tradition, I could testify that 'observation', the most modest one of the four agendas, indeed can be perceived as not only immodest sometimes, but highly controversial (compare the 'Science Wars' triggered by observations of how the 'politics of epistemology' permeate also the sacred core of science).

A pragmatic reading of the model, coming dangerously close to an anticlimax perhaps, could suggest that it may anticipate the emergence of different social-science based nano cohorts that group themselves around the foci of observation, communication, remediation, restructuring, while largely developing their own research methodologies. In this paper I tried to draw attention to some highly explicit and some more tacit practices (lumped together as 'Lilliput Politics') that are possibly conditioning or mapping the agendas for those cohorts in the making. Trivial as that may be for many readers, politics is here not confined to a White House or Brussels macro phenomenon. Instead politics is multi-

faceted and kaleidoscopic, extending its presence and impact all the way down to the 10^{-9} -bottom of human knowledge.

Recognizing this, we should be ever so attentive on how the course of politics may affect our various accounts of the nanoscale world. That does not in my thinking imply that those accounts should rest on a moralist or political footing per se. It is both feasible and desirable to pursue a combined approach – where we remain agnostic and symmetrical in designing our investigations, and at the same time ever so sensitive to political processes when reflecting further upon the accounts that are produced by our investigations. That sensitivity must also include ‘the nano imprints’ we ourselves will make. When people from the social or human science camps set out on expeditions to the nanoscale regions they will certainly not merely ‘discover’ those realms of science and its practitioners. They will also construct them while making them visible, which then includes their politics.

Notes

- ¹ Quote from www.nwe.ufl.edu/sls/abstracts/botta.html. See also e.g. Brown, S.D. (2002) and for some abstracted material used: www.studyoftime.org/weiwert/PV_SERR.HTM.
- ² Mihail Roco chairs the National Science and Technology Council’s subcommittee on Nanoscale Science, Engineering and Technology (NSET), and is a Senior Advisor for Nanotechnology at the National Science Foundation. He also directs research opportunities in mechanical and chemical processes, and coordinates the NSF programs on academic liaison with industry (GOALI). Prior to joining the NSF, Roco was Professor of Mechanical Engineering at the University of Kentucky (1981-1995). He is the key architect of the National Nanotechnology Initiative, and coordinated the preparation of the National Science and Technology Council reports on Nanotechnology (NSTC, 1999) and National Nanotechnology Initiative (NSTC, 2000). Roco in 1999 received the U.S. National Society of Professional Engineers and NSF joint award ‘Engineer of the Year’.
- ³ The committee organized by the National Research Council was set up at the request of officials in the White House National Economic Council. SITA was assessed in highly positive terms: “... it may be a policy exercise after which future policy initiatives will be modeled; ... a model for our times. We can use it over and over again if we do it right!” As a field still in its infancy, nanotechnology provides a unique opportunity for developing a fuller understanding of how technical and social systems actually affect each other: “... a relatively small investment in examining societal implications, has the potential for a big payoff.” Source: NRC 2000.
- ⁴ This refers to the NSF-sponsored Nanotechnology and Interdisciplinary Research Initiative at the University of South Carolina in Columbia.
- ⁵ The basic arguments of that rebuttal and the use of the anthropomorphic metaphor ‘finger’ to characterize the manipulator function of the mechanical nano-sized robot implied in self-replication can be traced back to a talk Smalley gave at a conference in Houston, Oct 1996. For more details, see Fogelberg and Glimell 2003, pp. 20-22. (The seminal argument, in Smalley’s own words, is also available online at http://discuss.foresight.org/critmail/sci_nano/4584.html)
- ⁶ This was not entirely so, however. Roco did pay lip service to the SITA rule-of-conduct even while rebutting Suchman. Hence, in between the two strong rejections quoted, *i.e.*, in place of the ellipsis between ‘fiction’ and ‘Moreover’, the missing text should be: “However, sociologists warn that even if the construction of such entities/machines/beings might be impossible, from a sociologist perspective they already ‘exist’. Indeed, the perception of risk can exist even if the risk itself does not, and vice versa. Consequently, analysis and communication based on rationality are indispensable” (Roco 2002, p. 23).
- ⁷ The ETC Group (formerly RAFI) is an international civil society organization based in Winnipeg, Canada. It is dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights. The combined themes of Erosion (cultural as well as environmental); Technology; and Concentration (of corporate power) form the framework for the Group’s work. Its recent report on nanotechnology (ETC 2003) was sponsored by the Dag Hammarskjöld Foundation.
- ⁸ See, e.g., “Brave new world or miniature menace? Why Charles fears grey goo nightmare”, *The Guardian*, April 29, 2003; and “Nanotech Un-goood! Is the Grey/Green Goo Brouhaha the Industry’s Second Blunder?”, *etc group Communique*, July/Aug 2003.
- ⁹ This is not to say of course that Smalley is the only one mobilizing strong or seductive metaphors here; neither Feynman nor Drexler hesitate to draw on one’s imagination. The emotional engagement one can sense in Smalley’s metaphorical language has its equivalence in an emotional reading of Smalley from

Drexler's side. His undisguised feelings of disgust when confronted with 'the tiny fingers theory' erupt, I suggest, out of a profound relationship with the physicist legend on trial here.

¹⁰ For the next few pages I am greatly indebted to Mark Elam. For a more thorough account of the contemporary debate on public engagement with science, see Elam & Bertilsson 2003.

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Deciding the Future of Nanotechnologies: Legal Perspectives on Issues of Democracy and Technology

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Abstract. What potential problems do emerging nanotechnologies present? Who should decide how, where, and by whom new nanotechnologies should be pursued and regulated? This paper begins with a brief review of two attempts to deal with issues such as those emerging alongside nanotechnologies. In the first, Frederick Fiedler and Glenn Reynolds draw attention to new technologies in the medical field. In the second, Paul Lin-Easton deals with environmental concerns over these new (potential) technologies. I use the concerns raised in these two law reviews to draw attention to issues that must be addressed if societies are to maintain control over the design and production of new technologies, including nanotechnologies. Specifically, I focus on issues of technological determinism, technology-society relations, and building a base for broad public participation in the creation, acceptance, and use of new technologies.

Introduction

The coming of the age of nanotechnologies has raised many new concerns and rehashed old debates in new guises. For present purposes, I would like to approach this topic from an often neglected perspective – that of the law. My intention here is not to offer an exhaustive or intensive look at the interrelations of nanotechnologies and laws, but instead to demonstrate how concerns raised in some corners of the legal world echo those arising from other sectors embroiled in this current debate – including issues of safety, risk, precaution, and public involvement in decision-making processes concerning emerging technologies. To that end, I will provide a look at two specific law reviews related to nanotechnologies. In the first, the authors – Frederick Fiedler and Glenn Reynolds – tackle the problem of classification of new nanotechnologies designed for medical use. Their review highlights the importance of dealing with conceptual issues at an early stage because the results of such seemingly mundane classificatory work can have dramatic resonance when it comes to determining who will have access to these technologies and under whose supervision these technologies will fall.

In the second review, Paul Lin-Easton deals more explicitly with issues of safety and risk with regards to pre-emptive regulation of nanotechnologies. His review outlines concerns raised by the possibility of these new technologies. To prepare for these, Lin-Easton advocates a modified use of the “Wingspread Statement on the Precautionary Principle” to propose how and under what conditions we ought to proceed in our research. Perhaps most importantly, Lin-Easton advocates the participation of a broader public in deciding how research should be carried out and to what end(s).

What role can/should the public play in decisions about nanotechnologies? I will close with a discussion of how the development of nanotechnologies might be more demo-

cratic. This will involve challenges to traditional cultures of expertise and the creation of spaces for public debate, dissent, and decision-making. To begin answering this question, we must first challenge the popular notion of technological determinism, which disempowers people by removing their agency from technological developments. An answer will also require a rethinking of relations between the ‘social’ and the ‘technical’ in order to view technologies not as something separate or distinct from the social but as inextricably linked to the social – creating what is sometimes called a ‘sociotechnical’ system. Finally, I’ll discuss briefly what it might mean to have a ‘democratic technology’. Drawing on the work of Andrew Feenberg, I hope to highlight what possibilities exist for the creation of technologies of production and dissemination that empower rather than disempower the public(s).

1. Nanotechnology and Medicine: Drug or Device:

In their overview of legal problems stemming from nanotechnology, Frederick Fiedler and Glenn Reynolds point out one important classification used by the government for regulatory purposes that may face serious challenges with the introduction of nanotechnology in the medical field: the distinction between “drug” and “device”. Current legislation defines a drug as:

(A) articles recognized in the official United States Pharmacopeia, official Homoeopathic Pharmacopoeia of the United States, or official National Formulary, or any supplement to any of them; and (B) articles intended for use in the diagnosis, cure, mitigation, treatment, or prevention of disease in man or other animals; and (C) articles (other than food) intended to affect the structure or any function of the body of man or other animals; and (D) articles intended for use as a component of any article specified in clause (A), (B), or (C). (quoted in Fiedler and Reynolds 1994, pp. 607-8)

And a device is defined as:

[A]n instrument, apparatus, implement, machine, contrivance, implant, in vitro reagent, or other similar or related article, including any component, part, or accessory, which is –

- (1) recognized in the official National Formulary, or the United States Pharmacopeia, or any supplement to them,
- (2) intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease, in man or other animals, or
- (3) intended to affect the structure or any function of the body of man or other animals, and which does not achieve its primary intended purposes through chemical action within or on the body of man or other animals and which is not dependent upon being metabolized for the achievement of any of its principal intended purposes. (quoted in Fiedler and Reynolds 1994, p. 608)

In essence, then, the distinction between drug and device is a difference between chemical and mechanical operation (*ibid.*, p. 608). However, as Fiedler and Reynolds point out, the potential uses of nanotechnology in medicine blur this distinction. Often, the forces at work on an atomic scale are difficult to distinguish from one another. At this level, “it becomes virtually impossible to separate ‘mechanical’ from ‘chemical’ or ‘electrical’ effects” (*ibid.*, p. 609).

As an example, Fiedler and Reynolds discuss the potential role of “nanorobots” working to remove the atherosclerotic plaque from coronary arteries. Current methods for the removal of this plaque involve the use of “a variety of relatively small devices: wires, drills, balloons, and lasers, small enough to be inserted into the coronary arteries by catheter” (*ibid.*, p. 610). In the future, it has been proposed, doctors could use nanodevices for the

continual removal of this plaque. These devices would operate by searching out plaque deposits and removing them metabolically one molecule at a time. The key question here, Fiedler and Reynolds point out, is *how* this removal will occur: chemically or mechanically. Current technologies, they argue, are already capable of similar actions. “Conceptually, nanorobots scraping away at arterial plaque simply represent a more refined version of current technology, and thus should be regulated as devices” (*ibid.*, p. 610). But, what if we view the action of the nanorobots not as scraping the plaque from the arterial walls, but instead acting as a solvent, dissolving the plaque? From this perspective, we may perceive the nanorobots to be drugs, metabolizing the plaque and drawing energy from the host cells (*ibid.*, p. 611). Our characterization of the plaque, too, may prove important in deciding how to classify these nanorobots: “If the tiny bits of atherosclerotic plaque are individual cholesterol molecules or individual calcium atoms, then there is cause for uncertainty over whether an action is chemical, mechanical, electrical or otherwise” (*ibid.*, pp. 610-11).

Does it really matter whether or not we understand fully how these actions occur? What concern should we have if little nanorobots don't fit neatly into our current schemes of classification? Fiedler and Reynolds argue that in these early stages it is of the utmost importance to deal with these conceptual issues: “While in an academic sense, or even a practical one, it may not matter whether the action of such nanorobots is conceived of as chemical or mechanical, it is very important in a legal and regulatory sense, at least until regulators begin to take cognizance of nanotechnology in an organized fashion” (*ibid.*, pp. 611-12). Finding ways to deal with these issues will be crucial as new products begin to enter markets. Often, the time during which new technologies begin to enter the marketplace overlaps with an unprepared legislative structure – and, I would argue, an unprepared public. Fiedler and Reynolds note that: “For emergent nanotechnology, there will most likely be a window during which the old laws will lag behind the new technology. Within that window opportunities will arise for mismanagement of new products” (*ibid.*, p. 612).

If the current language of the laws pertaining to drugs and devices fails to accommodate nanotechnology, Fiedler and Reynolds suggest preemptive changes to the wording of such laws to help alleviate some of the possibilities for mismanagement. In place of a classificatory system based upon how the technology operates (*i.e.*, “force oriented”), the authors suggest a functional approach to regulation. Functions could be divided into three categories: repair, “the restoration to a previous normal state, analogous to bonesetting or suturing a cut”; replacement, “like organ transplants or the introduction of artificial joints”; and augmentation or enhancement, “the truly novel situation ... in which cells are programmed or modified to perform in ways not called for by nature” (*ibid.*, p. 616). These three functions are analogous, the authors contend, to current medical procedures, and could thus be accommodated easily within the medical and legal institutions. Additionally, each of these three functions could be regulated differently – with repair being the most loosely regulated and augmentation requiring the most oversight.

The legal concerns related to the use of nanotechnology are not limited to classification and regulation. Additional effort will be required to deal with, for example, whether or not nanotechnology should be patented like hardware or copyrighted like software (*ibid.*, pp. 613-4, 619), the maintenance of regulatory competence (*ibid.*, p. 618), how insurance companies will treat nanotechnology in medicine (*ibid.*, p. 622), and threats to notions of personal identity (*ibid.*, pp. 623-624).

Aside from the legal concerns raised by Fiedler and Reynolds with respect to the introduction of nanotechnology into medicine, some environmentalists and environmental lawyers are concerned about unforeseen challenges that this new technology may present for them.

2. Nanotechnology and the Environment: Pleas for the Precautionary Principle

In addition to the often optimistic outlook offered by those working in the nanotechnology field, some scientists and environmentalists are concerned about the unintentional consequences that these new technologies may have on the global environment. In his 2001 law review, “It’s Time for Environmentalists to Think Small – Real Small”, Paul Lin-Easton issues a call for environmental lawyers to get involved in the development of anticipatory precautionary principles to be applied to nanotechnology research, design, and manufacturing. In particular, the author develops a policy plan modeled on the “Wingspread Statement on the Precautionary Principle”. The Wingspread Statement asserts three principles that should be followed when dealing with potentially harmful agents:

Where an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.

In this context, the proponent of an activity, rather than the public bears the burden of proof.

The process of applying the Precautionary Principle must be open, informed and democratic, and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action. (quoted in Lin-Easton 2001, p. 121, note 100)

Lin-Easton divided these three principles into four, and applies them to the issue of nanotechnology. First, the proponents of nanotechnologies should bear the burden of proving its safety; conversely, opponents should not have to demonstrate its harmfulness. Second, all alternatives to nanotechnologies should be explored before the decision is made to proceed; this includes the option of relinquishment of the technology. Third, governments, businesses, and individual researchers involved in nanotechnology research, design, or manufacturing have a duty to prevent harm by taking anticipatory action. And fourth, the application of the precautionary principle must proceed in an environment that is open, informed, and democratic (Lin-Easton 2001, p. 123). These four points provide the structure for the remainder of his article, and I will discuss his views on each.

2.1 *The Burden of Proof*

As stated above, the precautionary principle places the burden of proof upon the proponents of nanotechnology. Additionally, those involved with the development or production of nanotechnologies – governments, businesses, or individuals – will be held responsible for any damage caused by these technologies: “This responsibility includes financial responsibility in the form of assurance bonds and tort liability, and a duty to ‘routinely monitor their impacts, inform the public and authorities when a potential impact is found, and [to] act upon that knowledge’” (*ibid.*, p. 123).

Opponents of the precautionary principle often draw attention to the fact that nothing can ever be proven completely safe, and that this position simply declares nanotechnology to be guilty until proven innocent. Proponents of the use of the precautionary principle do not see this as an absolute ban, but an assurance that development objectives include not only economic goals, but also ecological and health considerations (*ibid.*, p. 123).

2.2 *Relinquishment*

The second principle discussed by Lin-Easton states that when evaluating nanotechnology, all alternatives must be considered, including relinquishment. Relinquishment is the position that has been advocated by Bill Joy in his *Wired* magazine article “Why the Future

Doesn't Need Us" (2000). It involves the abandonment of a research project if engagement in that research threatens the environment or human health. Much of this sentiment stems from what many see as the tremendous potential for catastrophe that nanotechnology possesses. And while scientists involved with nanotechnology research may be uncertain about the potential dangers of this emerging field, proponents of the precautionary principle note that this uncertainty is precisely why a full evaluation of alternatives must be explored.

However, the tremendous economic and military advantages offered to businesses and governments that pursue nanotechnology make it unlikely that relinquishment could ever be a realistic option. And past experiences in the international community give little hope for such a policy to be adopted. Lin-Easton notes that:

The United States ... has shown little support for the inclusion of the precautionary principle in international agreements and has resisted binding targets and timetables for the reduction of greenhouse gasses. [T]he United States has recognized the importance of nanotechnology to its economic and military competitiveness and is no more likely to support bans on nanotechnology development than it is to support reductions on its carbon emissions. (Lin-Easton 2001, p. 125)

Some scientists even note that the adoption of relinquishment would be unethical. They argue that we have a "historical imperative" to move beyond our current limitations and to acquire new knowledge. And because of the tremendous opportunities available through this new technology, turning our backs on nanotechnology would be akin to "turning our backs on the poor and suffering" (*ibid.*, p. 126).

Lin-Easton notes that given the economic and military advantages afforded to those that do fund research in this new area, it is unlikely that any government will adopt this strict precautionary principle. With that in mind, Lin-Easton outlines some anticipatory moves that can be made.

2.3 *The Duty of Those Involved*

To this point, Lin-Easton notes, it has been the scientists who have called for regulatory standards to be established. These proposals usually recommend the unabated research of "safe" nanotechnology while buying time to implement safeguards against more destructive forms of these technologies. Many of these proposals stem from the guidelines established by the Foresight Institute, an organization founded and chaired by Eric Drexler to educate and prepare society for "anticipated advanced technologies" (quoted in Lin-Easton 2001, p. 127). Lin-Easton summarizes the Foresight Institute's regulatory approach as "protective in development and liberal in production" (*ibid.*, p. 128).

The approach of the Foresight Institute is an attempt at self-regulation, and replaces the precautionary principle with risk assessment. This move, according to Lin-Easton, is an attempt to follow "sound science" in decision making. However, this approach relies on the ability of scientists to model complex human and environmental conditions accurately and to make predictions based on those models. Opponents of this approach note: 1) that it is precisely this sort of uncertainty in modeling that the precautionary principle attempts to overcome; 2) that it refers to acceptable risk instead of relinquishment in the face of dangerous activities; 3) that risk assessment is not democratic; and 4) that the use of cost-benefit analysis creates a false dichotomy between economic development and environmental protection (*ibid.*, p. 129).

Despite these philosophical differences, Lin-Easton writes that at least three design principles and guidelines have been generally agreed upon. The first constrains autonomous self-replication. Attempts to develop safeguards to this end include the proposed use of broadcast transmissions for replication, and refusing to design any nanotechnology that would use an abundant natural resource for fuel. Second, most agree that new nanotech-

nologies should lack evolutionary capabilities, including artificial evolution and sexual inheritance mechanisms. Finally, guidelines should be established to prevent data corruption. This includes ensuring that if any part of the nanosystem fails, the whole device fails (*ibid.*, p. 130).

Many of these guidelines have been criticized for being naïve and placing too much trust in an “honor system” amongst scientists (*ibid.*, p. 131). And environmentalists will quickly note that risk assessment often fails in its efforts to prevent human or ecological damage (*ibid.*, p. 132). To combat this, Lin-Easton argues that “much wider participation in these discussions is needed to tighten the proposed guidelines and to address the necessary regulatory mechanisms that will be required to implement them” (*ibid.*, p. 132).

2.4 Creating a Forum for Discussion

As mentioned above, much of the discussion about regulation has come from within the nanotechnology community. However, because nanotechnologies are poised to have such broad effects, many like Lin-Easton are calling for an open discussion of these new technologies. To accomplish this, the public need to be made aware of recent developments, and must be afforded the opportunity to participate in discussions concerning the research, development, and manufacturing of new nanotechnologies. Lin-Easton describes the relevance of the Rio Declaration to this situation: “The Rio Declaration calls for the discussion of environmental issues to include the ‘participation of all concerned citizens’ and for states to ‘facilitate and encourage public awareness and participation by making information widely available’” (*ibid.*, p. 133).

Lin-Easton closes by saying that dialogue needs to begin now. And while the nanotechnology community may resist some demands, the early involvement of the public may prevent over-reaction in the future. “The resulting debate is likely to be contentious, but dialog needs to start now, so that proactive precautionary social and legal controls can be developed while this new technology is still in its early development, rather than rushing to rash reactive policies in response to a rude awakening thirty to fifty years from now, if not sooner” (*ibid.*, p. 134).

3. Creating a Space for a More Democratic Discourse

The fact that nanotechnologies should be regulated sooner rather than later is clearly evident from the work of Fiedler and Reynolds and Lin-Easton. The question is not “if”, but “how” regulation should be implemented. To this end, these authors have called for further involvement on the part of their respective communities – lawyers, environmentalists, doctors, and scientists. But, given the possible ramifications of the development for these new technologies – socially, economically, politically, environmentally – I want to argue for the involvement of an even broader spectrum of voices to be heard in these discussions. The key to this, as Lin-Easton points out, is the education of the various publics and the opening of a forum that includes them. Therefore, I would like to close with a discussion of a few topics that will be important for claiming this space for debate and empowering those involved, that is, restoring a sense of agency to them.

3.1 Re-Defining Social-Technological Relations

Technology does not impact society. This is the impression that we are given when we look at discussions of how society must prepare for the coming of nanotechnologies. Very little, if any, attention is given to the role that society plays in shaping, choosing, designing, and reinventing technologies, both before they are ‘closed’ and after they have been in use for

years. The role of the social in the design and implementation of technologies has been thoroughly explored, from the introduction of the bicycle to the creation of tactical aircraft.¹ Rather than accept this model of society as inheritor or society as impacted by technology, we ought to stress the ways in which technology and society are inextricably linked, and how we are as much the creators of technologies as technologies are the creators of our societies. The ways in which societies decide to develop and manufacture nanotechnologies will be a reflection of who they are. Concurrently, these new technologies will recreate our society as they begin to offer new hopes in medical treatments and environmental cleanup, and new dangers – both accidental and intentional. Thus, focus should not be exclusively on preparing society for nanotechnologies, but equally on deciding what kinds of nanotechnologies societies want to create.

3.2 *Technological Determinism*

The development of technology does not proceed down a predetermined linear path from point (a) to point (b) with nothing to stand in its way. That is, there is no technological determinism. And while this topic has been dealt with extensively over the past few decades in the history of technology and less so in the philosophy of technology, there are still those – including many policy makers – who assume that this is the way things work. In order to create an educated and empowered public capable of participating in the development of nanotechnologies, the myth of technological determinism must be cast away. It may be true that technologies gather a sort of momentum – as the historian Tom Hughes has argued – the further along the technology develops.² After all, that is the reason why the authors I have discussed here are pushing for early regulatory action. But, we must remember that we are never powerless. Moves made in the past may constrain our moves in the present, but they certainly do not determine our future. And while ideas like relinquishment may seem unlikely, they should not be treated as impossible.

The issue of technological determinism is surely not only a concern in the public sector. The idea that – like it or not – we are subject to the continuous development of technology is a popular one in all sectors of society, including the professional groups working on the development of nanotechnologies. Groups such as the Foresight Institute take as their base assumption that these technologies *will* be developed – it is only a question of *when* and by *whom*. As Lin-Easton points out above, relinquishment is never considered as an option. Instead, we, the public, are given the impression that nanotechnologies *will* be developed and produced and that we need to prepare ourselves as best as possible for this in the near future. But, *who* should be preparing us?

3.3 *Overcoming Expertise*

According to Fiedler, Reynolds, and Lin-Easton, the legal world ought to be doing more to prepare for new developments in nanotechnologies. But scholars such as Sheila Jasanoff point out that the courts are usually ill-equipped to deal with new or changing technologies (Jasanoff 1995, especially chapter 3). This leaves a heavy burden on the courts and legislators to find reliable experts. Despite numerous attempts to deal with issues of expertise in the courts,³ there remains little consensus on how to regulate expertise itself. This particular landscape often creates an environment where scientists are left to regulate themselves by playing the dual role of concerned citizen and regulatory advisor. Take for example the work of the Foresight Institute. Learning lessons from the trouble encountered by genetic engineers in the 1990s, those working at the Foresight Institute have attempted to move preemptively to clear the path for emerging technologies, such as nanotechnologies. The institute is a site for educating the public, providing information to lawmakers, and for debunking perceived popular misconceptions about the potential dangers that could accom-

pany this new class of technologies.⁴ To be sure, organizations such as the Foresight Institute express the seemingly good intention to educate the public about their vision of emerging nanotechnologies and – in the words of their mission statement – to “help prepare society for anticipated advanced technologies”, But despite these intentions, there is a noticeable lack of attention given to *involving* the public in this discourse. The work of the Foresight Institute (and similar institutions) thus runs into the same problems encountered by those who formulated the “Public Understanding of Science” movement in the UK. As part of that movement, questions arose around issues such as: who would be doing the educating, what information would be disseminated, and how? But, more importantly, concerns were raised about the overtly paternalistic approach of the movement and the homogenization of ‘the public’ into a single group that needed to be educated. Critics argued that efforts should be made to engage the various publics and to make them active participants in the *debate*, not passive and docile recipients of advanced sciences and technologies.

Is there a way around this ad hoc creation of expertise? Is there a way to educate the publics without removing their ability to actively engage in critical debate? As Lin-Easton remarks above, there is not only a desire but also a need to involve a broader public in the debates concerning new and emerging nanotechnologies, and the “Wingspread Statement on the Precautionary Principle” is certainly one place to begin. But does this address the entire problem? Rather than rely exclusively on articles such as the Precautionary Principle, we ought to be working to create a more inclusive, democratic approach to these new technologies.

3.4 *The Creation of a Democratic Technology*

New technologies should serve the needs of our entire society, not specific interest groups. And because the greatest risk from new technologies often falls upon those least likely to benefit, every effort should be made to create an open and democratic approach to the regulation of new nanotechnologies. This is the message of the “Wingspread Statement on the Precautionary Principle” that is echoed by Lin-Easton. But how does one go about creating a democratic technology? Well, there are several ways. Certainly the calls by Fiedler, Reynolds, and Lin-Easton are legitimate. They ask for the involvement of lawyers, environmentalists and others to become involved in the project of regulation. Clearly, this is an important means of intervention. However, as the philosopher Andrew Feenberg points out, working within the traditional structures of democracy is only one option (Feenberg 1999, pp. 105-6). He offers three other modes of intervention for including citizens from multiple walks of life. First is the creation of technical controversies. “Controversies draw attention to violations of the rights and health of those affected by the enterprise” (*ibid.*, p. 122). The result can often be the exposure of the complexity of the elements threatening health and environment – in this case nanotechnologies – and the ideological views that previously characterized the technologies. The second mode of intervention is innovative dialogue. These dialogues often occur when intellectuals from the “inside” – engineers and scientists involved in the creation of nanotechnologies – actively engage the public. The active engagement with local participants can lead to two possible outcomes: 1) the dialogues are marginalized and suppressed by those with greater resources, or 2) what is learned in these dialogues is internalized and becomes a part of the new technologies (*ibid.*, pp. 123-4). The third mode of intervention proposed by Feenberg is creative appropriation. This approach involves the “interpretive flexibility” of a technology, that is, the ability to rethink, reinvent, or transform the technology through new uses – and concurrently the society that uses it: “At issue in this transformation is not just the [technology’s] narrowly conceived technical function, but the very nature of the advanced society it makes possible” (*ibid.*, p. 127).

In the end, we must remember that it is we – society writ large – who will decide what nanotechnologies will be and how they will mesh with our society. We must not for-

get that it is never too late, or too early, to rethink the types of technologies we want our society to create, and how we want these technologies to alter our societies. I close with a final quote from Feenberg: “Even as technology expands its reach, the networks are themselves exposed to transformation by the individuals they enroll. Human beings still represent the unrealized potential of their technologies. Their tactical resistances to established designs can impose new values on technical institutions and create a new type of modern society” (*ibid.*, p. 128). It’s never too late to begin including new voices, new ideas, and new goals in the designs and implementations of our society’s technologies.

Notes

- ¹ For the debates surrounding the design of bicycles, see for example Pinch and Bijker 1987. For discussion of the British TSR2 Tactical Strike Fighter, see John Law 2002.
- ² See, specifically, Hughes 1987. The concept also receives some attention in Hughes 1983.
- ³ Specifically, the cases of *Daubert*, *Kumho Tire*, and *Joiner* have dealt with the issue of expertise in the courts. For some analysis of how the *Daubert* case has functioned, see Jasanoff 1995, especially chapter 3. For a more recent discussion, see Berger 2000.
- ⁴ As an example of the debunking efforts of the Foresight Institute, look at the Press Releases that followed the publication of Michael Crichton’s book *Prey*, found on its website www.foresight.org.

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The Expert's Role in Nanoscience and Technology

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Abstract. Richard Sclove writes in *Democracy and Technology*, “if citizens ought to be empowered to participate in determining their society’s basic structure, and technologies are an important species of social structure, it follows that technological design and practice should be democratized” (p. 27). This paper will begin exploring what this view of democracy implies for the development of nanotechnology. In particular, I will look at the role of “the expert” in both communicating and guiding the development of nanotechnology. This will lead us to an exploration of both the relationship between the expert and the nanovisionary and the expert and the citizen in the context of public decision-making about the prospects of nanotechnology. The foundation of my argument will be the claim that the appropriate role of an expert in a democratic society, at least when acting in the realm of public science policy, should be to make possible informed decisions on issues of science and technology by fellow citizens.

If citizens ought to be empowered to participate in determining their society’s basic structure, and technologies are an important species of social structure, it follows that technological design and practice should be democratized.
(Richard Sclove, *Democracy and Technology*, p. 27)

Introduction

I want to argue for a fairly straightforward proposition. *In a democratic society the appropriate role for a scientist or engineer when participating in the process of public decision-making as an expert in his or her field, is to facilitate informed decisions on issues of science and technology by fellow citizens.* The claim here is normative. When an individual dons the role of a scientific expert participating in the public policy process his or her primary obligation is to help produce the conditions necessary for legitimate and significant public participation in that process. An underlying assumption to my argument is that in democracy, legitimate political decisions have to be, in some reasonable sense, ‘by the people’.

That this proposition be correct is critical as I am going to go on to argue that this idea of the expert as facilitator must be foundational to any public debate about nanoscience and technology. Without experts effectively playing this role nanoscience and technology risks becoming and being understood as an inherently authoritarian technology. What I mean by this is a technology that because of the structural elements it imposes places in the hands of a relative few power and decision-making ability, or what is properly called authority over vital elements of individual’s lives.

1. Expertise and Technoscience

There is a significant authoritarian tendency in technoscience¹, that is, in the social networks that lead to the application of scientific ideas to social life, whether it be in the creation of material technological artifacts, or in the application of scientific ideas to social structures.² This tendency stems from the very specific epistemic demands that usually accompany decisions about the application of science and technology. The decision process for the application of any technoscientific item is complex. But from a normative point of view, a necessary condition is some understanding of the item in question. The decision makers need to have a basic understanding of the item, its use, its function, and its risks. If this is not the case, the decision probably cannot qualify as a good (where good is taken to be synonymous with some sense of rational) decision. Roughly speaking, you cannot make a good decision about technoscience without understanding the science.

Understanding the science, however, reduces to some fairly specialized disciplines. The development of specific scientific expertise arises from the difficulty of grasping anything more than a very small subsection of what we think of as science. Experts are around precisely because of the division of labor that contemporary science and technology seem to require.

John Hardwig calls the epistemic situation I'm describing 'rational deference' and argues that it is built into the structure of expertise. The basic structure of expertise demands that the individual or group ('A' below) who comes to depend on the expert must place him or herself in a subservient position within an authoritarian relationship.

Rational Deference

1. A knows that B says p.
2. A has good reason to believe that B (unlike A) is in a position to know what would be good reasons to believe p and to have the needed reasons.
3. A believes (and has good reason to believe?) that B is speaking truthfully, that B is saying what she believes.
4. A believes (and has good reason to believe?) that B actually has good reasons for believing P when she thinks she does.

(Hardwig 1994, p. 88)

The individual or group that comes to depend on an expert has to depend on the authority of the expert. The value of expertise is precisely that it allows one to have a reason to accept certain judgments in situations where one does not have access to the information necessary to make the judgment. It is the authority of the expert that serves as the foundation for accepting the judgment in question. Deference implies a necessary trust between expert and layperson. A non-expert judges the reliability and character of the expert rather than the information provided. The trust in the expert is legitimated by the community to which the expert belongs and the status of that community in the larger society.

The obvious upshot of all of this is that scientific decisions either are or should be made by experts. To the degree that a basic understanding of the science involved is necessary for a rational decision only those who have that understanding can or should participate in the decision. 'Expert' becomes not just an epistemic category, but also a political category. Experts not only know, they decide. This leads to some obvious conflicts with at least certain conceptions of democracy.

At the heart of these conflicts is the idea that in our contemporary society technology is a crucial social structure that shapes the real possibilities of individual's lives. Technology is (or perhaps more accurately, technologies are) not just a set of gadgets at the periphery of our lives, but rather a central element in the material reality of our existence. The types of technologies and our access to them make a crucial difference to what we can be as

individuals, and the type of and access to technologies that individuals' have stem from decisions made in the political and social realm.

If the claims in the previous paragraph are correct, and this paper assumes that they are, then deference produces significant problems for democracy when democracy is understood as depending on autonomous decisions on the part of the citizens. Autonomy implies that individuals participate in some significant way in decisions that affect the possibilities of their own flourishing. Here, however, it is the experts who are making decisions about things that profoundly affect individuals' lives. Citizens are simply depending on the authority of the experts.

There is a quick response available to this problem. One can deny the problem and claim that autonomy is unaffected because while the experts are making the decisions, the citizens can in some sense choose and remove the experts. The idea here is that as long as the authority, both epistemic and political, of the experts is legitimate, then there is no real conflict with autonomy. We can have a kind of representative theory of expertise.³ I think this response fails and this failure is perhaps nowhere more apparent than in the case of nanoscience and technology.

2. Nanoscitech

I want to discuss nanoscience and technology⁴ both to illustrate what I am arguing and more fundamentally because the issues raised so far are not best understood as abstract issues, but as issues connected to the actual decision making of science policy. Science policy is itself an abstraction. Policy is not usually made about science, but rather policy is made about a technoscientific process, item, or approach. There is no official physics or biology policy in the United States or the European Community, but rather policies about genetically modified foods, building particle accelerators, funding alternative fuel research, etc. Policy is made at an intermediate level of abstraction and nanoscience and technology is at the moment at that level. Of course one of the questions to ask is whether nanoscitech should be at this level, but that is for another paper. The reality of the moment is that both the US and Europe are in the process of developing a national and international nanoscience and technology policy. This reality allows us to ask just how this policy ought to be made. It is in the context of this more specific normative question that the concerns about expertise become concrete.

What are these concrete concerns and what is it about nanoscitech that produces them? There are two features that offer entry into the normative issues raised by nanoscitech. Nanoscitech is both interdisciplinary and transformative. It is interdisciplinary in a fairly strong sense in that what nanoscitech shares in common is concern about a specific size of objects.⁵ What it does not share in common is any shared approach or specific theoretical context that guides it. As it stands, individuals from almost every discipline in science and engineering participate in nanoscitech. This leads to a wide variety of assessments of the goals, methods, and prospects of nanoscience and technology. These assessments are sometimes at odds with each other and lead to some very significant disagreements about what is possible and not possible for nanoscitech. But perhaps more interestingly, these assessments lead to disagreements about what is to count as 'real' nanoscitech and what is simply some pseudoscience.⁶ Interdisciplinarity, often considered a strength by the practitioners of nanoscitech, is paradoxically also a source of controversy and contention.

Simultaneously, nanoscitech is one of a suite of relatively new NBIC⁷ technosciences that seem to have the capacity to radically transform our world and ourselves. This is perhaps the most notable and certainly the most publicized feature of this technoscience. Wherever you look you will find some very large claims being made about nanoscitech.

Bill Joy has very public concerns about the dystopian future that might await us if we proceed with nanoscitech (Joy 2000). A series of organizations such as the ETC Group (ETC 2003) and Greenpeace (Arnall 2003) have called for public scrutiny and control over the development of this technology. Michael Crichton has given us a fictional vision of just how badly this technology can go wrong (Crichton 2002). At the same time, Eric Drexler and the Foresight Institute see the emancipatory possibilities of nano (Drexler 1986, Foresight). The United States pursues the National Nanotechnology Initiative and commits substantial funding to this research (NNIb).⁸ Forbes, among others, develops a newsletter, with a significant subscription fee on the investment possibilities of nanoscitech (Forbes). Utopian claims about the coming nanoscitech revolution are ubiquitous in science literature (Crandall 1996). And Hewlett-Packard is now running ads touting the coming benefits of nanotechnology on U.S. television.

While the organizations and individuals mentioned above offer a wide variety of assessments of nanoscitech, they all agree, at least in their rhetoric, that nanoscitech will in the immediate future transform the world we live in. This transformation might be benevolent, malevolent, or simply profitable, but it is inevitable. Like all the NBIC technosciences, nanoscitech seems to provide tools for the transformation of the human self and environment so that lines between the artificial and natural are obliterated. In the case of nanoscitech these tools are the ability to manipulate, assemble, and disassemble molecules. The idea itself is very simple. Change the atomic structure of a molecule and you get a different molecule. If we can remove and attach atoms and small molecules from and to each other or other molecules, we can assemble and disassemble almost any substance. Molecules, in theory, can be used like LegosTM⁹ and we can, from fairly common, easily available materials, assemble materials with the specific properties required for whatever task we are trying to perform.

Of course, the description I have just provided is itself highly contentious. While everyone agrees that nanoscitech allows one to manipulate molecules, to what extent and degree this manipulation is possible, indeed what manipulation in this context means produces considerable disagreement. Just how far the LegoTM metaphor works is not at all clear and like many metaphors the LegoTM metaphor is as misleading as it is enlightening. In fact the LegoTM description is a version of the preferred description of nanoscitech of those who agree with Eric Drexler and the Foresight institute, though this agreement (Bill Joy comes to mind here) might only be about the nature of the science and not its benefits. This description also appears to be the most common description of nanotechnology in non-technical discussions.¹⁰

This last claim is based on an admittedly non-systematic survey. For example if we google (a new and useful verb favored by my students) nanotechnology, the first web site listed (making it the site with the most cumulative hits) is Ralph Merkle's web site about nanotechnology. Ralph Merkle recently moved to Georgia Tech where he is the director of Georgia Tech's Information Security Center in the College of Computing. He is a well-known expert on encryption and is also the vice-president for technology assessment at the Foresight Institute. Until recently he was also working with Zyvex and I assume some sort of connection is still maintained because as of this writing the Zyvex logo is prominently displayed at the top of the web site. Merkle is closely connected to Drexler and the Foresight Institute. This site describes nanotechnology as follows, "Manufactured products are made from atoms. The properties of those products depend on how those atoms are arranged. If we rearrange the atoms in coal we can make diamond. If we rearrange the atoms in sand (and add a few other trace elements) we can make computer chips. If we rearrange the atoms in dirt, water and air we can make potatoes" (Merkle). Here nanotechnology looks like modern alchemy. We can finally get gold from lead.

There are much tamer descriptions of nanoscitech. If we turn to the U.S. National Nanotechnology Initiative (number seven on the google hit parade) we get the following description. “[Nanotechnology is] research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size” (NNI). Clearly the NNI description promises less, but there is still a strong sense of the transformative power of nanoscitech. This sense is clearer in the following text from the executive summary of *Societal Implications of Nanoscience and Nanotechnology: NSET Workshop Report*.

Advances in nanoscience and nanotechnology promise to have major implications for health, wealth, and peace, in the upcoming decades. Knowledge in this field is growing worldwide, leading to fundamental scientific advances. In turn, this will lead to dramatic changes in the ways that materials, devices, and systems are understood and created. The National Nanotechnology Initiative (NNI) seeks to accelerate that progress and to facilitate its incorporation into beneficial technologies. Among the expected breakthroughs are orders-of-magnitude increases in computer efficiency, human organ restoration using engineered tissue, “designer” materials created from directed assembly of atoms and molecules, and the emergence of entirely new phenomena in chemistry and physics. (NSF 2001, p. iii)

The transformative nature of nanoscitech is still apparent here, and it is only in comparison with Merkle's claims that the NSF/NNI vision appears less radical. What is different is both the scale and the type of transformation foreseen. Many different groups agree that nanoscitech is the next big thing, but just what that thing is, is not at all clear.

3. Expertise, Nanoscitech, and Democracy

This potential for transforming our social life is a good starting point from which to consider the types of problems nanoscitech might pose for a democratic society.¹¹ Agreement that nanoscitech will be transformative and disagreement about *how* it will be transformative, together produce potential problems. Because nanoscitech promises to transform society in important and even fundamental ways, there is a significant question about who gets a say in how and whether this transformation happens. But having a say in this transformation is difficult when there is no real agreement about just what is the nature of the transformation. Here I am pointing to more than the standard problem about the unintended consequences of a new form of technology, but rather to some basic disagreement about the direction of and the intentions behind the science and technology.

The problems around expertise become particularly telling here, as the most obvious response to the issues being raised is to simply go ask the nanoscitech experts and use their answers as at least a starting point. *But there are no experts in nanoscience and technology!* Admittedly the last claim is there to catch your attention. Of course there are experts, but the notion of an expert is used equivocally, and there is an important sense in which the claim that there are no experts in nanoscitech is true.

To see why this is the case we need to distinguish the loose everyday sense of ‘an expert’ – which can mean no more than an individual who knows a lot about a topic – from a more specific sense of the term, which is used when we are discussing the social role that experts should play. There are four features of expertise important to this social role that should be made explicit: 1) The expert has specialized training and knowledge not easily available to a layperson; 2) this knowledge is usually technical (what this means is at least that the knowledge is of specific methods for knowing or doing things); 3) the expert is

recognized as such by his/her own professional community; 4) the professional community is recognized as legitimate within the larger society. While the first and second feature apply unproblematically to nanoscitech, the third and fourth are more complicated.

In order to examine the third feature we need to return to the interdisciplinarity in nanoscitech. As I suggested earlier, interdisciplinarity is so strong in nanoscitech precisely because there is neither a paradigm nor a tradition guiding the work. Nanoscitech is so novel that it is not clear that it should yet be called a field. The frequent appeal by nanoscitech that size matters is here – as in its lewder version – open for debate. But with neither a tradition nor a paradigm to draw from, it becomes difficult to be recognized as an expert by one's professional community since the professional community itself is in the process of being constructed.

What in fact we see in nanoscitech is a real debate about where the limits of legitimate expertise lie. Bill Joy, Eric Drexler, Ralph Merkle, Richard Smalley, George Whitesides among others all appear to have legitimate scientific credentials and yet they have all been accused, often by each other, of not really understanding nanoscitech. Part of the problem is that there are few ways, formal or informal, of legitimizing claims for expertise internal to nanoscitech. Nanoscitech finds itself in an odd situation. It is not so much the case that there are no experts as it is that there is disagreement about who is to count as these experts. Again interdisciplinarity is part of the problem. Expertise in nanoscitech depends on the perspective from which one looks at the discipline, as there are significant differences in what is thought possible in nanoscitech.¹² This is not particularly unusual in a young discipline, but when the promise of the discipline is that it can have a profound and relatively immediate effect on the lives of citizens, the inability to legitimize expertise becomes a significant social issue.

The fourth feature of expertise comes into play precisely because of the issue of legitimacy. A science matures as a professional discipline when society recognizes the legitimacy of that community of knowledge. When the science matures then we have a situation where the social role of an expert is possible. A catalyst expert is not simply someone who knows a lot about catalysts, but someone who is recognized as having this knowledge by both her professional community (I would assume an appropriate subsection of inorganic chemistry or chemical engineering) and society at large. The way this recognition is conferred would require a very long digression about professionalism and the development of professions, but the central points are simple. Without some significant societal recognition of the community of knowledge from which an individual emerges, that individual cannot play the social role of an expert. The social recognition that allows for the creation of experts is a deeply political activity embodying values as much as facts.

All of this takes us back to the discussion of rational deference. When we look at the second and fourth elements of deference¹³ we see that in fact it is not at all clear that the public has the "good reason(s) to believe" in the authority of the nanoscitech expert. Again it is not because the experts are not knowledgeable, or because the public is not able to judge whether they are knowledgeable or not, but rather because the institutions that allow the public to trust the experts are not in place. But this produces some very significant problems for anything that looks like the representative theory of expertise I describe at the end of the first section. What is in question in nanoscitech is the epistemic and political authority of experts. The representative theory assumes an already existing cadre of experts, but at least in the case of nanoscitech this is not yet in place. Instead we are only in the process of the production of legitimate nanoscitech expertise.

The concern that nanoscience will have a strong authoritarian tendency becomes more significant here, since what we are in the process of developing are the criteria of expertise for a technoscience with transformative potential. Those criteria must include a series of political and normative judgments. But it seems that there are no experts who can

legitimately guide this process. So the possibility of this process being dominated by a small group produces significant worries about authoritarian technoscience.

4. Democratic Nanoscience and Technology

There appears to be a rather simple way around the problems I have been laying out. All we need do is move to a mode of decision-making that is more effective at including the public. If we can lay out an appropriately participatory model of decision-making then the concern about nanoscitech as authoritarian should be mitigated. Here the role of expert as facilitator becomes essential and we can return to the thesis that is at the core of this paper, namely that in a democratic society the appropriate role for a scientist or engineer when participating in the process of public decision-making as an expert in his or her field is to facilitate informed decisions on issues of science and technology by fellow citizens. The approach I am indicating here takes as a guiding model a common sense approach to how an expert should function in legal and quasi-legal proceedings. Here, objectivity is the guiding goal. The normative requirements of expertise demand that the experts efface any subjective bias and stick to as Joe Friday demands, 'just the facts, ma'am'. The expert's role is to present unbiased testimony that can serve as a foundation for judgment by citizens. The goal is to explain the information needed in order for citizens to make a rational decision. Martin and Schinzinger therefore refer to the expert as value neutral analyst. Here the expert is completely impartial and avoids any type of advocacy (Martin & Schinzinger 1996, p. 373). The crucial skills needed by an expert under this conception are the ability to communicate technical concepts effectively to a lay public and a commitment to objectivity. The expert supplies citizens with the information necessary for them to come to a reasonable decision.

While the goal of this paper is to defend a version of the expert as facilitator, the version as stated above is likely to appear both overly simple and naïve. And this naïveté becomes apparent when we apply it to nanoscitech. The version stated above is subject to several criticisms. It denies rational deference, because it requires the public to be able to judge the experts' knowledge, but this is precisely what deference thinks cannot be done. It overestimates the possibility of value neutrality and objectivity. And in the case of nanoscitech it is beside the point since the problem with nanoscitech is that the public is not able to identify legitimate experts in the first place. Of course, the notion of the expert as representative is subject to the second and third criticisms as well. The absence of objectivity and value neutrality is just as pernicious to the representative model of expertise, and the inability of the public to recognize experts is a problem for any conception of nanoscitech expertise.

It is important to note that all these criticisms target the possibility of the expert as facilitator; they do not question the desirability of this conception. They are all versions of the "ought implies can" problem: at the heart of each criticism is some version of the claim that it is not possible for the experts to facilitate democratic decision making in the way suggested above and that therefore it is not reasonable to demand that they do so.

The response to 'ought implies can' problems is straightforward. Show that the impossibility claims are not particularly strong and the problem is solved. This can be done in the case of nanoscitech, but to do so we need to consider just what the goals of a nanoscitech expert in this role as a facilitator for public decision making on science policy would be. This is not as difficult as it sounds, once we are clear that the autonomy of the citizens is the motivating value. People affected by a decision or a policy should, if possible, have a significant part in making that decision or policy. This claim seems to summarize a minimal demand of autonomy that is at the heart of democracy. The role of the expert becomes to disclose relevant information to the public in ways that can be understood. The

questions around rational deference suggest that the public is simply incapable of understanding the information. The questions around objectivity and value neutrality suggest that the experts' cannot adequately make decision of relevance and will therefore not disclose the appropriate information. The questions around legitimacy suggest that we cannot discover who is most appropriate to play the role of the expert. Roughly speaking, people are ignorant, experts are biased, and we wouldn't recognize a real expert if one fell out of a tree and landed on us.

But the situation is simply not this bad. What we must keep in mind is that we are making political decisions in a democratic society. These are by their nature decisions under a certain degree of uncertainty. The primary virtue of a political decision is that it be legitimate, not correct. Ideally the decision will be both, but a series of illegitimate decisions call into question the justice of the system as a whole, while a series of wrong decisions, particularly in a democratic system with methods in place for changing the government, tends to simply get new people elected. This sounds counterintuitive in the context of science where one would really like to get things right, but democratic societies are structured with the assumption that we can get things wrong (within reason) as long as we protect autonomy.

What we have to avoid, then, is not mistakes, but rather, catastrophic mistakes. And here, nanotechnology becomes interesting. There is the underlying fear of the catastrophic mistake. This is why Bill Joy's article raises such a specter. But once the stakes are raised this high, the problems raised by rational deference, bias, and the absence of experts actually lessen.

If one wants to exclude public participation because of the problem of bias, one has to argue that experts or the public are so inherently biased that the tendency toward deception or self-deception guarantees not just that some mistakes will be made, but that catastrophic mistakes will be made. This bias needs to be constant and pathological. The other option is to argue that the accumulation of small biases somehow aggregate into the functional equivalent of this pathology. Moreover, any control mechanisms in place for managing bias has to be ineffective or nonexistent and the public must be incapable of detecting bias.

If one wants to exclude public participation because of the problem of rational deference, one has to argue that the knowledge gap between experts and lay people is simply unbridgeable. But this ignores the obvious point that lay people, in order to avoid making a catastrophic decision, do not need a full knowledge of a discipline like nanotechnology. Experts should be able to offer enough of an explanation so that individuals can make informed decisions. This does not require knowledge of the details of the formation of buckyballs for example, but rather access to an effective overview of the research.

Finally, when we look at the problem of identifying appropriate experts we once again find the problem to be quite tractable if the goal is to both preserve autonomy and prevent the catastrophic mistake. While the question of expertise in nanotechnology remains an unsettled question, it is not a field without limits. This is not astrology, though on occasion some fairly outlandish claims are made. Nanotechnology draws from already established disciplines and is embedded in the scientific institutions of the nation and world. These existing structures serve to grant enough legitimacy so that expertise can be established within reason.

If ought implies can, and the problems of bias, deference, and expertise are tractable, then the only conclusion to be drawn is that we ought to think that a legitimate and important role of experts in a democracy, at least when it comes to nanotechnology, is to facilitate democratic decision making. To reject the role of expert as facilitator is to reject the idea that individuals can make decisions about the sciences and technologies that most directly impact their lives. Clearly the level of scientific illiteracy is alarming and individuals, whether in or outside of science, are far from bias free. But any position that takes decision-

making about technosciences away from citizens – particularly for their own best interest – is disturbingly authoritarian, paternalistic, and deeply undemocratic.

Notes

- ¹ I borrow the term 'technoscience' from Bruno Latour, though I use it in a slightly different way (Latour 1987, pp 174-5).
- ² Science also has a significant democratic tendency particularly in the publicity that is ideally required of science, though this tendency is often only internal to the scientific community. The scientific community itself is often cited as a model of rationality that is appropriate to democracy. These congruencies with democracy however tend to distract from the authoritarian tendencies that I discuss.
- ³ Joseph Schumpeter and, from my point of view, some social choice theorists favor such an approach. They see these experts as the most competent representatives of the people (or of appropriate interest groups) and give the democratic process only the negative task of eliminating from decision-making those positions that seem to egregiously fail in their representative function. Max Weber is much more negative about such a society, but seems resigned to its existence. The Frankfurt School, contemporary critical theorists, and perhaps most notably Jürgen Habermas, are all critical of this approach (though the late Adorno for example follows Weber in his resignation). This paper reflects this debate but does not directly engage much of it. Such engagement would require an exegetical task that would turn the paper away from its point. It is also worth noting that the basis of this debate is really as ancient as Plato's *Republic* with its argument that political legitimacy depends on knowledge of the good.
- ⁴ I am using the awkward phrase 'nanoscience and technology' both to be accurate and to keep before the reader the variety of activities that are subsumed under this heading. I avoid shortening this to simply nanotechnology, for example, because there is significant research here that is not particularly interested in application. Early work with buckyballs for example seems not to have been motivated in a strong sense by a concern with application. Nanotechnology, then, seems too narrow a name. The same of course goes for nanoscience. I have in the course of the paper reverted to using the unfortunate neologism 'nanoscitech' for brevity.
- ⁵ Nanoscience and technology is concerned with the study, manipulation, and construction of or from molecular sized objects in roughly the 1-100 nanometer scale.
- ⁶ A significant example of this is the public debate between Eric Drexler, Richard Smalley, and George Whitesides about the possibility of constructing nanoreplicators. (Smalley 2001, Whitesides 2001, Drexler et. al 2001a and 2001b). At the heart of this debate are a series of fundamental questions about what is possible with nanoscitech. But these assessments of possibility might partially depend on the different disciplines, methods, and traditions of the participants. It would be very interesting to try and understand the disagreement between Drexler, Smalley, and Whitesides along disciplinary grounds (Smalley and Whitesides are chemist while Drexler is a computer scientist and engineer) and see how much their different starting points affect their assessments of what is possible.
- ⁷ Nanotechnology, Biotechnology, Information Technology, and Cognitive Science (NanoBioInfoCogno). Independently each of these allow human beings to alter their environment and themselves in what appear to be fundamentally new and different ways, whether it is the creation of "intelligent" machines, the ability to manipulate the genome, or the ability to manipulate molecules. And more powerfully the convergence of these technologies amplifies the effect of any of them individually so that both the human self and the material world can appear to be much more available for manipulation and transformation (NSF 2002).
- ⁸ Including funding for the writing of this paper.
- ⁹ Arne Hessenbruch should get credit for this comparison between how some nano folk understand the recombination of molecules pursued in nanoscitech and Lego™. See his "Nanotechnology and the Negotiation of Novelty" (this volume).
- ¹⁰ This is at least partially due to how active both Drexler and the Foresight Institute have been in publicizing nanoscitech. It is also the case that this description offers the kind of sexiness that makes it very attractive to journalists. How nanotechnology is and ought to be represented is a significant issue and one that is being pursued by colleagues here at the University of South Carolina and at Cornell University. The University of South Carolina hosted a conference on "Imaging and Imagining Nanotechnology" in March of 2004.
- ¹¹ Much of what I argue in this section might well apply to any of the NBIC technosciences, but there needs to be some caution in making such a claim. For example the question of legitimate expertise appears much less vague in biotechnology, while the human enhancement issue is more significant. This might well make a significant difference in the types of issues posed by biotechnology. Of course where the technosciences overlap, the problems do as well.

- ¹² There seems to be a real difference in the assessment of some of the more optimistic claims in nanoscitech, particularly about the possibility of self-replication, between researchers with a background in computer science and those who come from chemistry. Whether this is a real or apparent difference is worth exploring.
- ¹³ See above: 2. A has good reason to believe that B (unlike A) is in a position to know what would be good reasons to believe p and to have the needed reasons. 4. A believes (and has good reason to believe?) that B actually has good reasons for believing P when she thinks she does.

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Military, Arms Control, and Security Aspects of Nanotechnology

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Abstract. We consider the social impact of nanotechnology (NT) from the point of view of its military applications and their implications for security and arms control. Several applications are likely to bring dangers – to arms-control treaties, humanitarian law, military stability, or civil society. To avoid such dangers, we propose some approaches to nanotechnology arms control.

Introduction

The announcement of the US National Nanotechnology Initiative and its counterparts in other countries has been accompanied by expressions of concern about ethical, legal and social implications, and some allotment of funding to address them, but concerns arising from military uses of nanotechnology, presumably in the service of national security, have been largely left out of the working definition of “societal and ethical implications”. From the perspective of international security and arms control analysis it appears that systematic study by scholars in the hard and social sciences has hardly begun, with only a few scholarly articles published.¹ This is curious, since the parallel popular discourse on nanotechnology (NT) has not failed to notice that promises made for the possibilities of NT would in practice have profound implications for military affairs as well as relations between nations and thinking about war and international security. Superweapons made possible by nanotechnology are stock items by now in science fiction, and to some extent that literature has already begun to explore the technical logic to see where NT may lead us.² Military writers have also taken note of these emerging ideas,³ while in the USA the military enthusiastically spends one quarter to one third of all Federal nanotechnology research and development funds, and its visionary powerpoint artists portray a future of nano-enabled supersoldiers fighting on nanotech battlefields.

Here we try to consider the impact of evolving and possibly disruptive military NT applications within the context of history, conflict, international security and world order. The international community seeks to avoid war through a variety of mechanisms, including military deterrence, international organizations and treaties, arms control and disarmament. These mechanisms are created and evolve in a changing technological environment. Arms control in the past has included restrictions on new or emerging military technologies. Today, emerging military NT applications and their consequences need to be analyzed. We advocate preventive arms control where one can identify specific negative impacts which may be subject to feasible controls.

1. General Aspects of War and Peace

Throughout history, improved technology has provided advantages in battle. In the 20th century, science and technology became tightly integrated with the system for waging and preparing war. Following the Second World War, military research and development (R&D) continued to expand, in particular in the USA and USSR. The 1950s to 1970s, roughly, marked the era of “big science” – big in budget and in physical scale, while often in pursuit of control over the very small. Nuclear bombs, nuclear-driven submarines, long-range ballistic missiles, and orbiting satellites mark some of the important milestones in the qualitative and quantitative arms race of the Cold War – achieved at extremely high cost and effort.

Even though the Cold War is over, military threats are still at work as instruments of geopolitical will as well as the basic mechanisms of national and international security. Nuclear deterrence is a doctrine still in effect, and thus nuclear war could still start at any time, although this may be improbable. Despite massive reductions (from a high of 65,000 in 1986), there remain about 20,000 nuclear warheads on Earth.

The experience of the World Wars has led to a fundamental change in international law. Through the centuries, states assumed a natural right to go to war – for whatever reason or purpose. With the founding of the UN and the acceptance of its Charter in 1945, maintaining international peace and security became the central imperative (Art. 1). The use of force and threat to use force in international relations were forbidden (Art. 2), with few exceptions: one is force legitimized by the UN Security Council to restore peace and security (Chapter VII, Art. 39-51), and the other is in self-defense until the Security Council has taken its measures (Art. 51).⁴

The security mechanisms foreseen in the UN Charter were hardly implemented, and nuclear war after 1945 was not prevented by adherence to its articles, but rather by the threat of mutual annihilation. Yet the norm established in the UN Charter has had strong effects on the international community. Wars waged since 1945 have usually been claimed to be defensive, and when such claims have been rejected the offending power has often come under collective pressure to cease or restrain its aggression.

Of course, the principle of refraining from the use of force except in self-defense is severely endangered if preventive wars are being waged based on perceptions of threats, not on actual aggression. Thus, we believe the 2003 US war against Iraq has weakened the UN and the international mechanisms of maintaining and restoring peace and security.

When armed conflict occurs, regardless of whether it constitutes legitimate or illegitimate use of force according to the UN Charter, the warring parties are limited in their choice of means and methods of warfare by international humanitarian law, which consists of basic as well as specific rules, often written down in international agreements, which evolve over time. Many rules have become customary international law and are binding for all parties to a conflict; this holds, *e.g.*, for the principle of attacking only military targets or of humane treatment of combatants *hors de combat*. Some rules are only obligatory for the respective signatory parties, *e.g.*, the Additional Protocol 2 to the Geneva Conventions of 1949 on non-international armed conflict. Before introducing a new weapon, means or method of warfare, the states are obliged to check whether its employment would be prohibited by international law.⁵

2. New Military Technologies

The purpose of armed forces is to break the will of an organized opponent by violent force. Who will prevail depends to some extent on comparative recklessness. Thus, war and the

preparations for it do not only go beyond civilized behavior, but carry an inherent tendency to transcend all other rules, including the ones applying to armed conflict.

Innovation in military technology can become an extension of warfare itself. Being ahead in technology provides an important advantage in armed conflict, and if the lead position is not attainable, then one should at least stay as close as possible behind. Thus, all potential opponents have constant strong motives for military research and development and for incorporating their results into the armed forces. Secrecy and worst-case assumptions – both to some extent necessary elements of military preparation – increase these motives.⁶

Military applications of new technologies take place in a framework that is quite different from civilian ones: the bad and ugly uses are not results of accidents or criminal actions – they are prepared in an organized way on a large scale by and with the resources of the state. A special problem arises here: states have to reckon with an opponent using any means at hand. If technology allows new, more effective weapons, they might be used – even if they violate the law of warfare. In order to protect oneself, one needs to know the characteristics of the new weapon; this creates a motive to research and develop the new weapon oneself – which, in turn, creates mistrust and fear between potential opponents.⁷ An example of this mechanism can be seen in the debate regarding biological-weapons – what constitutes legitimate defensive research, and where does forbidden development of biological-warfare agents begin?⁸

Of course, the economic capacity of the state limits its pursuit of weapons, and limitation is also possible by political decision. Self-restraint may be exercised in respect of national or international public opinion. Limits are also implied by the international law of warfare. Finally, potential opponents may agree on mutual limitations (arms control). In general, for these to be effective, there need to be reliable ways of verifying compliance.

3. Arms Control and Disarmament

Despite the nuclear threat that loomed throughout the 1950s, limitation talks between the Cold War antagonists were unsuccessful until the experience of the Cuban missile crisis (1962) when nuclear war seemed imminent. Real progress in arms control started with the Partial Test Ban Treaty in 1963. Important multilateral treaties that followed included the Outer Space Treaty (1967) and the Nuclear Non-Proliferation Treaty (1968). Political relations between the USA and the USSR improved enough to permit the bilateral Anti-Ballistic Missile (ABM) Treaty and SALT I (1972), later SALT II (1979). Another tense period of confrontation and impasse in bilateral arms control followed, until the Soviet approach changed under Gorbachev, leading to the INF and START I Treaties (1987/1991).⁹ Full disarmament, that is reduction to zero, was agreed for biological weapons (1972, multilateral), and chemical weapons (1993, multilateral).¹⁰ Nuclear test explosions (1996), and anti-personnel land mines (1997) have also been banned. These agreements have been mostly successful, despite the lack of full participation by all relevant powers, and despite some serious violations which have been detected and exposed – most notably with respect to the Biological Weapons Convention which was implemented without provisions for verification, inviting contempt.¹¹ General and complete disarmament (all countries, all armaments and armed forces) has been the declared goal of the UN and was mentioned in several arms-control treaties,¹² but this goal has not been seriously pursued in actual policy.

Arms control must be considered an unfinished project, and important gaps remain: there is no ban on nuclear weapons, there is no prohibition on space weapons (except for weapons of mass destruction deployed in space), and limitations on conventional arms and forces exist only in Europe. Recently, arms control and humanitarian law have become endangered by actions of the USA. Even before Sept. 11, 2001 the US refused to ratify the

Comprehensive Test Ban Treaty and blocked the negotiations on a Verification Protocol to the Biological Weapons Convention. Recently there have been moves towards easier resumption of nuclear tests. In 2002, the USA abrogated the ABM Treaty. The US has also systematically sought to undermine the International Criminal Court that was instituted by the international community.

4. Preventive Arms Control

Preventive arms control is qualitative arms control applied to the future; it is about stopping or at least limiting dangerous military developments before they become actual, in particular weapons exploiting or based on new technologies. Limitations can be designed to intervene at the stages of development or testing, or sometimes research. Precedents include: i) the ABM Treaty, which prohibited not only deployment, but also development of anti-ballistic missile systems that are sea-based, air-based, space-based or mobile land-based; ii) the nuclear testing treaties, which preclude certain experiments with actual nuclear explosions; and iii), the Protocol on Blinding Laser Weapons (1995), which explicitly bans only the use of blinding lasers but led to halting their development.

Preventive arms control assesses a potential new military technology using several criteria. One group of criteria concerns dangers to arms control and the international law of warfare: will the new technology undermine existing controls, law and norms? Another set of criteria concerns stability: will the new technology destabilize the military situation, *e.g.*, by reducing reaction times? Will it lead to a technological arms race? How about proliferation, in particular to regions with high probability of conflict? Finally, one needs to consider unintended hazards to humans, society or the environment.

If there are good arguments for restricting a particular technology, then one needs to take into account any positive uses – in particular in the civilian realm – and if possible devise rules that exclude the negative applications without overly restricting the positive ones. Methods for verifying compliance also have to be thought out – they must provide assurance that illegal activity would be detected, but must not be too intrusive or too burdensome.

5. Military Nanotechnology

Nanotechnology will change many aspects of our lives. Powerful computers will be ubiquitous. With the advance of artificial intelligence, the replacement of human labor by artificial systems will accelerate. New materials will lead to higher energy efficiency. Therapeutic drugs will be designed for the individual. Along with opportunities, there are also potential risks, be it to health, the environment, social justice or privacy. Convergence of nano-scale, biomedical, information, and cognitive science and technology (NBIC) can lead to applications with profound impacts on the human condition. The 2001/2 U.S. workshop on NBIC convergence mentioned, *e.g.*, nano-implant devices, slowing down or reversing aging, direct brain-machine interfaces, human-like artificial intelligence.¹³ These and other far-reaching concepts of manipulating the human body and mind imply risks and dangers, as well as ethical challenges, on an unprecedented scale. Containing abuse and unintended consequences will be difficult even in the civilian realm.

Military NT applications pose special risks – first, because of the preparations for destructive uses and second because of secrecy. Tackling this problem calls for special efforts. In order to provide reliable information, one can look at actual military NT research and development in the USA, which is both the leader in military NT and also much more transparent about its military research and development than any other country. In addition,

one can extrapolate scientific-technical advances and assess what military applications will become possible in principle.

5.1 Military NT R&D in the USA

In the USA, military research and development in nanotechnology (NT) has surged. Of the funds for the National Nanotechnology Initiative, one quarter to one third goes to the Department of Defense – in 2003, \$ 243 million of \$ 774 million.¹⁴ This is far more than any other country – the UK expenditures, for example, were stated as about \$ 2.6 million in 2001.¹⁵ Assuming total West European funding five times as high, with similar levels respectively for Russia, China and the remaining countries that are active in military NT R&D, the US expenditure would be five times the sum of all the rest of the world. (In military R&D at large, the USA accounts for two thirds of the global total.)¹⁶

U.S. work spans a wide range in the spectrum from basic research to advanced technology development – development of actual systems for deployment is still several to many years off. University research grants fund nanoscale machines, carbon nanotubes, quantum computing and magnetic nanoparticles. The Defense Advanced Projects Agency funds projects in magnetic memory, bio-computing, bio-molecular motors, sensors for chemical and biological warfare agents, and micro robots, among many others. The research laboratories of the armed services work on self-assembly of nanostructures, organic light-emitting diodes, carbon nanotubes and composites, nanomaterials for explosives and propellants as well as for armor and projectiles, and many similar topics.

In 2002, the Army selected the Massachusetts Institute of Technology to house an Institute for Soldier Nanotechnologies, with up to 150 staff to work in seven multidisciplinary research teams. Their goals include a battle suit that protects against bullets, chemical and biological agents, and stiffens on demand to act as compress or splint. Sensors are to monitor the body status. For carrying heavy loads, an exoskeleton with “muscles” from artificial molecules is envisaged.

5.2 Potential Military Applications of NT

In general, NT can lead to improvements in traditional military systems and to qualitatively new ones. Very small but highly capable computers will be used in weapons, uniforms, logistics, and communication systems. Increasingly sophisticated and discriminating sensors may become very small, and cheap enough that they can be scattered in high numbers to saturate an area, ostensibly yielding “total awareness”. Guns will shoot farther, projectiles and missiles with cheap guidance systems will become smaller and more accurate. Vehicles will become lighter and more agile, with more powerful engines and greater range. Energy storage is a key problem for many military systems, and NT is often considered a key to solving it. Autonomous vehicles (robots) for reconnaissance and communication, but also for fighting, will arrive; some of them may be very small. NT ultimately raises the prospect of even microscopic mobile robots, although macroscopic vehicles are needed for high speed or long distance travel. Sophisticated fighting robots, the successor to today’s killer drones and prototype robot combat planes (UCAVs), will be enabled by advanced computers, smart materials, advanced energy and propulsion systems, and other NT-based refinements. Similarly, NT will contribute to lowering the cost and increasing the capability of space systems, including possibly very small antisatellite weapons. Robotics will be used in logistics, production and automation of complex weapons systems. A key enabler of robotics applications will be advanced computers capable of situation assessment and action planning, for example the motion planning needed to coordinate dextrous manipulators, or to maneuver through “battlespace”.

New chemical or biological warfare (CBW) agents may become possible that act selectively only against the intended targets. Nanobiotechnology is ambitious enough to propose robotized artificial microbes, which could become tools of assassination or mass murder. At the same time, nanomaterials for filtration and neutralization, and NT-based sensors and nanomedicine in general may provide new approaches to CBW defense. Advances in biocompatible materials and portable biomedical systems may allow the creation of body implants to monitor health status, release drugs or interface to the nerves and brains of fighters. Their portable computers may evolve into wearable information appliances producing an “augmented reality” which simultaneously gives the fighter access to information from the net and also gives command access to the soldier, placing her under some degree of “remote control”. The tendency toward cyborgization follows directly from such military goals and culminates in the vision of direct brain-technology interfaces, but the possibility of improving in this way on the performance of well-trained human senses and bodies, whether for fighting or for piloting or for thinking interactively, seems remote.

NT can be used in enhanced versions of existing nuclear weapons incorporating improvements to safety, reliability, etc., or possibly new types of conventional explosive in the fission primary. More speculative concepts include qualitatively new weapon types such as pure-fusion explosives of arbitrarily small yield. It is hard to predict how NT advances may impact nuclear weapons production and barriers to proliferation, but we have seen substantial advances in these technologies since 1945 and further improvement seems possible.

Scenarios along these lines, of more or less visionary character, are being discussed within the military and national security establishments of the world, particularly the USA, but many of these concepts will not prove militarily effective, as has been the case throughout history. Countermeasures to NT weapons will exploit NT as well, giving rise to complicated correlations of forces and complex arsenals within which unexpected interactions can arise.

6. Preliminary Assessment

When considering the various potential military NT applications under criteria of preventive arms control, one finds several that will be close to civil uses, such as small, fast, distributed computers or strong, light-weight structural materials. A few uses could help to protect against terrorism or would act mostly defensively. Examples are sensors and decontamination agents for biological weapons or improved injury care. Preventive limitation would be unrealistic or counterproductive in such areas.

However, there are several potential military applications of NT and/or NBIC at large that raise serious concerns under criteria of preventive arms control. In the medium term, the most dangerous ones involve:

- New selective chemical or biological warfare agents: These would violate the existing conventions, while posing new challenges to verification; they could be used either as weapons of mass destruction or for targeted assassinations, not only by armed forces but also by terrorists.
- Autonomous fighting systems – robots and robotic vehicles on land, in water or air: They would violate the international law of warfare if they would produce superfluous injury or could not recognize non-combatants or combatants *hors de combat*. Autonomous tanks or combat aircraft considered outside of the definitions of the Treaty on Conventional Armed Forces in Europe could undermine and endanger that treaty. Small satellites capable of attacking other satellites by direct hit or by manipulation after docking would destabilize the situation in outer space – not without consequences on Earth.

- Mini-/micro-sensors and -robots, including biological/artificial hybrids: They could be pre-deployed covertly in an opponent's territory to strike at an appointed time or on command, or to guide other weapons. If such devices are produced at low cost in large numbers, diffusion to other countries and to criminals is probable, creating the possibility of their use in asymmetric warfare or terrorist attacks.
- Body manipulation including implants: Under the imperative of combat efficiency, armed forces may more readily explore new possibilities for body manipulation than civilian society. Soldiers might voluntarily, or maybe under some pressure, accept risky or ethically questionable technologies that modify body chemistry, rewire brain, nerve and muscle, or otherwise radically alter the human organism. This could create "facts" and circumvent barriers in civilian society, preempting a thorough debate on benefits, risks, ethical aspects and needs for regulation.

7. Recommendation for Preventive Arms Control

These dangers can be contained by preventive arms control. Regulation need not focus on NT as such, but should take a wide view and address military mission areas. In many cases, the dangerous NT uses come under the headings of general agreements that exist already or that the international community has long asked for. In concrete terms, we recommend:

- The existing arms control and disarmament treaties that are in force as well as humanitarian international law should be respected and preserved. The Biological Weapons Convention should be augmented by a Verification Protocol.
- A general ban on space weapons should be adopted, with special rules for small satellites.
- There should be limits on military autonomous vehicles and robots, in particular with a combat function. Particularly important is a ban on autonomous killing.
- Small mobile systems should be mostly prohibited in the military as well as in civilian society, with very few exceptions (*e.g.* for search of collapsed buildings).
- Implants and other body manipulations that are not motivated by a direct medical condition should be subject to a renewable moratorium of ten years' duration.

For consistency and completeness, all rules for the military need to be coordinated with the regulation that is to be developed for the civilian realm.

8. Aspects of Molecular Nanotechnology

Particularly dramatic issues are posed by the vision of "molecular" or "machine phase" nanotechnology (MNT) as conceived by Drexler, Merkle and others.¹⁷ In this vision, complex systems would be structured, like living systems, from the nanoscale up. Using tough materials and machinelike principles not found in naturally evolved organisms, they could manufacture products from molecular components in lifelike processes similar to growth and self-replication. The products of such a technology would have performance characteristics far beyond what is achievable today. For example, these might utilize carbon materials with fully-integrated nanostructure and nanosystems. Artificial intelligence supported by MNT hardware should easily surpass human capabilities and could be used to direct the production and use of MNT systems without requiring human supervision.

Realization of this vision would create extreme dangers under all the criteria of preventive arms control, with the greatest problems arising from the potential for an arms race using autonomous production, and destabilization by pressures to attack first.¹⁸ The first task in addressing this area is to provide reliable assessments of the feasibility and time frame to develop the technology. MNT proponents have suggested that their vision could

be realized in as little as a few decades. If this turns out to be a realistic possibility, the regulation, including international preventive arms control, needs to be developed well in advance.¹⁹

9. Topics for Further Research

Concrete interdisciplinary investigations in the coming years should examine military NT programs in several countries, including the USA, potential opponents (NT-capable as well as threshold countries), U.S. partners and friends. This should be done with a view to building cooperation and avoiding exaggerated perceptions as motives for NT arms races. Other important topics for research include the potential for terrorist uses, and the use of NT to improve verification of compliance with agreements.

10. Concluding Remark

Containing NT dangers in civil society will require rules, checks, and penal measures comparable to those in effect for dangerous chemicals, nuclear technologies, genetic modification of pathogens, etc. Reliably preventing dangerous military uses by international agreement will need similar degrees of monitoring and juridical prosecution. This is difficult to conceive in an international system where national security is built on the threat of using armed forces. Unfortunately, the logic of today's international system points to confrontations, at the level of deterrence at least, between states armed with nanotechnology-based weapons. As advanced capabilities mature, this could become a new arms race tending toward instability. We better decide early which road we are to take, and it better be the one that leads to regulation.

Will powerful new technologies act as a lever to qualitatively strengthen the rule of law and other elements of civil society in the international system? Or will they provide ways to circumvent existing rules and render them ever less meaningful, ushering in an unregulated future in which technology itself dictates the fate of humanity?

Notes

¹ Altmann, J. & Gubrud M. A.: 2002, 'Risks from Military Uses of Nanotechnology – the Need for Technology Assessment and Preventive Control', in: M. Roco & R. Tomellini (eds.), *Nanotechnology – Revolutionary Opportunities and Societal Implications*, Luxembourg: European Communities, 2002, pp. 144-148 (available at http://www.ep3.ruhr-uni-bochum.de/bvp/riskmilnt_lecce.html); Altmann, J.: 2004, 'Military Uses of Nanotechnology: Perspectives and Concerns', *Security Dialogue* 35(1): 61-79.

² This had begun as early as 1983 – see Lem, Stanislav: 1986, 'The Upside-Down Evolution', available in the collection *One Human Minute*, San Diego etc.: Harcourt

³ See, for example, Metz S.: 2000, 'The Next Twist of the RMA', *Parameters* 30(3): 40-53; available at carlisle-www.army.mil/usawc/parameters/00autumn/metz.htm (4 June 2004); Petersen J.L. & Egan D.M.: 2002, 'Small Security: Nanotechnology and Future Defense', *Defense Horizons* 8, available at www.ndu.edu/inss/DefHor/DH8/DH08.pdf (13 Dec. 2002); see also the section on National Security in Roco, M.C. & Bainbridge, W.S. (eds.): 2002, *Converging Technologies for Improving Human Performance – Nanotechnology, Biotechnology, Information Technology and Cognitive Science* (NSF/DOC-sponsored report) (Arlington VA) (www.wtec.org/ConvergingTechnologies/Report/NBIC_report.pdf (23 Sept. 2003)).

⁴ Use of force (armed struggle) for liberation from the colonialist powers or racist minority regimes was legitimized implicitly and explicitly by UN General Assembly resolutions, see, e.g.: Declaration on the Granting of Independence to Colonial Countries and Peoples, General Assembly resolution 1514 (XV) of 14 Dec. 1960, available at www.unhcr.ch/html/menu3/b/c_coloni.htm (1 June 2004); Importance of the universal realization of the right of peoples to self-determination and the speedy granting of independence to colonial countries and peoples for the effective guarantee and observance of human rights,

- A/RES/32/14 of 7 Nov. 1977; Policies of apartheid of the Government of South Africa, A/RES/39/72 of 13 Dec. 1984 (latter two available at www.un.org/documents/ga/res (1 June 2004).
- ⁵ Art. 36, Protocol Additional to the Geneva Conventions of 12 Aug. 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol I), of 8 June 1977 (available via www.icrc.org/ihl.nsf, 1 June 2004).
- ⁶ Forces who cannot compete in technology have the option of guerilla warfare or of asymmetric warfare.
- ⁷ This is an example of the so-called security dilemma in an international system without higher authority where military preparations for improving the security of one state deteriorate the security of the others.
- ⁸ Article 1 of the Biological Weapons Convention bans possession of biological agents “of types and in quantities that have no justification for prophylactic, protective or other peaceful purposes”, without further clarification of acceptable types, quantities or justifications (www.state.gov/t/ac/trt/4718.htm). In the wake of the 2001 attacks, it was revealed that the US has developed new weaponized forms of anthrax in recent years, ostensibly for defensive testing purposes (Washington Post, December 13, 2001, Page A16, <http://www.washingtonpost.com/ac2/wp-dyn/A34707-2001Dec12>). Some would argue that this reveals the existence of an offensive US BW program, in that testing of protective equipment does not require the use of virulent agents, much less the development of new ones. However, development of vaccines and treatments would clearly benefit from testing against a maximally virulent agent. See also note 11.
- ⁹ SALT: Strategic Arms Limitation Talks; INF: Intermediate-range Nuclear Forces; START: Strategic Arms Reductions Talks.
- ¹⁰ The INF Treaty brought reduction to zero in a specific category of nuclear-weapons carriers, namely ballistic missiles and land-based cruise missiles with ranges between 500 and 5,500 km.
- ¹¹ BWC parties Iraq (UNSCOM document S/1998/308, www.un.org/Depts/unscom/s98-308.pdf (4 June 2004)) and the USSR (Alibek K.: 1999, *Biohazard*, New York: Random House) each developed extensive biological weapons research and production facilities and produced hundreds of tons of biological agents, while publicly maintaining their adherence to the BWC. A number of countries are suspected today of biological weapons possession or activities, some of them parties to the BWC (cns.miis.edu/research/cbw/poless.htm (4 June 2004)).
- ¹² E.g., Art. VI of the Non-Proliferation Treaty reads: “Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a Treaty on general and complete disarmament under strict and effective international control.”
- ¹³ Roco & Bainbridge 2002 (note 3).
- ¹⁴ National Nanotechnology Initiative – Research and Development Supporting the Next Industrial Revolution – Supplement to the President’s FY 2004 Budget, Washington DC, National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, August 2003; available at nano.gov/nni04_budget_supplement.pdf (17 Nov. 2003).
- ¹⁵ *Nanotechnology: Its Impact on Defence and the MoD*, www.mod.uk/linked_files/nanotech.pdf (see also www.mod.uk/issues/nanotech/contents.htm) (18 Nov. 2003).
- ¹⁶ Annual expenditures for military R&D in recent years were about \$ 40 billion in the USA, followed by \$ 4, 3, and 2 billion in the UK, France, and Russia, respectively, Bonn International Center for Conversion: 2001, *conversion survey 2001 – Global Disarmament, Demilitarization and Demobilization*, Baden-Baden: Nomos; China’s spending was estimated in 1994 at about \$ 1 billion, E. Arnett: 1999, ‘Military research and development’, in: *SIPRI-Yearbook 1999 – World Armaments and Disarmament*, Stockholm/Oxford: SIPRI/Oxford University Press, pp. 351-370.
- ¹⁷ Drexler K.E.: 1986/1990, *Engines of Creation – The Coming Era of Nanotechnology*, New York: Anchor/Doubleday; Merkle R.C.: 1994, ‘Self replicating systems and low cost manufacturing’, in: M.E. Welland, J.K. Gimzewski (eds.), *The ultimate limits of fabrication and measurement*, Dordrecht: Kluwer, pp. 25-32.
- ¹⁸ Gubrud M.A.: 1997, ‘Nanotechnology and International Security’, Fifth Foresight Conference on Molecular Nanotechnology, www.foresight.org/Conferences/MNT05/Papers/Gubrud/index.html (4 June 2004).
- ¹⁹ The Foresight Institute has published proposed safety guidelines for an MNT industry which give valuable ideas for the civilian context, but dismiss arms control on the grounds that 100% verification may be impossible, apparently assuming that arms control can only mean shunning all knowledge and that everything is lost if anyone cheats. This accords with the idea of an “assembler breakthrough” that may shake the world. A more conventional view would suggest that rogue actors are unlikely to make great technological breakthroughs that cannot be detected in a timely fashion and countered by the world’s major powers. *Foresight Guidelines on Molecular Nanotechnology*, Revised Draft Version 3.7: June 4, 2000, www.foresight.org/guidelines/current.html (13 May 2004).

Perception of Risks and Nanotechnology

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Abstract. There is no scientific evidence to support the notion that nanoparticles and nanotubes – basic components of nanotechnology-based products – pose risks to human health and the environment. Yet, there already have been considerable discussions in the mass media and the U.S. Senate about the potential hazards of nanoparticles and nanotubes, on how they possibly interact with living organisms and non-living systems, and further disseminate in the human body and the environment. For now, though, the lack of genuine scientific data on the potential hazards of nanotechnology on human health and the environment has misled the discussions: debate about the risks of nanotechnology today truly amounts to the *perceived* risks of nanotechnology – since the technical, scientifically estimated risks remain at bay. This paper argues that the perceived risks of nanotechnology are likely to overestimate and overrate the risk of nanotechnology. Contrary to what the nanotechnology community, policy makers, and funding agencies might be inclined to believe, the soon-to-be-released reports on nanomaterials toxicology will not necessarily put an end to public controversies over the potential risks and benefits of nanotechnology.

1. Assessing the Risks and Benefits of Nanotechnology

For scientists studying nanotechnology, defining risk-benefit trade-offs generally means weighing the risks and benefits of nanoparticles, fullerenes, nanotubes, nanowires and the like compared to those associated with materials that are currently in use. A case in point is the application of nanoshells to treat cancer. Nanoshells, made of silicate or silver core nanoparticles surrounded by a gold coating, have unique optical properties (Jackson & Halas 2001, Lal *et al.* 2002). The hope is that chemically modified nanoshells could identify, bind and – unlike traditional chemotherapy – selectively destroy cancer cells. The results could be a significant reduction of chemotherapy side-effects and a higher survival rate by early detection of cancer cells.

Recently though, some concerns about the potential hazards of nanoparticles and nanotubes for human health and the environment have been raised in the media (Brumfiel 2003, Dagani 2003, Feder 2003a, Feder 2003b, Nature Editorial 2003, Service 2003, Stuart 2003, Witchalls 2003). The focal point of these discussions is the size of these nanomaterials – typically one billionth of a meter, that is to say approximately 70 times smaller than a red blood cell in size and close to a DNA molecule in diameter. There is concern that these dimensions might allow them to penetrate the skin and possibly even elude the immune system to reach the brain. From an environmental standpoint, issues such as the pace and strength with which nanomaterials may bind to organisms and non-living species in water, soil, and air, as well as their stability over time and potential bioaccumulation in the food chain, are being discussed, too.

2. What is Known, What is Not

As of Fall 2003, no peer-reviewed scientific article has concluded that nanoparticles and nanotubes are dangerous for human health and the environment. At present, the only two studies published on the hazards of nanomaterials did not find carbon nanotubes to be toxic. More specifically, these initial studies concluded that fullerene soot with a high content of carbon nanotubes does not induce pulmonary dysfunction or show any signs of health hazards related to skin irritation or allergic risks (Huczsko *et al.* 2001, Huczsko & Lange 2001). Still, there is no consensus among scientists whether nanomaterials are risk-free.

More toxicology studies are currently being carried out at the Johnson Space Center, at the Dupont Haskell Laboratory for Health and Environmental Sciences, and elsewhere. The preliminary results of these investigations were presented at the 2003 American Chemical Society's annual meeting, but are not yet published in peer-reviewed journals. Additional toxicology studies are also expected to be carried out as a result of the July 2003 call for proposals by the U.S. Environmental Protection Agency (EPA). It dedicates \$4 million to the study of the impacts of manufactured nanomaterials on human health and the environment.

To summarize, any health and environmental hazards from nanomaterials remain unidentified for now. Interestingly, insights from controversies over genetically modified – GM – crops reveal that the perception of risks can quickly overtake reality in the court of public opinion, and dominate public acceptance for years to come even when data suggests that the fear is overblown. In fact, a close look at the GM crop story suggests that at the heart of the debacle was public perception of risks, not scientific facts.

3. A Digest of the GM Corn Debacle

Genetically modified corn with Bt – *Bacillus thuringiensis* – bacteria was seen as a seductive option that provides an alternative to spraying crops with pesticides. In the US, corn generates over \$17 billion per year and over \$4 billion in exports. One of the problems in growing corn is that it can be attacked by insect pests. Among them, the European corn borer is the worst enemy. Bt corn was engineered to produce toxins with pesticidal properties that selectively kill European borers but that are inoffensive to other insects, animals, birds, humans and the environment.

As a result of a series of risk assessment studies, the EPA approved marketing of the first genetically modified crop in 1995. The controversy over Bt corn was triggered four years later, when Cornell entomologists published a scientific correspondence in *Nature* with the provocative title “Transgenic pollen harms monarch larvae”. The study suggested that Bt corn pollen may harm the beautiful and already endangered monarch butterfly (Losey *et al.* 1999). The day after its publication, on May 20 1999, both the U.S. and European mass media covered the story with sensational headlines: “Biotech vs. ‘Bambi’ of insects? Gene-Altered Corn May Kill Monarch” (*Washington Post*); “Engineered corn kills butterflies, study says” (*USA today*); “Pollen from GM maize shown to kill butterflies” (*The Guardian*). Opponents of bioengineering were quick to point out that scientists might not be able to anticipate the negative consequences of introducing engineered plants into the environment.

The controversy had devastating consequences for the GM crop industry. Monsanto, the world's leading Bt corn producer, experienced a 10% drop in the value of its stock; while Gerber Products, a baby food producer, announced under public pressure that it would not use GM ingredients. While there were definite concerns in the US, the study only served to intensify Europe's fear and disgust with GM crops. The EU chose to suspend the approval of Bt corn in 1999 – though there is only a small population of monarch butterflies

in Europe – fearing that native moths and butterflies may be endangered. Soon after, the EU called for a moratorium on GM foods.

In November 1999, a consortium made of Bt corn producers – namely Monsanto, Novartis and Dupont – and the US Department of Agriculture hosted a conference on the impact of GM crops on the environment. After investing \$150,000 in nine research projects commissioned to academic institutions, the scientific community failed to reach a consensus on Bt corn hazards, but acknowledged that there is some level of risk that needed to be further understood. A month later, in December 1999, the EPA held hearings on GM foods. In the spring of 2000, in response to a petition by activist groups, the EPA undertook additional risk assessment studies that concluded, “EPA is confident in Bt crops”.

Meanwhile, Bt corn producers and the Department of Agriculture spent an additional \$200,000 on research projects. The results, published in October 2001 in the Proceedings of the National Academy of Sciences concluded that Bt corn presents little risk to monarch larvae (Hellmich *et al.* 2001, Oberhauser *et al.* 2001, Pleasants *et al.* 2001, Sears *et al.* 2001, Stanley-Horn *et al.* 2001, Zangerl *et al.* 2001). The US EPA then extended registration of Bt corn for seven years. After maintaining its moratorium on the farming and import of genetically modified foods and grains for several years, the EU partially lifted the moratorium in July 2003 by establishing a rule that would allow the marketing of GM foods on the condition that all food with more than 0.9% GM ingredients be labeled.

The GM corn debacle suggests that the mere allusion to Bt corn risks to the monarch butterfly, amplified by the media, profoundly altered the trajectory of some genetic engineering applications and considerably damaged the financial wherewithal of major companies. Intriguingly, the initial negative perceptions of the unknown risks were not subsequently overcome by the agreed upon evidence that Bt corn is harmless. Promoters of nanotechnology hope that such a scenario will not be repeated. The question that deserves to be looked at with scrutiny is this: what factors are most important in affecting these perceptions of risk?

4. Perception, Judgment, and Reaction to Risk

To many, the monarch butterfly is a vivid symbolic image of nature’s fragile beauty. The association of this vivid image with a catastrophic event, namely the potential extinction of the monarch butterfly by involuntary exposure to Bt corn pollen, stigmatized Bt corn in the view of the public. This grave image that an endangered and beautiful species could be wiped out due to human tinkering created strong negative feelings in the mind of the public. Had the story been about beetles or flies, the mass media, consumers groups and environmental groups probably would not have responded in the same way – essentially because the association of images with beetles and flies is considerably weaker and less positive than with the monarch butterfly.

What seems counter-intuitive is that the initial formulation “Bt corn = monarch butterfly killer” stuck to the public mind, even after the publication of convincing evidence for “does not do harm” eighteen months later in the Proceedings of the National Academy of Sciences. In fact, the industry, regulatory, and funding agencies probably hoped that failure to link Bt corn to undesirable consequences on the monarch butterfly would make public opinion tip towards public acceptance of GM crop. It did not. Instead, the initial framing that GM crops are bad remained persistent in the public’s mind throughout the controversy. At best, it fed into public skepticism in the U.S.; and at worst, it fed into the public backlash against GM food in Europe.

These observations are consistent with what psychologists, behavioral and decision science researchers have described over the last two decades. In fact, psychologists Amos Tversky and Daniel Kahneman – recipients of the 2002 Nobel prize for economics– have

long ago shown that presentation of information and formulations of risks causes significant shifts of preference in the choice between different options (Tversky & Kahneman 1981) – that is, such choice is sensitive to the way stories and problems are framed (for example, in terms of the probability of the outcomes expressed as loss of human lives or, on the contrary, as gain of human lives).

In other words, judgment about risk strongly depends on the way risks are presented (or framed) and communicated to the lay public. In the case of the Bt corn controversy, the mass-media have contributed to framing the debate around “Bt corn = monarch butterfly killer”, insidiously stressing the negative consequences of Bt corn use over its potential benefits – limiting the spraying of pesticides – and putting the burden of proof on the scientific community and Bt corn producers.

Paul Slovic and coworkers demonstrated that initial public perceptions are in fact strong and difficult to overcome (Slovic 1987). The initial and controversial perception that Bt corn is bad, as framed by the mass media, was indeed resistant to change, even in the presence of subsequent agreed upon, contrary evidence. The persistence of the initial perception is reinforced also because risks stick to the public mind to a higher degree than the associated benefits (Starr 1969).

Along the same lines, Slovic concluded in a recent study on nuclear technology that negative trust-destroying events are more visible and carry greater weight than positive, trust-building events (Slovic 1999). For example, in the Bt corn story, the publication of the article in *Nature* entitled “Transgenic pollen harms monarch larvae” received much more attention from the media than the series of articles published in *Proceedings of the National Academy of Sciences* in early October 2001 whose titles were much more neutral in tone, as illustrated by these two examples: “Impact of corn pollen on monarch butterfly populations: A risk assessment” or “Assessing the impact of Cry1Ab-expressing corn pollen on monarch butterfly larvae in field studies” (Sears *et al.* 2001, Stanley-Horn *et al.* 2001).

5. Decision Process and Risk Overestimation

Though the mass media played an important role in framing public debate and shaping public opinion on Bt corn, individuals’ characteristics are also decisive in perceiving risks. In the lay public mind’s eye, the association of a vivid image with a catastrophic event that can potentially be a threat to future generations leads to risk overestimation. Other factors that distort risk judgment are the newness of a technology, its dreadful character, the lack of knowledge and lack of controllability of risks. Risk distribution – who shares the risks and the benefits – also play a significant role in the way non-technical persons comprehend risk. All these factors lead to the overestimation of risk (Slovic 1987). More recently, Sjöberg showed that risks created by interfering with the process of nature – that is, natural *vs.* unnatural risks – affect risk judgment (Sjöberg 2000).

In brief, risks are often misjudged. Contrary to what the scientific community is inclined to believe, reactions to risks are not exclusively guided by evidence collected in the scientific tradition. Instead, risk assessments are rooted in human values such as common sense, intuition, imagination, memory, and past experience. This may explain why scientists and staffers from regulatory and funding agencies tend to believe that open public debate over technology often distorts the truth about facts and claims, which eventually results in poor social decisions. But research in decision science clarifies these concerns. It shows that individual response to risk is likely to be conditioned by feelings like worry, anxiety and fear (Loewenstein *et al.* 2001).

Moreover, fear – and its perception – is big business. Marginal pressure groups such as environmentalists and consumer groups have a great impact on public debate because they feed on the fear factor of new technologies to raise funds, to increase their member-

ship, and to become more visible. The media, too, benefit from the fear factor. Events that are novel, rare, vivid, and that generate tensions and negative feelings are far more newsworthy – thus leading to increased newspaper sales and higher advertisement revenues – than ordinary, mundane, and happy events. To some extent, funding and regulatory agencies also profit from the fear factor. In fact, the FDA, EPA, and OSHA justify part of their budgets by increasing the scope of hazards monitored in our food, drugs, the environment and our working place – even more so in the aftermath of 9/11 and the Iraq war.

Perceptions of risk and decision processes about new technology have been the topic of key articles published in *Science* (Tversky & Kahneman 1981, Slovic 1987, Starr 1969). But the troubling development of genetic engineering controversies over the last five years or so suggests that the scientific community, NSF, EPA and FDA among others have failed to take notice. So long as such studies are overlooked, tensions between the lay public and the scientific community are unlikely to fade away.

6. Perceptions of Risk and Nanotechnology: What to Watch For?

The perceived risks of nanotechnology are likely to overestimate the risk of nanotechnology. Some of the concerns expressed in the media by environmentalist groups, and by a handful of scientists as well, happen to be the trigger points that lead to risk overestimation. They catalyze the lack of familiarity with nanotechnology among the public, the uncertainty over equitable distribution of knowledge and equitable balance of the risks and benefits, the difficulty in predicting the potential hazards, and – last but not least – the association of nanotechnology with the public backlash against genetically modified foods. Along with these, dimensions like beliefs, conviction, morality (what is wrong, what is right), and ethics (what is good, what is bad) have so far received little attention from scholars in nanotechnology and deserve to be explored.

Collecting information on the perception of nanotechnology risk is as important as – or perhaps more important than – the mere collection of scientific data about the potential hazards of nanomaterials. So far, the burgeoning field of nanotechnology risk assessment has emphasized data collection and factual judgment based upon the utilitarian framework of technically calculated cost/benefit analysis rather than emphasizing the values of individuals that have long been known by decision theorists.

The failure to understand or acknowledge how non-technical persons perceive, assess and make decisions about risk may hamper the trajectory of nanotechnology as public policies and business practices are adopted. In conclusion, perceived risks are real. Perceived risks may very well constitute the tipping point that will decide whether nanotechnology succeeds.

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Nano-Ethics

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Abstract: Nanotechnology will bring surprises, both beneficial and harmful, and so will create ethical issues for its practitioners and for society. If we are to have some understanding of what lies in store, we need to distinguish between ethical issues internal to a practice and thus of particular concern to its practitioners, and ethical issues external to a practice. We also need to understand how artifacts can produce harms and how rapidly developing technologies produce harms by provoking errors, wholly unintentionally, among those who use its artifacts.

Introduction

Any developing technology brings surprises. We are not now in any position to know the details of how nanotechnology will develop, what it will produce, or how it will affect our lives. We can only draw inferences from what we can argue, hope, or fear are analogous technological developments – with no way to gauge the extent and limits of any analogy. One certainty, however, is that ethical problems will arise within and because of nanotechnology, exacerbated by particular features of nanostructures.

Suchman (2002) lists three features of nanostructures that, according to Glimell, “will generate novel issues of responsibility and control”:

- (1) *Invisibility*: nano-machines would be among the first complex constructions intentionally engineered to accomplish human purposes at a microscopic level, and their introduction into the technological armory would dramatically increase the potential for orchestrated covert activities;
- (2) *Micro-locomotion*: (the ability to move through and within macroscopically solid matter): free ranging nano-machines will radically challenge our traditional understandings of macro-boundaries and barriers; fences, walls and even human skin are largely open space, at the nano-scale;
- (3) *Self-replication*: as difficult as it may be to realize as of yet, self-replication will be a common attribute for any nanotech production passing market conditions, thus becoming socially significant; it poses profound challenges to human foresight and control, since without a carefully designed ready ‘off switch’, a population of self-replicating nano-machines could grow exponentially. (Glimell 2004, this volume, quoting Suchman 2002, p. 97)

At least two other features are relevant to ethical issues that nanotechnology will bring:

(4) *Behavioral unpredictability*: things do not behave at the nano-level as we would expect given how they behave at the macro-level. We shall thus find ourselves surprised at the ways in which invisible, free-ranging and perhaps self-replicating nanostructures penetrate our lives.

(5) *Ontological status*: the ontological status of nanostructures is contested. Even the understanding of why nanotechnology will be so important mirrors a contest between seeing nanostructures as Lilliputian machines that are constructed atom-by-atom, and seeing them as organisms, mirroring nature’s reproductive processes.

Of these five features, the third, self-replication, is most problematic. What underlies the third feature is a concern that nanostructures be inexpensive so that they become a significant part of the market. But presuming that self-replication is the only solution to expense puts limits on our imaginative capacities – never a good idea with developing technology. The potential harms of nanotechnology could be considerably greater if nanostructures turn out to be self-replicating, but in what follows, I will ignore this possible feature of nanostructures, keeping in mind only that their social impact will no doubt be affected by their cost. We shall find that the potential harms are still significant.

Two more comments about these five features are necessary. If we do not presume that nanostructures are self-replicating, then micro-locomotion does not imply that nanostructures are self-driven, only that they are capable of moving through what we have traditionally thought of as barriers to movement – our skin, for instance. In addition, to claim unpredictability is to claim no more than what we have discovered already. No one predicted that carbon nanotubes would exhibit the great strength they display. We are going to be surprised by the behavior of nanostructures, and only a *Candide* would not think that at least some of those surprises will be harmful to us.

Those potential harms are of two sorts, what I call external and internal. We need to begin by clarifying that distinction, at least in a rough way.

1. Internal and External Ethical Problems

Ethical problems are internal or external to a developing technology just as they are to any profession. One often finds in engineering texts such claims as that engineers are not responsible for the misuse of the artifacts they design. Why should an engineer be held responsible when someone drives a car into a crowd? The ante is then upped by adding that, for example, although an engineer could make a car that would be significantly safer to drive – a tank is the standard example – anything an engineer designs can be misused by someone in some way. After all, the range of stupidity, the capacity for inattention and carelessness, and the failure to learn are far greater than the capacity of even the best and brightest engineer to anticipate these. Besides, anticipating problems will not preclude the tradeoffs required in terms of cost, for example, that hem in engineering design. The implication of upping the ante is that engineers are not accountable for any use at all of what they design – although if that conclusion were ever drawn explicitly, its falsity would be apparent.

A clear example of what an engineer would be responsible for is an artifact that provokes a user to cause harm. An engineer who designed such an artifact would have made an engineering and a moral mistake and be ethically at fault. No tradeoffs in cost, efficiency, simplicity or any other desiderata can justify an engineering design that entices a user to do or fail to do something that will produce harm, particularly if the harm is grievous.

Engineers are not responsible for every use of what they design, but they are responsible for what they design, and it is easy to find examples of artifacts that entice users to cause harm. Such error-provocative designs, as I call them, are the responsibility of engineers. We do not need philosophical imagination here, but can draw on our own experiences.

Consider doors whose design signals they should be opened one way, when they open the other (so that wrists are wrenched as we pull when we should push, or vice versa) or double glass doors that fail to signal that they are locked. We come into a building by pushing on the right-hand door, but when we attempt to exit by pushing on the other one, we discover it locked and so wrench our shoulders or get hit by those behind us. Nothing about the door indicates that it is locked, and, indeed, the situation implies it is unlocked. Why

make those who are coming in and going out use the same door so they block each other's way?

An engineer who purposefully designed artifacts to entice users to cause harm would be thought ethically perverse. I am not at all suggesting that engineers are perverse – no matter how many examples of apparently perverse designs we run into daily. But let us suppose an evil genius of an engineer. Understanding how such an engineer could cause harm will show us how deeply ethical engineering is.

Consider what happens when an accident occurs – a train wreck, for instance. Three variables matter: the operator, the artifact, and the situation in which the accident occurred. Of the situation, we ask if there was fog, something amiss about the signals, or something else that would cause problems for even the best and brightest of operators. Of the artifact, we ask if something about it led to the accident. Did the throttle stick? Of the operator, we ask about what can go wrong – inattention or lack of intelligence or training.

'Inattention' covers a variety of problems, all having to do with the mental state of the operator – sleeping, inebriated, dead, high on drugs, distracted, and so on. When police investigate an accident, they try to see if the driver was inattentive for some reason. "Do you have a cell phone?" "Please step out and take this test (to determine if you are drunk)." Any one of these and similar failures in the driver could be the culprit, that is, the decisive factor that led to the accident.

Such questions presume that the operator is intelligent enough to use the equipment in question and well enough trained so as not to make simple mistakes. But not all operators are well enough trained, and some are not the brightest and best. So a thorough inquiry into an accident would investigate the training the operator received and the general level of intelligence the operator displays.

Yet a real evil genius of an engineer would presume intelligence and training. Failures of intelligence and training take care of themselves, as it were, causing enough harm without any help from an evil genius. A really evil genius would ensure that the more attention we paid to using an artifact, the more likely harm would occur. A really perverse design would entice even the most cautious of the best and the brightest to cause harm. To assure that such operators do not always approach artifacts with caution honed by failure, a real evil genius of an engineer will randomly introduce artifacts that mislead, such a genius would hone through practice and research what best misleads. A real evil genius of an engineer would take most pride in artifacts so designed that even the most intelligent and well-trained operator, alert to all the difficulties that might occur, will be misled by the design into producing exactly the opposite of what was intended.

My Subaru SVX has a shoulder harness that automatically closes on passengers as the door is shut, giving the illusion of safety but ensuring that if the seat belt is not fastened, "severe head trauma" will result, as the car manual puts it, when the harness belt slices through one's neck in an accident as one's forward momentum is checked so one slides down in the seat. I cannot count the passengers who were surprised when I asked them to fasten the seat belt, which meant that they thought the harness protected them automatically.

That we would think an engineer evil who intentionally designed such artifacts, tells us that good engineering is not ethically neutral. We should expect tradeoffs between safety and other criteria. But a good engineer minimizes the risks to those who are to use the product and does not design an artifact that signals a way to use it which guarantees that the end for which it appeared to be designed will be defeated. We should look ethically amiss at an engineer who designed an artifact that consistently misled the normal user, the user who is not the best and the brightest, sometimes distracted or inattentive, and often not well trained.

“But surely,” any engineer would say, “we can’t be held responsible for every mistake that’s made!” Right. A line needs to be drawn between what an engineer is responsible for and what not. An automobile can be a lethal weapon, but an engineer cannot be held ethically liable for someone using it to run down pedestrians. Such use is possible, no matter how a vehicle is designed, and so no engineer can be held ethically liable for having produced a design that did not preclude this possibility. The ethical problems which arise because of that sort of misuse are what I call external to the profession of engineering.

An automobile could be made into a lethal weapon by design features not essential to it. A cowcatcher on a hood with spikes for impaling pedestrians would be such an example. Or, for those with a perverse sense of humor, the ‘Spring Surprise’ of the chocolate manufacturer in the Monty Python sketch serves even better: the chocolate covers a spring-loaded set of hooks and, as one sucks, the tension in the spring finally overcomes the thinning coat of chocolate to release the hooks so you are, well, surprised. A design triumph of perversity.

What is required for an engineer to maintain ethical innocence regarding the use of the design is that nothing about the design itself causes harm or tempts anyone to cause harm. Put another way, what is ethically internal to the profession is what we could attribute to an evil genius of an engineer. Ethically internal is also when we call an engineer good who produces engineering design solutions which minimize as best as possible the harms that could result from an artifact.

Such a distinction is rough, of course. The examples I have used are all relatively benign artifacts – automobiles, doors. A different set of concerns arise if an engineer is designing, for instance, an artifact whose purpose is to cause harm – a bomb, a land mine. But the distinction will serve our purposes here.

If we map this rough distinction between internal and external ethical problems onto nanotechnology, we ask the following:

- a) Are there ethical issues that arise, or will arise, internal to nanotechnology?
- b) Are there ethical issues that arise, or will arise, external to nanotechnology, but resulting from it?

We will first consider examples of ethical issues external to nanotechnology. These are perhaps the easiest to understand and the most likely to capture one’s imagination.

2. Lilliputian Artifacts

An essential feature that sets nanostructures apart from other artifacts is size. They are from 1 to 100 nanometers, from one- to 100-billionths of a meter, significantly less than the 50,000 nanometers of a human hair. Obviously, they cannot be perceived by the naked eye (Ratner 2003, p. 6), and can thus be produced and deployed without ever being observed by any human being – except indirectly through highly sophisticated instrumentation. A consequence of their unobservability is that their deployment would be virtually undetectable.

I taught with an engineering colleague who started his career in electrical engineering and switched to industrial engineering when he realized the danger of working with something of which you cannot see that it can kill you. His insight should not be lost when we consider nanostructures. We can be harmed by them without even realizing they are in the vicinity. The kinds of ethical issues this unobservability creates can be illustrated by noting three problems. These problems are external to nanotechnology. They arise through what are predictably the ordinary uses made of nanostructures or as a consequence of there being nanostructures at all.

Privacy: One problem is readily predictable – and has been predicted. Sensing devices so tiny they are invisible to the naked eye and to any readily available instrument will be and, no doubt, are being developed. With such devices, we open the prospect of spying

on individuals in ways that would make 007 and his handlers salivate with anticipation. There would be no need to open a phone to install a listening device or hide one in the electrical circuitry. We could simply add nano-sensing devices to the paint or a composition floor to turn a 'safe' room into a recording and transmitting studio. Alternatively, such devices could be put into our bodies without our being the wiser. The average citizen would be at the complete mercy of anyone familiar with nano-sensing. Those interested in someone's conversations could readily listen in by putting nano-sensing structures into jacket pockets or into a Trojan horse of a gift. Even someone with reason to suspect eavesdropping would be ill-prepared to track down the nanostructures that could be anywhere nearby. Their detection would require what we can presume to be special highly sophisticated equipment.

When nanostructures are free-ranging, the level of concern rises. Put on us or in us, they may migrate where they wish, penetrating our skin and embedding themselves wherever they end up in our bodies, perhaps in our fatty tissues – along with any HIV virus, PPB (Robison 1994, pp. 1-2), and other contaminants that find a semi-permanent home there. If they were self-replicating as well, we would need to multiply the problems astronomically.

We thus have with nanostructures a new reason to be concerned about invasions of privacy, and especially in the current political climate new reasons to be concerned about governmental surveillance. We can better understand how our privacy is likely to be invaded, and the various harms those invasions entail, by examining three of the four different privacy torts in American law – intrusion, disclosure, and appropriation (Prosser 1960). The tort of false light seems of little relevance here (Robison 1997), but the other three torts are crucial to understanding the different ways in which we will be harmed and the differing magnitudes of harm those invasions will produce. Consider intrusion first.

The standard sort of example for intrusion as an invasion of privacy is having someone come into one's bedroom while one is making love or into some other space where one has every reasonable expectation of being left alone. Sticking your hand into someone else's pocket, without permission, is a nice example of intrusive behavior, and letting loose nanosensors into that pocket or otherwise putting them onto or in a person to gather information is another instance. We have an expectation that our bodies are ours, not to be trespassed upon, as it were, without our permission. When someone sprinkles nanosensors on us, or in us, we will have no idea that intrusion has occurred. A pickpocket may be skillful at putting a hand in a pocket without the owner being any the wiser, but it is still intrusive and the owner will be the wiser once the wallet or other valuables are missed. What is added by the Lilliputian size of nanosensors is that no one could reasonably expect us to know that our privacy has been invaded. When someone bursts into our bedroom while we are making love, we generally know it or, at least, could know it. When nanosensors are in us, sending out information about our temperature, movements, and so on, thus telling someone outside our bedroom what we are doing, we are helpless to help ourselves from such intrusion.

We are also helpless to preclude disclosure, the second privacy tort. The standard sort of example is someone's passing on a secret. The secret is disclosed. We all keep some information to ourselves. This is, among other things, one way of distinguishing between friends, acquaintances and strangers. We tell friends things about ourselves that would be inappropriate to tell our acquaintances (although that would be one way of beginning to turn an acquaintance into a friend). Telling such things to strangers would mark us as addled, if not crazy. Control over information about our personal lives allows us to keep, among other things, control over who we are publicly and privately. Nanosensors would allow a stranger to know everything about us that we would want to control, from private conversations with one's spouse or lover to intimate details about one's body temperature

and state of health. A stranger could well know far more about us than we can know about ourselves.

That someone knows as much or more about us as we do, permits the last relevant privacy tort, namely appropriation. That occurs when someone takes another's identity. Identity theft is the most recent variation of an old problem of someone pretending to be someone else and thus appropriate identity. Such theft will become that much easier as information about us is relayed to a stranger who will pick up all those conversations we think are private (about finances, sex, our mother's maiden name, whatever) and use that information to appropriate our identity.

In each case – intrusion, disclosure and appropriation – our privacy is invaded. While this is a harm in and of itself, the effects of such an invasion can obviously also be harmful. We encourage privacy because we value, among other things, keeping some things to ourselves and keeping control over what others know and do not know about us. With nano-sensing devices easily spread wherever one might wish to spread them, and with their being undetectable without special devices, and perhaps not even then, we may find ourselves liable to far greater harm than we now experience through present devices such as video cameras.

We have had a marked increase in the ways in which our lives are being recorded since the concept of privacy was first introduced into the law by Warren and Brandeis in 1890 (Warren & Brandeis 1890). We have surveillance cameras observing us as we transact business at the bank, or watching us as we walk the aisles of a store. We have cards that allow stores to record our purchases so files can be compiled about us that are much more complete than anything we would ever have thought to compile for ourselves about our buying and spending habits. There are files on us in the computers in our physician's office, at our place of employment, in the various agencies of our government (regarding our driving, taxes, voting), at the schools and universities we attended, at the bookstores and websites we frequent, and so on. It does not take much skill to put much of this together to form a rather complete dossier, and if, as Leibniz argued, we are individuated and identified by that set of predicates that are true of each of us, someone with such information can know far more about us than even we might have occasion to pay attention to, recall or know ourselves.

We are not now aware of all the ways in which our privacy is invaded. We cannot keep track of how data about us is transmitted from one place to another – as happens, for instance, when security checks are run, or when we are stopped for speeding and our place of employment is checked as well as our driving history and record of convictions, or when a physician's office informs our insurance companies of a claim, which then informs our employers. We are so used to surveillance cameras that we rarely notice them, and they can be so readily concealed, in any event, that they become like nanostructures – unobservable to the naked eye although all-observing of what we are doing.

The introduction of yet another device for gathering information about us should come as no surprise. Knowledge is power, after all. But the minute character of nanostructures and the subsequent ease with which they can be sown in any soil at all, whether barren or fertile with possibilities for those doing surveillance, means that the stock of information about us available to those with the technology will increase exponentially. The likelihood is high that such devices will be relatively inexpensive, eventually making it to the open market, black or otherwise. The consequence is that we shall not only have governmental bodies using such devices to gather information about us, but the general public – our acquaintances, employers, spouses, voyeurs.

I have provided invasion of privacy as an illustration of how nanostructures may profoundly affect our lives and increase the risk of harms to all of us. I could have chosen other

illustrations, but I suspect none is as unnerving as the second sort of illustration we need to consider about how our lives may be profoundly affected by nanotechnology.

Bionanotechnology: The worry is that bionanostructures will be created that would do for worries about anthrax and other deadly biological agents what AIDS did for herpes. One researcher in nanotechnology argues for a moratorium on all work in bionanotechnology and even defines ‘nanotechnology’ in a draft of the second edition of his book in such a way as to exclude bionanotechnology from the field (Lyshevski 2000). He says that he can give no details about why a moratorium is necessary, but the clear implication of his suggestion is that he is aware of potential developments that would put “all mankind at risk”.

Two possibilities seem likely – new kinds of biological agents or a new means of delivery. It does not take much imagination to have concerns. We would be dealing with free-ranging Lilliputian structures. One mistake on the part of a researcher who fails to scrub thoroughly could mean a new infectious agent or a new mode of delivery out in the world, capable of moving without hindrance throughout our bodies and its organs. That healthcare practitioners are still puncturing themselves with needles used on AIDS patients is some evidence of how even the most careful and informed of practitioners can make mistakes.

The worries are multiplied when we presume that there are not just well-intentioned researchers trying to avoid mistakes, but others who purposely want to introduce new biological agents or new ways of delivering them. How could any border guard who is checking those coming into a country know who is carrying bionanostructures and who is not? The question is not rhetorical: technological means for detection of nanostructures will advance as nanotechnology advances, but the lag time in development, necessary in order to have some idea of what it is that we are trying to detect, will ensure windows of opportunity. As we have discovered in trying to intercept drugs, the cleverest will always figure out some new way to bypass the standard practices for detection. Defensive measures always lag behind offensive innovations.

How a bionanostructure might pose grave danger is unclear: presumably there would be serious consequences for us only if it were either self-replicating in some way or if it were so inexpensive to produce, that billions upon billions could be made and somehow spread for consumption. But there is no more use speculating here on what might come about regarding nano-biological agents or nano-delivery systems, than there is in proposing a moratorium on research in bionanotechnology. As the world discovered with Dolly, the clone whose creation startled those working in the field, we have little control over what those with the talent and technique can do and, rather obviously, we have few ways of knowing what they are doing. The same holds for nanobiotechnology. In a commercial world of secret development, made necessary to ensure patents, knowledge is gold, and there is no likelihood of anyone or any government ever being in a position to ascertain what the state of the field is in nanobiotechnology. Perhaps that is just what concerns the researcher who wishes for a moratorium.

Environmental health: Nanostructures are already being used in many products, from rearview mirror housings to skin cream. Their introduction into our environment and, indeed, into us, has proceeded without any thorough testing of, for instance, the consequences to our health. To state the obvious again: we have had no testing of the long-term consequences of exposure to nanostructures and, in particular, to the long-term consequences of exposure to the billions upon billions of nanostructures we shall soon have in our environment, given the pace of commercial exploitation. That means that we will all be part of a large-scale experiment on the health effects of the introduction of nanostructures into our environment and into us. We cannot now know how that experiment will turn out.

We ought to be concerned – just one analogy from what we know about other small particles. We know that particulate matter smaller than 10 microns will “infiltrate the tiniest

compartments in the lungs and pass readily into the bloodstream and have been most strongly tied to illness and early death, particularly in people who are already susceptible to respiratory problems” (Revkin 2001). The relationship between such particles and death and ill-health is well substantiated and obvious. When we breathe, the smallest particulate matter is most likely to be taken into the deepest parts of the lungs and stay there, eventually clogging the lungs and, as they make their way into the bloodstream, causing whatever problems foreign particulate matter can cause (Environmental Protection Agency 2001).

The most recent reports on what experiments have been done on the health effects of nanoparticles are anything but reassuring. When researchers at DuPont “injected nanotubes into the lungs of rats”, fifteen percent “died quickly”. The research leader, David Warheit, said that it “was the highest death rate we had ever seen” – this from a researcher who “began his career studying asbestos and has been testing the pulmonary effects of various chemicals for DuPont since 1984”. The problem appears twofold: the material is drawn deeply into the lungs because it is so small, and “the cells that break down foreign particles...have more trouble detecting and handling nanoparticles than larger particles” that have been the object of concern for toxicologists (Feder 2003; see Service 2003, p. 243.).

Research has not been limited to inhalation into the lungs. A recent study also indicates that minuscule particles in air pollution put the heart at greater risk than the lungs. The danger comes from “particulate matter less than 2.5 microns”, and what was discovered through an examination of “pollution data from more than 150 cities over 16 years” and about a half million people was that for each increase of 10 micrograms per cubic meter of air, “the risk of death from ischemic heart disease went up 18 percent” (Nagourney 2003). Preliminary research also shows that nanoparticles in nostrils make their way “directly into the brain”, with as yet unknown consequences. They also change their “shape as they move from liquid solutions to the air” in apparently unpredictable ways so that forming general conclusions from experiments about particular substances is complicated (compare European Commission Consumer Protection 2004). What is not complicated is the claim that we ought to be concerned about the health effects of nanoparticles.

One ethical concern we thus ought to have is that nanoparticles in and of themselves will cause harm to us. It is not just that some evil genius of a bionanotechnician may produce a new kind of nano-agent or nano-delivery system that will somehow inaugurate a new millennium plague, as it were, but that the very introduction of nanoparticles into our environment will itself produce the equivalent of a plague.

These three illustrations of ethical problems – regarding privacy, bionanotechnology, and the environment – fasten on features peculiar to nanostructures, namely, that they are free-ranging Lilliputian entities. Indeed, even if we concentrate only upon their Lilliputian size, nanostructures will create ethical problems.

These problems are external to the practice of nanotechnology. Nanosensors and nanobiological artifacts, like delivery systems, can serve good ends, and so they will be developed, and nanoparticles will enter into the environment. No nanotechnician can alter the characteristics of those nanoparticles or of the nanostructures that will cause ethical problems when those developed for good ends are misused. As for the development of new toxic biological agents, for instance, we will be dependent upon the judgment of individual practitioners, and, clearly, we live in a world where real evil geniuses thrive.

3. Harmful Surprises

An additional feature of nanostructures is that they can behave in surprising ways:

For example, a nanoscale wire or circuit component does not necessarily obey Ohm’s law, the venerable equation that is the foundation of modern electronics. Ohm’s law

relates current, voltage, and resistance, but it depends on the concept of electrons flowing down a wire like water down a river, which they cannot do if a wire is just one atom wide and the electrons need to traverse it one by one. This coupling of size with the most fundamental chemical, electrical, and physical properties of materials is key to all nanoscience. (Ratner 2003, p. 7)

The failure to obey Ohm's law is predictable – although we might not have thought through the requirements of Ohm's law before discovering its limits at the nanoscale.

Other features of nanostructures seem unpredictable. Nano-gold, if we may call it that, does not look yellow, for instance. “Nanoscale gold particles can be orange, purple, red, or greenish, depending on their size” (Ratner 2003, p. 13). It is only when they are allowed to congregate, or “combine” (Ratner 2003, p. 15), that the yellow reappears. And trying to achieve new computer chips means working with the unknown “since properties change with size at the nanoscale” so that there is “no particular reason to believe...chips will act as expected” (Ratner 2003, p. 18).

That Lilliputian structures may not behave like larger objects will no doubt mean huge benefits for us. A single recent example will suffice. It is helpful to be able to distinguish, and distinguish quickly, different kinds of gases. Think of a terrorist bringing a deadly gas into a country masquerading as something benign. Because gases ionize at different temperatures, we can distinguish them by how they react to different voltages. Yet current machines for detection are expensive and bulky, on the order of four to five feet square to generate and accommodate the high voltages necessary to distinguish gases. But “the tips of many nanotubes ‘amplify the local electric field by many orders of magnitude’” with the high voltage being nano-localized, as it were (Ramirez 2003). So nano-detectors can sniff out differences in gases – at very low cost per unit, with no danger from high voltage, and, obviously, without bulk. The sniffers are not yet perfected, but we will soon have tiny sniffers available to monitor gases without intrusive and time-consuming procedures. Police officers will not need to test drivers to see if they are drunk and, if so, on what.

If we are to have some idea of what properties will be uncovered by particular investigations, we need a way of understanding, and of predicting, how nanostructures will behave. The problem is not new. John Locke says of gold that

he that, to the yellow shining Colour of *Gold* got by sight, shall, from my enumerating them, have the *Ideas* of great Ductility, Fusibility, Fixedness, and Solubility, in *Aqua Regia*, will have a perfecter *Idea* of *Gold*, than he can have by seeing a piece of *Gold*, and thereby imprinting in his Mind only its obvious Qualities. But if the formal Constitution of this shining, heavy, ductil Thing (from whence all these Properties flow) lay open to our Senses, as the formal Constitution, or Essence of a Triangle does, the signification of the word *Gold*, might as easily be ascertained, as that of *Triangle*. (Locke 1975, III.XI.22.4-13)

Some of the qualities of substances, color, for instance, we perceive by seeing the substance itself; some, such as ductility, by working with the substance and perceiving what Locke calls its powers. But no matter how complete our list of qualities, it is a list, a compendium of what has been observed by us about gold.

Any such list has at least three limitations. It can vary from individual to individual, the bulk of us not having observed gold closely enough or manipulated it to note its many properties. Second, even if we had, the set of properties we perceive may be incomplete, and we would never know that. New instruments of observation may add to our list of observables. Think here of what the discovery of the microscope made possible. Manipulating a substance in new ways, or with different substances than before, may produce more observables. Locke would have been unaware of what happens when gold is irradiated.

The third limitation is that the list is a set of conjunctions, tied together only by their being observed in relation to – a weasel phrase – the substance we call gold. The list provides us with no way of understanding why all these qualities are conjoined. What is it about what we call gold that accounts for its having all those qualities?

Locke assumes that seeing the “formal Constitution” of *e.g.* gold would allow us to see the relations between what we do observe and know about gold. We would then have a single determinate understanding of gold. As he says, “the real Essence is the constitution of the insensible parts of that Body, on which those Qualities, and all the other Properties of Gold depend” (Locke 1975, III.VI.2.27-30).

With an understanding of the real essence of gold, Locke suggests, all of gold’s properties would be as open to our understanding as the properties of a triangle.

Nanotechnology seems to promise the sort of knowledge Locke thought possible. Having the capacity to manipulate nanodots of gold gives us an opportunity to understand whether and how its appearing yellow to humans under normal lighting is dependent on its nano-properties. Working at the nano-level, that is, gives us the opportunity to prove the truth of, or give the lie to, what we might think of as Locke’s conjecture. It allows us to position ourselves to understand how a substance’s properties depend upon its nanostructure.

If gold appears yellow once its nano-particles are permitted “to combine” and its nanodots appear different colors “depending on their size” (Ratner 2003, pp. 15, 13), then different sized combinations of gold nanodots – two here, four there – give rise to our perceiving different colors. Descartes said that our perception of color depends upon the spin of the particles we see. Whatever the explanation, our concern is not with the promise of nanotechnology and nanoscience, but with its perils.

We have enough evidence, it seems, to hoist at least a tentative general truth about nano-particles: we will be surprised. The worry is one with which we are all too familiar from research in other pristine areas: we may unwittingly produce something harmful. We have considered one possibility in bionanotechnology, but the concern is broader, namely that we will produce a nanostructure – a new form of substance, as it were – that will do for the physical world what purple loose strife and kudzu have done for native North American plants. The world is filled with our mistakes, and the concern is that at a minimum we avoid doing something that will make the world irremediably worse.

Just as the unobservability of electricity has prevented ‘better living through electricity,’ this concern about accidentally producing something immensely harmful will and should not prevent the development of nanotechnology. Working with something of which you cannot see that it can kill you, is not a good idea – unless you take protective steps to insulate yourself and others from harm. We need to think through ways of working with nanostructures so as to minimize potential harms. In this, we face at least four problems.

(1) We have no agreed-upon standard that will serve as a guide for the rational development of nanotechnology. We have at hand a relatively well-developed understanding of what risks we as a society can accommodate and what risks are beyond the pale. We can accommodate some high fliers on our highways, however much we might prefer they not fly near us. The risk of our driving is increased by such high fliers, but the harms are localized, no matter how great. But the harms of nanotechnology will not necessarily be localized, and what is needed, at the minimum, is a decision-procedure for research and development that takes full account of the potential for great harm, even if unwittingly produced. What society cannot tolerate are high fliers who put all of society at great risk.

And yet, that statement’s truth is a function of its generality. Once we proceed to cases, disagreements abound. Get to a specific case – *e.g.*, genetically modified food – and its failure as a guide for action becomes clear. Disagreements abound about whether something is risky, about how risky something must be to curtail work on it, and about what we

ought to do when we have no way to measure the risk. We have no agreement on how to proceed in the face of such uncertainties (Robison 1994, pp. 148-63).

The controversy over CFC's and the ozone is an instance of how we disagree. Those who argued we should do nothing until we are absolutely clear about the causes of the known harm had a point: doing something of which we cannot be sure that it addresses the causes of the harm may just aggravate the situation or make it more intractable. Yet it is hard to disagree that a failure to act now, even without the full assurance usually necessary to preclude harm, will ensure that the harm being produced will become far too great to countenance. The disagreement about how to proceed turns on the weight one gives to these competing understandings of what is rational in the face of possibly great harm. That we have banned the production of CFC's is a sign that we can all reach agreement about some matters when we have disagreement about uncertainties, but that agreement stands alone.

(2) Even if we had an agreed-upon standard, it would be essentially contestable. We will have the most well-intentioned and brightest of individuals disagreeing about whether some form of research is or is not in accord with 'standard and acceptable practice.' There is no way to settle such disputes. By its very nature, no standard can guarantee its own application in particular cases. Each standard needs a set of interpretive rules by which it is to be applied. What counts as an 'out' in tennis is not self-evident, for instance, and those who must apply the standard must have some way to determine what counts as outside the line. Hitting the outer edge of the line is not the same as brushing it, for instance, and some will see the latter as out while others see it as in. The same holds for any standards we may come to have regarding research in nanotechnology. We may think we have clarified matters by hoisting a standard for what is acceptable and unacceptable experimentation, but no matter what the standard, we will come upon disagreement about what it means in particular cases.

(3) Even if we had a rational guide for development and it were somehow not contestable, not everyone would follow it. With no rational guide, the range for disagreement about what is acceptable and what is not will permit all sorts of experiments that some would not countenance. The experiment that produced Dolly is perhaps one such example. The problem is that any researcher into nanotechnology may be a high flier, a Jack-in-the-beanstalk of investigators, willing to bet the family livelihood on the promise of a bean.

Any rational guide would be unenforceable, and we would find that even for the most well-intentioned individuals, the temptations to experiment in areas deemed dangerous might overcome reluctance. The hubris of being the first to find a cure, the drive for funds to further additional work in the area of one's expertise, the biased evaluation of the risks and potential harms and benefits to be expected by those who stand to gain from success and lose by inaction – all these conspire to motivate even those who do not want to cause harm. How much the worse for all of us when we have someone whose motivations are less pure.

(4) In addition, the fastening upon a standard and the adoption of an enforceable one requires a politically loaded procedure, complicated beyond measure by its needing to be international in scope (Robison 1994, pp. 62-82). I will not pursue what ought to be obvious to us all or draw the skeptical conclusion about research that follows.

Nanotechnology and nanoscience will bring surprises if only because of the very nature of developing technologies. With surprises will come unintended harms. We can at best attempt to control what happens regarding research within a country and apprise those working at the nano-level of the complications they, and we, may face when we are surprised. But that means that we are dependent upon the ethical integrity of the professionals in the field. Put another way, we are looking at an ethical issue internal to nanotechnology and any attempt to minimize it will depend primarily upon its practitioners, not upon soci-

ety and not upon those who will make use of the technology. That is why any evil genius working with nanotechnology is of such concern.

4. Ontological Status

During an interdisciplinary yearlong seminar in nanotechnology sponsored by the Provost at my university, an engineer and a chemist were discussing the use of nanostructures to deliver medication within the body or provide the silver (gold, actually) bullet to a cancerous cell where radiation would focus on it, killing the cell but leaving everything else intact. The engineer was frustrated. "Tell me what the parts are, and I'll make it!" The chemist replied, "But it's not a mechanism. It's a living organism." "I don't care," the engineer replied. "It has parts, and if I knew what they are and how they work together, I can build it."

The Cartesian allusions are not irrelevant. At issue is the nature of nanostructures. The chemist and the engineer each saw nanostructures from the perspective of their own disciplines and squared off, as it were, because each held to their own discipline. But saying that misses the more important issue. One essential feature of nanostructures appears to be that by their very nature their ontological status is contestable.

Nanostructures are, it is claimed, the smallest machines we will ever be able to build. True or not – and we should be skeptical of claims that we shall never be able to do this or that – that feature means that nanostructures are interdisciplinary, if we may put it that way, in the way nothing else has ever been. They are objects of interest to engineers, who can manipulate the atoms to create mechanisms; biologists, who can begin to understand how the smallest organisms function; physicists and chemists, who can investigate the properties of substances such as gold by understanding the nanostructure of gold, as it were, and so on.

Disciplines are so specialized that no one can be conversant with them all, let alone keep track of what is happening in them all. Someone not steeped deeply in chemistry simply cannot understand articles in chemistry journals. Someone not deeply steeped in physics cannot understand articles in physics journals. So seeing nanostructures from the perspective of all the different disciplines looks to be a pipe dream.

Barriers to understanding and cooperation are thus integral to nanotechnology and science. Yet that understates the problem we are noting. Practitioners of each discipline – *e.g.*, biology, engineering – not only will see nanostructures as objects within their discipline, but will have a vested interest in seeing them that way.

A discipline can obtain funding for its initiatives only if its object of concern is part of its subject matter. So an engineer interested in nanostructures will see them as mechanisms: they are then objects of professional interest and projects involving them are fundable. Just so for someone in biology. If nanostructures are mechanisms, their proper field of study is engineering, not biology. So someone in biology must see them as organisms to justify a professional interest in them and to justify funding. So the engineer and the biologist must be at odds. Three consequences are of importance for nanotechnology.

First, the status of nanostructures will remain essentially contested as long as competition remains for funding and for the field of study. If the ontological status were determined to be mechanisms, for instance, engineering would have them to itself. Just as biology took in all DNA research, so engineering would take in all research in nanostructures – much to the chagrin, no doubt, of other disciplines and to the detriment of what ought to occur if we are to understand fully what nanostructures are. We should be looking at them as they are from the perspective of every relevant discipline and communicating with each other as best we can about why they can be perceived as mechanisms and as organisms, for instance. But attempts at a common understanding may be difficult.

Second, the drive for funding will create distortions in our understanding of nanotechnology and nanoscience. Just as we have spent much more money investigating the properties of oil to the detriment of our understanding of the full range of natural substances in the world, so we may find ourselves spending far more money on, say, nanostructures as they are in biology than as mechanisms.

Third, such distortions are not ethically neutral. Funding that might go towards a general understanding, will go to that discipline which makes the best case for nanostructures being just the kind of object that discipline studies. And the best case for funding initiatives will be made by that discipline which makes the “best” and quickest use of nanotechnology.

Biology is advantaged because the concern for medical advances is a perennial winner in funding competition. Presumably, something good will result: we will have new cures and new ways of delivering medication. Yet these benefits will not be driven by an objective assessment of how best to proceed to make use of what we discover in nanoscience. Any benefits will be based on who makes the best case for funding. It might turn out that an objective consideration would produce just the result we get, but that would be a happy accident.

In following some discipline’s success down whatever road it happens to take, we will be eschewing other paths that might have been equally or more beneficial. The attendant ethical harms are a result of the way emerging technologies are now developed. The harms are thus internal to nanotechnology: it is, after all, just another technology. Yet the way a technology develops is what I call a social artifact and so can be changed (Robison 1994, pp. 14-34). In that sense, the harms are external to the practices of nanotechnicians because those harms are not the fault of any particular practitioner. There is a degree of responsibility because one is a participant in an ongoing practice. But one would be no more responsible than someone who pronounces ‘milk’ as ‘melk’ and thereby encourages a curious colloquial variant.

5. Error-provocative Designs

Stories abound of computer programs that were rushed to market untested and, apparently, even untried. A reviewer of a program that gave driving directions told of the warning that appeared on his screen telling him that he had neglected to put in his state when he filled out the information about his current location. Unable to go forward or back, he had to crash the machine, only to discover, on rebooting, that the lines for one’s address did not include a line for one’s state. Such examples are all too common in a new technology which is market-driven. The faster a product is out the door, the more quickly the needed funds flow back in.

Similarly, a developing technology driven by grants requires success for continued funding. Success says, “We are on the right track: continue to fund us!” The temptation to shade the truth and the likelihood of touting success before thorough testing are thus high, with all the attendant problems of misleading other researchers, who may follow what is touted as a promising path when it is not, thus setting back development, and so on.

In a mature technology, the history of our successes and mistakes can guide product design. By the mid-thirties, certainly, the standard black desk phone could be dropped off a desk without disturbing a connection. The cutoff buttons were cradled between the prongs that held the receiver when the phone was not in use. Comparison with cell phones is striking – from the ease with which we can break a connection accidentally to the lack of a standard design, increasing the difficulties in figuring out how to operate them.

A rapidly developing technology, driven by external funding or the market and without a history, will produce mistakes. The worst sort are, as I have said, error-provocative designs. These need not be the intentional result of an evil genius of an engineer. They can

just as easily be the unintended result of a rush to product, no history of failure to curb the imagination, no time to determine what could go wrong with an artifact so designed.

When the designs concern telephones, the harms are generally relatively minor. With some technologies, the harms could be disastrous. We are only now beginning to understand how flawed computer programs can cause major problems with our energy production and transportation systems because terrorists or hackers may use the flaws to infect and corrupt, disable, or reprogram our systems. Nanotechnology presents just such a concern:

First, the stakes are enormous. The company that patents a nanostructure to deliver medicine will reap a fortune. The company that patents the device that powers nanostructures will earn even more. The first country to utilize nanostructures as listening devices will gain a huge advantage on the battlefields, industrial and military.

Second, the technology is new. We have already been surprised by such small things not behaving as we might expect from their macro- or even micro-siblings.

Third, we have no lag time for discovery. One of the most impressive features of Darwin's development of his theory of evolution is that he took his time so that when his work was published, the evidence was massive and detailed. The vision of a nanotechnologist working slowly and methodically, or sitting in a study mulling over what needs to be done has no place in the development of nanotechnology. Neither does the vision of a cooperative scientific community reading each other's papers and sharing information that will guide future development and prevent the repetition of mistakes and errant investigations. The delay between discovery and publication in a journal is so great that by the time of publication, the technology has already passed it by, either incorporating it or ignoring it. Governmental and industrial initiatives will be secret, and so each lab, in government and in industry, will be working in a relatively isolated position, dependent on what scuttlebutt they can pick up through friends and acquaintances or through reverse engineering of products that are marketed or heard about.

Fourth, what drives nanotechnology gives little time for experimentation. As with genetically altered food, we will be running a full-scale experiment on the world without any clear conception of what harms could result. Think of asbestos here, or birth-control pills. We are still uncovering the difficulties their introduction into our lives has produced. This is not to say that benefits have not resulted, only that harms have occurred which perhaps could have been avoided with a larger time frame between discovery and application. Yet because the benefits of first discovery are so enormous, and the demand for new technological fixes so insistent, we will be introducing products that will likely cause harms – just as the introduction of nanoparticles already may well be causing harm.

So, fifth, we will predictably produce harmful 'stuff.' With the best of intentions, the best practitioners will be working quickly in an area in which they will be surprised.

The lesson is not that we should prohibit work in nanotechnology or in any area of nanotechnology, like bionanotechnology. We could not do so even if we wanted to. The implication to draw is more pessimistic than the one we drew about the harmful surprises we will uncover. We will not be able to control what happens regarding research within a country, and even if we apprise those who work at the nano-level of the complications they, and we, may face, any additional caution they might take will be based on the generality that they may be surprised. That is not a very helpful admonition. They will already know that.

What we have is a feature of an emerging technology supporting the conclusion we drew from a feature of the object of that technology. Nanostructures will conspire to surprise us with harms we will not have anticipated and against which we thus cannot readily protect ourselves.

6. Summary

Ethical problems will arise from features of nanostructures – their Lilliputian and perhaps free-ranging nature, with unpredictable powers, to use Locke’s word – and they will arise because nanostructures are being developed in an emerging technology. Some of these ethical problems will be internal to the practice of nanotechnology and nanoscience. For example, we will have the inevitable failures of design and the subsequent harms that arise quite naturally, without intention, when an emerging technology is moving at such speed that it has no history of mistakes, that its practitioners lack the time to consider thoroughly whether there are design flaws, and so on. Some of the ethical problems will be external to nanotechnology and nanoscience. We will have the harms that occur when products of the new technology are used to invade privacy or create new biological agents or means of delivery. We will have the harms attendant upon the introduction of nanostructures into our world, new sorts of environmental hazards that we are ill-prepared to fend off or mitigate.

The ethical problems I have laid out were not randomly chosen. Some are readily predictable, such as the use of nanostructures to invade privacy. Some are scary, such as new nanobiological agents or delivery mechanisms. All require thoughtful decision-procedures on the part of the practitioners of nanotechnology and nanoscience and on the part of all of us, who will use the products of that technology and who will be exposed to nanostructures even if we do not use them. All tend towards a pessimistic view of our capacity to have any thoughtful decision procedures that will mitigate harmful surprises – or intentional harms. Yet I do not mean to provide a complete list of the ethical problems we will face with nanotechnology and nanoscience. Such an attempt would fly in the face of what we know about nanostructures, namely, that we are going to be surprised. It will help us get a handle on future surprises by distinguishing between those ethical problems that are internal to the practice and so of intimate concern to those who work in nanoscience and nanotechnology, and those ethical problems that are external to the practice. The distinction is rough, but is meant to provide a framework within which to place ethical difficulties and so begin to understand how best to respond to them. Whether the framework itself misleads, is itself an empirical question – its resolution depends, among other things, on how the use of this framework helps us grapple with the ethical issues produced by this new technology.

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Nanoethics: Assessing the Nanoscale from an Ethical Point of View

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Abstract: In this paper we raise and analyze three fundamental issues related to nanotechnology. First, although nanotechnology is frequently discussed, it is a difficult field to understand and define. We suggest at least a working characterization of the nature and organization of nanotechnology. Second, we examine the nature of nanoethics and motivate why it is a proper concern and possibly an emerging new field. Third, we elaborate several specific ways in which nanotechnology is likely to raise ethical issues. Some of these ethical issues will almost certainly confront us in the not too distant future and others, though not imminent, may well become serious issues some years from now.

1. What is Nanotechnology?

Does a field of nanotechnology¹ exist? This may seem like a strange question to propose given that many people, scientists and non-scientists, understand nanotechnology as today's hot scientific area. Governments are giving out millions of dollars, euros, and yen in research funds. Institutes for nanotechnology are springing up at major universities around the world. Courses and conferences in nanotechnology abound. And as the ultimate existence proof – there are academic journals for nanotechnology. Whereas all of that is true, nanotechnology is relatively new to the scientific scene and is inchoate. One has only to ask people, even those who self-identify themselves as nanoscientists, to define the field and eyes begin to dart. Asking people to describe the best example of nanotechnology produces a scientific smorgasbord of replies. As frustrating as it may be to get clear on what nanotechnology is or might be, it is important to make the attempt. Disputes about the nature and possibility of the ethics of nanotechnology may lie in differences in the conception of nanotechnology itself.

One feature that seems definitive of nanotechnology is that it is a technology that operates on matter on a very small scale – the scale of nanometers. A nanometer – one billionth of a meter – is very close to the dimensions of individual atoms whose diameters range from 0.1 to 0.5 nanometers. Hence, it is reasonable to regard nanotechnology as technology that manipulates atoms and molecules or utilizes the properties of them that occur on the nanometer scale. There is vagueness about where to draw the line. One hundred nanometers or less is a popular choice for a boundary of the nanoworld. But, some who consider themselves nanotechnologists may construct and manipulate even larger molecular structures. So, just to be generous, let us regard anything less than a micron (a thousand nanometers) to be a possible candidate for nanotechnology although obviously there are orders of magnitude differences within that range.

Size offers us an identifying characteristic for nanotechnology, but are there other defining features? A range of approaches regarding the means of production and operation of nanotechnology vie for attention. Recall how the possibility of nanotechnology was suggested originally in a famous lecture given in 1959 by the Nobel laureate Richard Feynman.

The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws it is something, in principle, that can be done; but in practice it has not been done because we are too big. (Feynman 1959)

Feynman recommended a path to accomplishing these feats – develop better electron microscopes. In 1981 his vision became a reality when the scanning tunneling microscope (STM) was invented by Gerd Binnig and Heinrich Rohrer at the IBM research facilities in Switzerland. The STM allowed humans to see atoms for the first time and earned the inventors a Nobel Prize in physics. With an appropriate selection of charge the STM can lift atoms out and deposit them elsewhere. This procedure allows the manipulation of atoms one by one. In a graphic demonstration of the power of the STM, researchers in the early 1990's created the smallest advertisement in the world by writing the letters "IBM" using xenon atoms. With the development of the STM two important missions of chemistry – the analysis of substances and the synthesis of substances – were made easier. A crucial tool for the development of nanotechnology is now available. But to what extent could an atom-by-atom assembly be practical? Clearly, manipulating atoms one by one with a STM is not an efficient method for the construction of useful amounts of any substance.

General chemical techniques can be used to produce large batches of nanoparticles. For example, sol-gel technology is sometimes regarded as nanotechnology. Sol-gels are colloids, suspensions of tiny particles, in liquids that keep their shape and can be used to encapsulate very small particles. This is particularly useful in developing products such as safe sunscreens. The active ingredients in sunscreens absorb, reflect, or scatter ultraviolet light. Unfortunately, when these active sunscreen ingredients do their job, they can produce photodegradation products and free radicals that can be absorbed through the skin. To prevent absorption these active ingredients are encapsulated in miniature sol-gel nanoparticles (Wilson *et al.* 2002, p. 71). General chemical techniques are effective and efficient, but they do not seem particularly special for a new technology.

The most elegant approach for nanotechnologists is to generate beneficial products through self-assembly. Self-assembly occurs when ingredients are added in the right sequence under the right conditions and the laws of nature construct the structure. Water turning into an icicle is a familiar, simple example of self-assembly. In this manner, rather than manufacturing a computer chip from the top down as we do now, a chip might be grown from the bottom up in a beaker. An example of this approach is the development of a biosensor in 1997 (Cornell *et al.* 1997). This biosensor has an ion-channel switch one and a half nanometers across that has a high sensitivity similar to chemical sensors in living creatures. It has a synthetic membrane that allows different ions to pass selectively. Two halves of a molecule set in the upper and lower layers of a membrane slide past each other. If nothing is detected, the molecule halves can slide into alignment and ions can flow from one side of the molecule to the other. If the target chemical is present and binds to the biosensor, alignment cannot take place and the circuit is broken. Variations of this biosensor could be used to detect blood type, bacteria, viruses, antibodies, DNA, drugs, or pesticides. Because the device is attached to a gold base, it can become an integral part of a microelectronic circuit. The biosensor is not built from the top down but grown from the bottom up by adding chemicals in the right proportions.

As we have seen, if we try to define 'nanotechnology' in terms of the means of its production, we have a choice among candidates such as atom by atom, general chemical techniques, and self-assembly. Possibly, we will be more successful in our search for defining properties of nanotechnology by seeking conditions on how the technology is expected to function. But here again we see a variety of approaches. Some nanotechnologists envision the construction of mechanical nanomachines that have parts such as wheels, axles, gears, hinges, and pumps. For example, carbon nanotubes, hollow tubes with graphite

walls, come in various dimensions. These can serve as axles and can be geared to translate or reverse motion. They can serve as pumps or pistons by moving the inner tube of a multi-walled nanotube. Such a nanopump already has been constructed in the laboratory (Wilson *et al.* 2002, p. 107).

In other cases the nano-objects are standard computing chips but are constructed on the nanoscale. Stan Williams and researchers at Hewlett Packard make computer memory devices by creating eight platinum wires 40 nanometers wide on a silicon wafer, putting switch molecules on top, and then running eight more wires running perpendicularly to the original wires. Each of the 64 points where the wires cross the molecules between them becomes a bit of memory. This structure is reminiscent of the core memory of the 1960's computers but on a dramatically reduced scale. It would take more than a thousand of these 64 bit chips to be the width of a human hair (Antonelli 2002, p. 3).

Eric Drexler, the leading prophet of nanotechnology, offers another conception of the future of nanotechnology in which nanomachines, mechanical or otherwise, operate as assemblers that will allow us to construct molecular structures.

Because assemblers will let us place atoms in almost any reasonable arrangement [...], they will let us build almost anything that the laws of nature allow to exist. (Drexler 1996, p. 14)

Drexler's vision of how the central nano-objects will function is the boldest. According to him, molecular computers will control these molecular assemblers. Molecular computers will operate electronically, mechanically, chemically, optically, or otherwise and will perform their calculations thousands of times faster than today's computers because of their decreased size. Drexler imagines these nanocomputers will have memory capabilities that will allow them to locate instructions and to record information as well. Whereas assemblers synthesize, disassemblers can be built to break down and analyze. Disassemblers are nanomachines guided by nanocomputers that through the use of enzymes and other chemical agents take substances apart a few atoms at a time and possibly record what they find in their analysis. Finally, replicators are assemblers programmed to make copies of themselves. If a replicator makes a copy of itself, and both of these make more copies, and so forth, in a reasonably brief time through exponential growth, literally tons of replicators could exist assuming the raw products needed for replication are available.

Although Drexler's conception of such assemblers, disassemblers, and replicators seems fantastic, he argues that nature already has them. Cells replicate by copying their DNA and dividing into two. The DNA in a cell provides the program for the cells to build the body. The information from the DNA is transcribed into RNA that is read by the ribosomes as a set of instructions for building proteins. Thus, biology provides a kind of existence proof for the possibility that molecular machinery can construct complex organisms from the bottom up.

It is not surprising that an incipient field like nanotechnology is not well-defined. There is a choice of size for which objects should be considered nano-objects. There are multiple means of construction of nano-objects (atom by atom, standard chemistry, self assembly, etc.). There are multiple means of operation of nano-objects (mechanical, electronic, chemical, etc.) Necessary and sufficient conditions are difficult to find for many concepts and the evolving, multifaceted concept of nanotechnology is among them. 'Nanotechnology' is probably better understood as a family resemblance term. There are some paradigm examples of nanotechnology and other cases that are related more or less closely to the paradigm examples. Paradigm examples of nanotechnology have an interdisciplinary flavor to them. A good paradigm of nanotechnology is a self-assembling object whose operation is best understood as part chemistry, part physics, part biology, part computing, and part engineering – all of which projected into the nanometer realm. The bio-

sensor described earlier is an instance of such a paradigm example. This is not to say that nano-objects that lack such an interdisciplinary orientation fail to be examples of nanotechnology but that they may be less clear examples.

We have been carefully surveying the multifaceted nature of nanotechnology because we believe this multifaceted nature can explain some disagreements about nanotechnology and its effects. For example, one could select certain examples and claim that nanotechnology has existed for a very long time. Chemists have been synthesizing compounds that depend upon self-assembly for centuries. Scientists have grown crystals, including semiconductor crystals, one atomic layer on top of another, for some time. Thus, one might conclude the field is not new at all, just old fashioned chemistry. Or one could pick other examples, such as some of Drexler's imagined artificial assemblers and argue that the field does not exist and may never exist. Both of these conclusions are extreme, but our point is that one's choice of a conception of nanotechnology can have a major impact on what conclusions one draws about it including conclusions about what its ethical and social implications are likely to be.

2. What is Nanoethics?

Nanoethics is the ethics of nanotechnology. But, if the choice of what counts as nanotechnology is not agreed upon, then obviously the importance of nanoethics may be difficult to establish. If one believes nanotechnology is just straightforward applied chemistry and nothing more, then nanoethics becomes the ethics of chemistry at best. Or, if one believes nanotechnology refers only to fanciful mechanisms that in principle cannot exist, then the value of nanoethics is dubious. To avoid confusions and disagreements about the nature of nanotechnology due to narrow definitions, we will assume a broad understanding of it. The size of its basic objects is on the nanoscale, and its means of production and methods of operation may vary considerably. And though many objects count as examples of nanotechnology for us, we find the compelling paradigm to be one that has an interdisciplinary appeal to physics, chemistry, biology, computer science, and engineering.

Often, discussions of ethics quickly focus on harmful practices. This may mislead some into regarding ethics as an attack on a field rather than on the potential negative outcomes of that field. Clearly, technology can produce benefits as well as harms. In particular, nanotechnology offers much hope for improving the human condition. In order not to focus exclusively on potential dangers, let's begin by considering some of the positive consequences of nanotechnology that we might expect. If we adopt our broad understanding of what counts as nanotechnology, then many good consequences from it are likely to materialize in the not too distant future. For example, nanotechnology might be employed to help clean up the environment. Dr. Braach-Maksvytis suggests creating artificial photosynthesis. Solar-powered paints could remove CO₂ from the atmosphere and convert sunlight into useable energy. Alternative systems could remove other pollutants from the air (Luntz 2001). Lighter but stronger materials could be developed from designer molecules. Planes made of lighter materials with the strength of diamonds would be more fuel efficient and safer. Clothing made of stronger materials would last longer. Further into the future health inducing nanobots might travel through blood vessels clearing away plaque and entering cancerous cells to destroy them. Nanotechnology might be able to manufacture food and clean water cheaply. Computer chips might be made inexpensively from chemical synthesis avoiding toxic byproducts. A technology that offers the hope of a cleaner environment, better materials, improved health, plentiful food, and cheaper computing is very attractive. Until recently, nature has been the chief nanotechnologist; now humans will get their share of the action. Even in the short run, the potential for improving human flourishing through nanotechnology is impressive.

Moreover, the possible application of nanotechnology in the long run is nothing short of breathtaking. If quantum computing becomes feasible, then an enormous number of independent calculations may be done simultaneously. And, theoretically any object could be constructed atom by atom if methods could be found to manipulate and assemble the atoms rapidly in the right way. Nanotechnologists would not be limited to what does exist or has existed but would on this vision be able to create radically new objects including new forms of life.

The potential benefits are immense but the potential dangers are immense as well. If nanotechnology becomes as fruitful as some expect, harmful outcomes are inevitable. Nanoethics will be needed (Weckert 2002). What would nanoethics be like if it became a field of inquiry? Sometimes, fields of applied ethics are organized under the rubric of a professional field, so called “professional ethics”. Medical ethics, legal ethics and engineering ethics are good examples. Almost any field that is a profession can spawn a field of applied ethics. Nursing ethics, architecture ethics, police ethics, and accounting ethics are examples. But nanoethics does not fit comfortably under this model, at least not yet. There is a growing number of professionals who do nanoscience and nanotechnology, but for the most part these individuals are not yet regarded as professional nanoscientists or nanotechnologists as opposed to say professional chemists doing nanoscience or nanotechnology. Nanoethics, if it becomes a separate field, would be better understood on the model of bioethics. Bioethics considers the ethical implications of activities and results not only of medicine but also of the biological sciences. Familiar issues in bioethics include whether euthanasia is justified, how stem cells should be used, how to fairly distribute scarce organs for transplant, and whether animals should be used in research. Similarly, nanoethics would consider ethical implications of activities and results of nanotechnology and nanoscience. Issues in nanoethics would include how to safeguard privacy in a world with nanosnooping devices, to what extent the manipulation of human beings should be permitted, and how to minimize the risk of runaway nanobots.

However, it is not our position that nanoethics need or will become a separate field of inquiry at all. What should concern us is that nanotechnology will raise various ethical problems, some new and some not new but only with a different slant. These ethical problems will need to be addressed. We take the business of nanoethics to be the ethical examination of the impact of nanotechnology whether or not it is regarded as a specific academic discipline.

It is a familiar cliché that ethics does not keep pace with technology. With the advent of nanotechnology it might be thought that we have an opportunity to do it differently – to do the ethics first. This is essentially the proposal offered by Bill Joy who suggests that we place a moratorium on such frontier science until we can understand the consequences of doing it (Joy 2000). The problem with the ethics-first model is that ethical assessment depends in large part on a factual determination of the harms and benefits of implementing the technology. But, when one asks nanotechnologists what the future of nanotechnology will be in five years or ten years, let alone twenty-five or fifty years, reaction varies from a blank stare to some cautious speculations about some narrow aspect of the field. A moratorium stops the technology but does not do much to advance ethics (Weckert 2001). The ethics-last model, the traditional default to the ethics first model, does not fare well either. Once a technology is firmly in place much unnecessary harm may have already occurred.

Our position is that the ethics-first model and the ethics-last model are popular but poor solutions to a false dichotomy. Nanoethics is not something one can complete satisfactorily either first or last but something that needs be done continually as the technology develops and as its potential consequences become better understood. Ethics is dynamic in that the factual component on which it relies has to be continually updated. Nobody can predict the consequences of complex technological changes far in the future. But, it is not

only the factual flux that forces us into a dynamic approach toward ethics. New technology often creates novel situations for which no ethical policy exists or seems immediately obvious. In the face of policy vacuums we need to consider how to formulate new and appropriate ethical policies given the new facts (Moor 2001).

To emphasize the need for nanoethics we present three key ethical issues that likely will be exacerbated by developments in nanotechnology. These issues are privacy and control, longevity, and runaway technology. These are not new issues by any means, but are ones that nanotechnology will give its own special twists. We selected these topics to further emphasize the dynamic nature of applied ethics because they vary in probability of occurrence and the degree to which we can currently know them.

3. Privacy and Control

Privacy is clearly an issue that will be impacted by nanotechnology. People often snoop on other people, and generally, when new technology makes accessibility to others easier and detection of snooping more difficult, illegitimate snooping can be expected to increase. When personal records, such as medical records, became electronic, new policies and safeguards needed to be put in place to protect people from invasions of privacy. Today miniature cameras are everywhere including cameras packed into cell phones. In almost any place, while going largely unnoticed, people can snap pictures of others and then send the pictures immediately anywhere in the world.

Now imagine that in our world of shrinking privacy we add nanotechnology. We will construct nanoscale information gathering systems. It will become extremely easy to put a nanoscale transmitter in a room or onto someone's clothing so that he or she will have no idea the device is present or that he or she is being monitored and tracked. Nanotechnology will make it easier for us to wear cameras invisible to others that can keep detailed movies of what transpires. It will make it easier to tap phone lines in ways that are virtually undetectable. It may become depressingly difficult to keep any secrets or live a life at a reasonable level of solitude.

Implanting tracking mechanisms within someone's body would also become easier with nanotech devices. A tracking mechanism might be put into someone's food so that, when swallowed, it would be absorbed into the body, possibly migrating to a desired location. If we regard anything as private, it is our bodies and minds. We have a natural barrier, our skin, that makes it difficult for most people other than doctors with special equipment to snoop inside. But, theoretically with nanotechnology and wireless transmission a person's brain functioning could be unknowingly tapped and information about it transmitted. Reading someone else's thoughts might be difficult, but capturing information that would be indicative of a particular mental state, such as anger or sexual arousal, might be rather easy.

Along with the lack of privacy engendered by nanotechnology would come a lack of control. Because in general people would know more about other people, we might be less capable of controlling the outcomes of our choices. Those who had the additional information about us might subvert our activities. And nanotech implants, injected or ingested, might literally turn control of one's body over to others. The chips, for example, might stimulate the brain's pleasure center when certain actions were performed. This would be an effective way for some people to control others without them being aware of being controlled. This is possibly an attractive option for parents, employers, and dictators, but not something most of us would want.

How the use of nanotech devices will work in these kinds of cases is still a matter for research. But, what is not speculation is that with the advent of nanotechnology invasions of privacy and unjustified control of others will increase. This has been our recurring his-

tory. When new technology provides us with new tools to investigate and control others, we use them. We already have nanoscale computing chips. That nanochips will be used for spying and control of others is a practical certainty.

4. Longevity

Developments in nanotechnology could have a dramatic effect on human life spans, in three ways. First, and least controversially, nanotechnology will almost certainly have medical benefits. Early diagnosis and new cures will have some effect on longevity. A more spectacular, but more distant possibility is the development of cell repair devices. If these are developed, it will be possible to reverse or prevent aging, so life spans could be increased enormously. A third way that nanotechnology might contribute to longevity is through the development, by growth or construction, of body parts to replace those worn out or otherwise damaged. Particularly significant could be the development of tissue that the body would not reject.

Many people, including nanotechnology enthusiasts, see longevity as obviously a good thing. After all, most of us are not too keen on dying and will do whatever we can to avoid it. But not all are so enthusiastic. Leonard Hayflick, an expert in gerontological research writes:

I have long been worried about the enormous power that humans will have if we ever learn how to tamper with the aging process or to extend our longevity – it is unclear whether people could cope with the psychological, economic, medical and cultural changes that would accompany vastly extended life spans, even if they prove physiologically possible. ... Although aging and death put an end to the lives of good citizens, they also make finite the lives of tyrants, murderers and a broad spectrum of other undesirables. Much of the continuing massive destruction of this planet and the consequent ills that this destruction produces for humans can be traced to overpopulation, [...] Extending the life of a population that already strains global resources is, in the view of many, unconscionable. (Hayflick 1997, p. 94)

The population problem would be a serious a problem. Increasing life spans does not change the rate of population increase, only the size of the population. However, the increased size of the population itself could be a problem, if life expectancy is long enough. In a country with a life expectancy of say 70 years, there needs to be one baby born for each adult every 70 years for the population to remain stable. Suppose that the average life span was 210, treble what it is now. To maintain a stable population, for each adult, a baby would be required only every 210 years. People may or may not be happy to spend only a very short part of their lives raising a family. There are going to be very few children around relative to the population in general.

Another potential area of concern is the lack of new ideas and “new blood”. Children and young people in general, bring new ideas, attack problems in new ways, and are generally more enthusiastic and innovative. This reservoir of vigor and innovation could be reduced significantly. This, of course, need not be a problem. It all depends on the type of long lives that people have. If all stages were elongated, the young would be young longer, so this problem would not exist. But the old would be old longer, too, and this might be a problem. But perhaps the bulk of our lives will be spent in what we now think of young adulthood and middle age. Or something else! We have some reason to be optimistic about being relatively sprightly both mentally and physically at 75, but we have no idea how we would be at 500.

The working assumption is that because a certain amount of life is good, more of it would be better. It is obviously not a general principle that if a certain amount of something

is good therefore more of it is better. Take alcohol, for example. Longevity is not attractive unless the life is a pleasant and enjoyable one. Living for a hundred years in poverty, pain, fear, boredom, or old age, does not seem to be desirable or attractive. But having an extra hundred years of interesting and happy existence does sound good. Does living happily for 500, 5000 or even 50,000 years seem even better? The longer the time frame, the harder it is to know what to say. Perhaps after some time, life would become sterile and boring, although this does not seem to be a necessary outcome.

Nanotechnology will almost certainly have benefits for the health of humans, and this is clearly desirable. What is not necessarily an unmitigated good is increased longevity in itself. Some potential issues of concern have been noted. Some of these will most likely be real concerns in the not too distant future, such as overpopulation, unless other developments keep pace, such as ways of cleaning up the environment. Other concerns are more speculative, but, as in the case of the runaway nanobots discussed in the next section, they are within the realms of possibility, so are worthy of discussion now.

5. Runaway Nanobots

In Eric Drexler's vision, assemblers are the workhorses of the nanotechnology revolution. In our genetic world, DNA, RNA, and ribosomes do the work of building and repairing bodies. The memetic nanocomputers and assemblers will do all of this and more. Assemblers, if they are working for our benefit, build what we desire. The danger is that replicating assemblers might build what we do not want. Even worse such replication might get out control. Drexler explains,

Tough, omnivorous "bacteria" could out-compete real bacteria: they could spread like blowing pollen, replicate swiftly, and reduce the biosphere to dust in a matter of days. (Drexler 1996, p. 172)

The problem of runaway replication is frequently called the "gray goo" problem. Of course, the legions of replicators need not be gray or gooey, but the phrase "gray goo" nicely conjures up an image of amounts of undesirable, amorphous, nondescript stuff that could clog up and damage parts of the world. At the very least a gray goo situation would be unpleasant. In its worst form, a gray goo situation would be deadly to humans. Replicators might make resources required for human life unusable or, for that matter, humans might be just the food that the replicators need to survive.

As scary as this scenario is, it is difficult to attach probabilities to it occurring. Are replicators really a possibility? Richard Smalley, who is an enthusiastic supporter of nanotechnology – not to mention a 1997 Nobel laureate for the discovery of fullerenes, important component of the nanorevolution – challenges the idea of robotic replicators. Smalley raises the question "How soon will we see the nanometer-scale robots?" and then he unequivocally responds, "The simple answer is never" (Smalley 2001, p. 76). Smalley raises two issues. The first is the fat fingers problem. The fingers of a self-replicating nanobot used to insert atoms in the target product must be made out of atoms. Because several fingers will be needed to control the atom being placed along with other atoms in the vicinity that will exert forces, there isn't enough room to accommodate all of the fingers required to completely control the chemistry. The other concern of Smalley is the sticky fingers problem. The atoms of the fingers of the self-replicating nanobot will adhere to the atom that is being moved. It will often be impossible to release the atom in just the right spot. Smalley concludes, "Both of these problems are fundamental, and neither can be avoided. Self-replicating, mechanical nanobots are simply not possible in our world" (Smalley 2001, p. 77).

As one might imagine, Drexler and his colleagues are not convinced by Smalley's claims (Drexler *et al.*, 2001). Although Drexler often speaks of atom-by-atom, he makes it clear that pieces of the final product can be assembled separately and then the larger pieces brought together. Hence, fat fingers need not be a problem. Moreover, if the sticky finger problem was fundamental, why would it restrict only mechanical assemblers and not biological assemblers such as ribosomes that obviously do work? Hence, the sticky finger problem for mechanical assemblers is not demonstrated or so Drexler claims. If nature allows it, why can't we do it? Drexler maintains that we should take seriously at least the eventual possibility of runaway replicators.

Replicators can be more potent than nuclear weapons: to devastate Earth with bombs would require masses of exotic hardware and rare isotopes, but to destroy all life with replicators would require only a single speck made of ordinary elements. (Drexler 1996, p. 174)

6. Conclusion

These three areas privacy and control, longevity, and nanobots, are very different but eventually nanotechnology will likely produce consequences of ethical concern in all of them. These areas differ in part because of their proximity in time and our knowledge of them. Given our broad definition of nanotechnology we already possess the kind of nanotech devices that can impact privacy and control. Privacy and control is a subject of major concern that will need immediate and ongoing attention. Longevity is likely to be increased by nanotechnology, but the impact of that undoubtedly lies in the future and is somewhat less certain. Nevertheless, it is a reasonable bet that nanotechnology will improve our health and safety and hence extend our lives. In time, humans may be forced to address questions such as whether some people should be allowed to have multiple sets of children over very extended periods of time and whether even the examined life is worth living beyond a certain age. Finally, the threat of runaway nanobots seems well into the future and a scientific debate rages over whether it will become a serious risk. Our point for now is that it is not just scientists who need to consider the potential risks of nanotechnology, for all of us will be seriously affected if privacy is greatly diminished, if human life is greatly extended, or if programmable nanobots become a reality.

Nanoethics is nascent but an important concern, if not yet a fully developed enterprise, that needs to be maintained in conjunction with the development of nanotechnology. Nanoethics encourages the skepticism and scrutiny required to keep nanotechnology within ethical boundaries so that this promising new technology works only in the service of human flourishing.

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Note

- ¹ For our purposes we will use 'nanotechnology' to cover both nanoscience and nanotechnology. Of course, within the field some researchers work in more applied areas and others are more closely associated with a purely scientific endeavor.

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