Editors
Joachim Schummer
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Nanotechnology Challenges

Implications for Philosophy, Ethics and Society

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World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication
Nanotechnology challenges : implications for philosophy, ethics, and society /
editors, Joachim Schummer & Davis Baird.
p. cm.
Includes bibliographical references and index.
ISBN 981-256-729-1
1. Nanotechnology--Philosophy. 2. Nanotechnology--Moral and ethical aspects.
3. Nanotechnology--Social aspects. I. Schummer, Joachim. II. Baird, Davis.

T174.7.N37355 2006
303.48'3--dc22

2006042564

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Printed in Singapore by B & JO Enterprise

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INTRODUCTION

Nanotechnology is a recently emerging and rapidly growing field whose dynamics and prospects pose many great challenges not only to scientists and engineers but also to society at large. Since forecasts of nanotechnology range from the next industrial revolution to severe threats to humanity, nanotechnology has already created enormous social disturbance. While the promises of nanotechnology have been exaggerated toward quasi-religious visions of a posthuman state of Salvation, the perception of risks also have been exaggerated, some to the level of apocalyptic doom-saying. Researchers in nanotechnology increasingly feel embarrassed by both public expectations and public mistrust; increasingly large parts of the public feel uncertain about the uses and abuses of science and technology; and science policy makers and administrators begin to worry if they still have control over the process they once initiated by launching huge nanotechnology programs.

All that poses great challenges to those whose profession is to reflect on science and technology and their place in society. This volume includes the state-of-the-art philosophical, ethical, and sociological reflection on nanotechnology. Rather than being a simple policy guide, it seeks first of all understanding of the philosophical, ethical and societal issues of nanotechnology. It unravels the philosophical underpinnings of nanotechnology, its metaphysical and epistemological foundations, and its conceptual complexity. It explores the ethical issues of nanotechnology, its impact on human, environmental, and social conditions, and the options for reasonable risk management. It examines the public discourse on nanotechnology and its related visions and provides both lessons from the past and outlooks into the future.

Nanotechnology has already impacted society by virtue of its visionary character and will do so more by means of its commercial products. And society has from the very beginning shaped nanotechnology through visionary ideas, science fiction stories, and innovative research and funding programs. Finally, the public relation and public debates have tried to keep up with these interactions between nanotechnology and society. As with all technologies, the future shape of nanotechnology – or nanotechnologies – will result from these interactions between human beings, with their creative minds and skills, their hopes and fears, and their values, interests, and power relations. The more we understand these interactions, the more we understand current and future nanotechnology, and the more are we able to shape it in a desirable and human way.

Since early 2003 the editors have organized biannual international conferences in the U.S. and Europe that have for the first time brought together scholars from the humanities, social sciences, natural sciences, and engineering to discuss interactions between nanotechnology and society.[1] Although the international community of this field, called nanoScience and Technology Studies (^{n}STS), is a recent arrival, it is now growing almost as fast as nanotechnology itself. In addition, numerous committees, expert groups, and centers have been founded, and the number of reports has grown accordingly. During periods of rapid change, it is important to provide space for well-informed and independent views that might not always be welcome in commissioned reports. To that end, we have published four special issues of the two journals we edit, *Hyle: International Journal for Philosophy of Chemistry*, and *Techne: Research in Philosophy and Technology*. The combined papers of these special issues are reproduced in this volume. They are written by leading scholars from the humanities and social sciences in North America and Europe, covering a wide spectrum of disciplines, including philosophy, ethics, sociology, history of science, literature studies, economics, innovation studies, and science.

The volume is divided into three parts, on (1) philosophical, (2) ethical, and (3) societal issues of nanotechnology. Each part is divided into sections and chapters that we briefly summarize below.

(1) *Philosophical Issues:* The first part, on philosophical issues, focuses on philosophy of science, metaphysics, epistemology, and com-

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[1] A selection from the first pair of conferences has been published in Davis Baird, Alfred Nordmann & Joachim Schummer (eds.): *Discovering the Nanoscale,* IOS Press, Amsterdam, 2004.

plexity. It starts with a section on what might be the most provocative challenge for scientists, the Drexler challenge. Two chapters compare chemical approaches to molecular manufacturing with nanotechnology in the sense of its visionary founder, Eric K. Drexler. BERNADETTE BENSAUDE-VINCENT explores the fundamental metaphysical differences between both approaches, particularly in their different notions of molecular machines and living systems. By analyzing the well-known Drexler-Smalley debate, OTÀVIO BUENO points out that these approaches are fundamentally incommensurable because they differ on the conceptual, methodological, and theoretical grounds.

The second section examines metaphysical issues of nanotechnology, particularly its relation to nature. ALFRED NORDMANN argues that, because some areas of nanotechnology resist our capacities of experience and imagination, they provoke a mixture of awe and abhorrence similar to "brute nature". Thus, they undermine the classical idea of controlling nature. GREGOR SCHIEMANN further discusses the distinction between nanotechnology and nature and suggests ways in which artifacts like nanotechnological machines and biological systems can be both distinguished and related to each other. CYRUS MODY critically analyzes the various arguments for technological determinism, according to which nanotechnology would, like a living system, unfold its own logic and completely transform the world beyond human control.

Section three addresses epistemological questions that arise from the imaging techniques that allowed nanotechnology to emerge. Several images of nanoscale structures have even become public icons of the field. In his epistemological analysis of scanning electron microscopy (SEM), JOSEPH PITT argues that, although SEM plots convey exact information, they should not be called images because they are not exact representations of reality. JOCHEN HENNIG documents the history of how data from scanning probe microscopy has been transformed into images of the nanoscale, and thus helps us understand how we – scientists and the broader publics – 'see' and comprehend the nanoscale.

The forth section deals with the complexity of nanotechnology both regarding its interaction with society and the various research fields involved. MARC DE VRIES develops a comprehensive systematics that, rather than taking nanotechnology as a complex whole, distinguishes between fifteen aspects, including physical, biotic, psychological, social, economic, ethical, and religious aspects, each with their own issues. In order to extrapolate future trends from the current research dynamics, MARTIN MEYER and OSMO KUUSI analyze the various research fields of nanotechnology according to technological paradigms.

(2) *Ethical Issues:* Although most ethical issues are clearly related to societal issues, and many of the chapters in the second and third parts of the book deal with both, not all societal issues are ethical issues. Furthermore, sociological analysis is not the same as an ethical analysis. Thus, the second part of this volume is primarily devoted to ethical issues, whereas the third part focuses on broader societal issues.

Section five provides a comprehensive analysis of what may count as ethical issues of nanotechnology through the complementary perspectives of social ethics and environmental ethics. BRUCE LEWENSTEIN, after surveying the social and ethical issues discussed in pertinent governmental reports on nanotechnology, argues that all these issues refer to principles of social and political ethics, such as fairness, justice, and power. CHRISTOPHER PRESTON analyzes nanotechnology from the different point of view of environmental ethics, and examines how to analyse projects and visions such as the creation of new materials, uncontrollable replicators, human enhancement, and material abundance.

As nanotechnology explores the unknown, we must carefully analyze, assess, and manage its potential opportunities and risks, including the way we perceive and handle them. The three chapters of section six deal with that topic. LOUIS LAURENT and JEAN-CLAUDE PETIT analyze the perception of risks in recent controversies about nanotechnology and argue that, while these concerns are culturally grounded, we need public forums to manage these controversies in an effective and responsible way. JEAN-PIERRE DUPUY and ALEXEI GRINBAUM develop an approach to project nanotechnology and its societal and ethical interactions into the future by the recursive inclusion of predictions of our nanotechnological future. SVEN OVE HANSSON provides a new analysis of how to think about the risks and benefits posed by nanotechnology, where, instead of approaching this issue from standard probabilistic risk assessment, one assesses arguments for the mere possibility of future harms or benefits.

(3) *Societal Issues:* At this point in time, the societal issues of nanotechnology are all tied to futuristic and visionary stories about nanotechnology. These have generated hype as well as public hopes and fears. Section seven takes a closer look at such stories and their authors. In his comparative analysis of Eric Drexler's visionary founding book of nanotechnology – *Engines of Creation* – and a report on nanotechnology by the U.S. National Science Foundation, JOSÉ LOPÉZ demonstrates that both texts employ classical tropes of science fiction to jump from current research to a promising future. ARNE HESSENBRUCH analyzes the emotional content in public material produced by a nanotechnology research group and argues that this plays an important role in the struggle for funding and is a driving factor in the creation of hype.

The final section investigates how the public might react to such nanotechnology visions. CHRIS TOUMEY compares the role of hyperbole in the public understanding of nanotechnology with that of previous technological developments (cold fusion and recombinant DNA). He draws lessons about how nanotechnology might be received in the future. Taking the recent public discourse on "societal and ethical implications of nanotechnology" as another forum for expressing nanotechnology visions, JOACHIM SCHUMMER analyzes the actors and the dynamics of that discourse and warns that it could lead to a major anti-science backlash.

In the late 18th century, the German philosopher and scientist Georg Christoph Lichtenberg wrote his well-known aphorism: "Those who understand nothing but chemistry, don't even understand chemistry". As scientists increasingly move towards engineering practice, the aphorism would nowadays read, "Those who create nothing but nanotechnology, don't even create nanotechnology". Rather than being a creation only by ingenious scientists and engineers, nanotechnology is the result of complex societal interactions. The failure to recognize this could easily lead to creations that, after the preliminary hype-cycle, will move into unintended directions, or end up in oblivion.

Joachim Schummer & Davis Baird December 2005

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CHAPTER 1

TWO CULTURES OF NANOTECHNOLOGY?

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Although many active scientists deplore the publicity about Drexler's futuristic scenario, I will argue that the controversies it has generated are very useful, at least in one respect. They help clarify the metaphysical assumptions underlying nanotechnologies, which may prove very helpful for understanding their public and cultural impact. Both Drexler and his opponents take inspiration from living systems, which they both describe as machines. However there is a striking contrast in their respective views of molecular machineries. This chapter based on semi-popular publications is an attempt to characterize the rival models of nanomachines and to disentangle the worldviews underpinning the uses of biological reference on both sides. Finally, in an effort to point out the historical roots of the contrast in the concepts of nanomachines, I raise the question of a divide between two cultures of nanotechnology.

1. Introduction

Over the past decade, Eric Drexler's successful volume *Engines of Creation* (1986) and the debates generated by its futuristic visions have been prominent in drawing public attention toward nanotechnology. Most scientists active in the field think that too much attention has been paid to this debate and they try to distance their own 'serious' research programs from Drexler's unrealistic scenario. At least the rejection of Drexler's rhetoric acts as a unifying principle in the otherwise heterogeneous crowd of scientists involved in nano-initiatives.

However as with many controversies in science, debates about Drexler's universal assemblers and the grey goo scenario have been extremely profitable as long as they helped clarify the philosophical assumptions underlying projects of nanoscience.[1] Without claiming that the future of nanotechnology hinges on such debates, I will argue that they enlighten the public about the cultural roots and cultural projects of nanoscientists and engineers. In this respect, it is equally important to point out convergences and divergences between Drexler and his followers on one side and chemists such as Richard Smalley and George Whitesides who criticized Drexler's views of universal assemblers on the other side.

Drexler and his opponents share a common interest in biological systems. Already in Richard Feynman's almost legendary prophecy, there was a quick reference to biological material, where enormous amounts of information could be stored in exquisitely small spaces. Since 1959 and the early days of molecular biology, chemists, materials scientists and engineers have intensified and diversified their references to biology, even before the term 'nanotechnology' was coined. Bio-inspirations prevailed when the 'bottom-up' approach, the design of structures molecule by molecule (rather than atom by atom) became one of the major goals of nanotechnology. In contrast to the structures usually designed by engineers at the macrolevel, biomaterials are built from bottom up. Life operates by bonding atoms or groups of atoms instead of by carving a structure from raw materials. The convergence of nanotechnologies and biotechnologies is rooted in the claim that 'bio is nano', that biomaterials are structured from bottom up.

It is not my purpose to discuss the validity of such claims through a comparison of nature's strategies and nanoscientists' biomimetic attempts (see Ball 2002). Rather I would like to emphasize that the debate about the potentialities of nanotechnology basically boils down to the question 'what is a nanomachine?' However the notion of machine is itself polysemic, so that it can support dissimilar views of living systems and teach quite different lessons to nanoscientists and engineers.

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[1] A major source on this controversy is the special issue of *Scientific American*, September 2001. See also the open correspondence between Richard Smalley and Eric Drexler available on the website of the Foresight Institute; *Chemical & Engineering News*, December 1, 2003, vol. 81, no. 48, pp. 37-42.

2. Machine: An All-pervading Metaphor

Over the past decades, the machine metaphor has invaded the language of biologists. In the early times of molecular biology, such metaphors were exclusively used for DNA transcription and translation. Nowadays each entity active in the cell is described as a machine: ribosomes are assembly lines, ATP synthases are motors, polymerases are copy machines, proteases and proteosomes are bulldozers, membranes are electric fences, and so on (Godsell 2003, Zhang 2003). Although biologists generally agree that living systems are the product of evolution rather than of design, they describe them as devices designed for specific tasks. Indeed, if biology can teach us about engineering and manufacturing, it is because the living cell is now viewed as a factory crowded with numerous bionanomachines in action.

At the same time, in chemistry and materials science, machine metaphors have also become prominent. One major objective of nanotechnology programs is to build nanomachines that will do a better job than conventional machines. As they seek to design functional materials, physicists and chemists readily redefine the product of their design as machines: wheelbarrow molecules, cantilever molecules, springs, and switches are specimens of the inventions commonly reported in materials journals.

Thus the languages of molecular biology and materials science remarkably converge in a stream of machine metaphors. Through a continuous process of mutual transfer of concepts and images, they have built a common paradigm based on an artificialist view of nature. Nature is populated with nanomachines that human technology should be able to mimic or even to surpass.

Drexler and other advocates of the nano revolution primarily find in molecular biology a reply to all nanoskeptics. The data of molecular biology is a chief argument about the feasibility of nanofabrication:[2]

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[2] Drexler 1986, p. 17. See also the comment posted by Lenester on Mind X 04/17/2003 on Drexler's 'An open letter to Richard Smalley' [www.kurzweilai.net/meme/frame.html]: The very idea that something which is clearly done in nature cannot also be done by us, is counter to the most basic spirit of science. It hearkens back to an age of magical descriptions, implying that there's some mystic Stuff out there which is beyond our mortal ken.

> One might doubt that artificial nanomachines could even equal the abilities of nanomachines in the cell, if there were reason to think that cells contained some special magic that makes them work. This is called vitalism. Biologists have abandoned it because they found chemical and physical explanations for every aspect of living cells yet studied, including their motion, growth, and reproduction.

Drexler thus rejuvenated the positivist crusade of 19^{th}-century synthetic chemists like Marcellin Berthelot against the limits imposed by superstition or by the metaphysical belief in a vital force. The existence of life itself is the proof that nanomachines are feasible according to Marvin Minsky from the MIT Media Lab and AI Lab:[3]

> It seems quite strange for anyone to argue that you cannot build powerful (but microscopic) machinery – considering that our very own cells prove that such machines can indeed exist. And then if you look inside your cells you will find smaller machines that cause disease. Most arguments against nanotechnologies are arguments against life itself.

From this quotation, it is clear that life provides more than just an invitation to build nanomachines; it rather constitutes an imperative. Life is a source of creativity, a legitimation of the enterprise as well as a reason to believe in its future.

In Drexler's view, nanotechnology is 'molecular manufacture'. The notion of molecular engineering is nothing new. As early as the 1950s, the term was used by a number of scientists who worked for the promotion of materials science and engineering (MSE) in American universities. Before the label 'MSE department' was adopted, this new branch was often referred to as 'molecular engineering'.[4] What is specific about Drexler's program is the notion of manufacture, which conveys the vision of mass-production that will transform society. From the publication of his very first article in 1981, Drexler shifted from the notion of mo-

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[3] Minsky 1995, p. 193; Rietman 2001, p. 2.

[4] For instance, as early as 1956, Arthur von Hippel, professor at MIT advocated an interdepartmental research center named 'molecular engineering'. The emerging discipline was aimed at designing new materials on the basis of molecular understanding. It comprised the structure, formation, and properties of atoms, molecules, ions, of gases, liquids, solids, and their interfaces. Electrical, magnetic, mechanical parameters were considered the most fundamental (MIT archives, AC 12, Box 71).

lecular engineering to that of manufacture. This early presentation of what could be a bottom-up process was clearly inspired by biology.

> Biochemical systems exhibit a 'microtechnology' quite different from ours: they are not built down from the macroscopic level but up from the atomic. Biochemical microtechnology provides a beachhead at the molecular level from which to develop new molecular systems by providing a variety of 'tools' and 'devices' to use and to copy. Building with these tools, themselves made to atomic specifications, we can begin on the far side of the barrier facing conventional microtechnology. [Drexler 1981, p. 5275]

The artificialist view of biological systems thus encouraged a project which focused on the imagination of small machines that could 'pick and place' and assemble pieces on the model of robots and assembly-lines in a car factory. A few years later, given the scale of operation, Drexler was embarked in the fiction of self-replicating assemblers which raised the prospect of myriads of nanoassemblers copying themselves and consuming all the resources of the earth. The now too familiar grey goo scenario was a direct and logical consequence of Drexler's choice of a manufacturing model. Although Drexler recently regretted his speculations on the grey goo, it is important to emphasize that for him engineering and technology basically consist in manufacturing.[5]

While the controversy raised by Drexler focused on the feasibility of universal assemblers, it became increasingly obvious that his opponents questioned the model of manufacture without rejecting the machine metaphor. Significantly, George Whitesides, a professor of chemistry at Harvard University, developed his argumentation against Drexler's molecular assemblers in a paper entitled 'The Once and Future Nanomachines' (Whitesides 2001). Whitesides contrasts human-made machines with natural machines but he never questions the machine metaphor.

> Nanoscale machines already do exist, in the form of the functional molecular components of living cells – such as molecules of protein or RNA, aggregates of molecules, and organelles ('little organs') – in enormous variety and sophistication. The broader question of whether nanoscale machines exist is thus one that was answered in the affirma-

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[5] *Nature*, vol. 429, 10 June 2004, p. 591. See also Phoenix & Drexler 2004.

> tive by biologists many years ago. The question now is: What are the most interesting designs to use for future nanomachines? And what, if any, risks would they pose? [Whitesides 2001, p. 78]

Drexler's molecular manufacture is depicted as an old fashioned and outdated model that has to be replaced by a more modern and more fashionable model taken from living cells. Mimicking human-scale machines is both inadequate and inefficient given the constraints of fabrication at the nanoscale. By contrast, mimicking the simplest cellular nanomachines is a marvelous challenge.

In other terms, the dispute between Drexler and Whitesides seems to rest on two rival models of machinery. Both of them agree that nanotechnology should take inspiration from living organisms, but they part company when it comes to the ways of making those nanomachines.

3. Drexler's Mechanical Machines

What is 'life' for Drexler and his colleagues of the Foresight Institute? From the outset, Drexler explicitly based his plan on a close comparison between biochemical components and the operating units of macroscopic machines as shown in his 1981 article (Table 1).

With struts, cables, fasteners, glue, motors, bearings, containers, pumps, and clamps, Drexler's living bodies are surprisingly reminiscent of Descartes' animal-machines. In both cases, the living machine is made of a set of independent pieces – a few building blocks – mechanically assembled by a designer. Drexler described molecules as rigid building blocks similar to the parts of tinker toys – whether they are Meccano or Lego construction sets. The functions performed by the various pieces of molecular machinery are also essentially mechanical. They position, move, transmit forces, carry, hold, store, *etc.* Although Drexler declared that his molecular manufacture is the extrapolation to the smallest scale – by a process of 'mental shrinking' of today's automated factories (Drexler 2001, p. 74), his automata look like Vaucanson's automata performing complex tasks thanks to an assembly of simple mechanisms. Drexler is fond of the metaphor of 'molecular hands' manipulating nano-objects and placing them wherever they need to go to perform the desired function. Nanosystems are like factories engaged in a rigid framework of controlled motions using the building blocks of matter as raw materials.

Table 1. Comparison of macroscopic and microscopic components (source: Drexler 1981).

Technology	Function	Molecular example(s)
Struts, beams, casings	Transmit force, hold positions	Microtubules, cellulose, mineral structures
Cables	Transmit tension	Collagen
Fasteners, glue	Connect parts	Intermolecular forces
Solenoids, actuators	Move things	Conformation-changing proteins, actin/myosin
Motors	Turn shafts	Flagellar motor
Drive shafts	Transmit torque	Bacterial flagella
Bearings	Support moving parts	Sigma bonds
Containers	Hold fluids	Vesicles
Pipes	Carry fluids	Various tubular structures
Pumps	Move fluids	Flagella, membrane proteins
Conveyor belts	Move components	RNA moved by fixed ribosome (partial analog)
Clamps	Hold workpieces	Enzymatic binding sites
Tools	Modify workpieces	Metallic complexes, functional groups
Production lines	Construct devices	Enzyme systems, ribosomes
Numerical control systems	Store and read programs	Genetic system

As in Descartes' theory of animal-machines, the tasks to be performed by the nanomachine, *i.e.* the direction of its movements, are embedded by the designer in the mechanical devices. The assembly process itself is described with the metaphor of "mechanosynthesis" or "the use of mechanical control to guide the placement of molecules so as to build complex objects" (Drexler 1995, p. 6). The keyword is "molecular assembler". This is the magic wand that binds together the pieces in an arrangement allowing them to perform useful tasks. Molecular assemblers are "devices able to guide chemical reactions by positioning reactive molecules with atomic precision" (Drexler 2003b). They are neither specific nor individual molecules. They are described as universal, all-purpose assemblers that can assemble all kinds of materials in the same way that ribosomes can assemble all kinds of proteins.

We know that Drexler shaped his program of molecular manufacturing while he was a research affiliate at MIT Space Systems Laboratory then MIT Artificial Intelligence Laboratory, under the sponsorship of Marvin Minsky. It is therefore not unlikely that his program was influenced by cyberneticians' concepts. Although Drexler's references to von Neumann in *Engines of creation* is limited to his studies on self-replicating machines, he might also have borrowed his notion of 'universal assemblers' which were able to grab components out of their location and put them together according to programmed instructions. Similarly, Drexler's assemblers would move atoms, place them in the right position, and selectively bind them.

Drexler's program thus seems to combine two models of machines. On the one hand, his description of molecular manufacture rests on classical mechanics, requiring only space, matter, and motion. In this sense, his matter is like Boyle's uniform, catholic matter, deprived of spontaneity as well as of individuality. Molecular machines, like clock mechanisms, require the hands and the brain of a clock-maker. As Georges Canguilhem emphasized in a commentary on Cartesian mechanism, such mechanical machines are not deprived of finality: all the teleology is concentrated at the starting point, in the act of design; and it is naively anthropomorphic (Canguilhem 1952, pp. 113-4). Canguilhem characterized the teleology inherent in Cartesian mechanism as 'technological anthropomorphism' as opposed to 'political anthropomorphism'. On the other hand, Drexler implicitly refers to computational machines, but without facing the challenge of complexity that von Neumann clearly prophesized.[6]

A second major feature that Drexler retained from biological systems is that they operate under programmatic control. He consequently shaped "a world in which digital data can be used to control general-purpose machines that will put the fundamental building blocks of matter in place

[6] Dupuy 2000. Drexler did his Ph.D. in Marvin Minski's laboratory, who wrote his doctoral thesis under von Neumann.

to build almost everything" (Drexler 1995, p. 17). The DNA-RNA system provides the code and the instructions for the machine to operate. Protein assembly works according to rigid instructions, in a clean and efficient manner. Drexler's molecular manufacture is described in stark contrast with chemical manufacture. Conventional chemical reactions are extraordinarily messy:

> Chemists today make complex molecular structures by taking smaller pieces, putting them together, stirring, and hoping that they will fall together to make the right product. If you imagine trying to make an automobile by taking parts, putting them into a box, shaking, hoping that they will fall togteher to make a working machine, you will conclude that it is very useful to have robots or hands, or something like them involved in the process. [Drexler, 1995, p. 2]

Chemistry looks so primitive and dirty when compared to protein machines that Drexler wonders how chemists, lacking the "molecular hands with which to put the parts where they want them", have managed to achieve such remarkable things. In living things, then, Drexler finds a precious guide to improving chemical technologies. Enzymes are his favorite model of assemblers. "[Enzymes] assemble large molecules," he explains, "by 'grabbing' small molecules from the water around them, holding them together so that a bond forms." In this manner they assemble DNA, proteins, and many other biological items. It should therefore be possible to put them to work on metal ions or complex structures in order to wield molecules with the precision of programmed machines. However, if enzymes and proteins show the way to build nanomachines, they do not provide a perfect model for nanotechnology. Drexler proposes to use protein machines only for the first generation of nanomachines because they present serious flaws as engineering materials. The amino acids of which they are composed are simply not tough enough for the construction of nanomachines. Drexler's ambition is to mimic life's devices working under genetic instructions in order to build machines more robust than organisms.

Finally, Drexler borrowed a third concept from biology – evolution – in order to legitimize his program. Drexler advocates an evolutionary model of technological changes, presenting human technology as the continuation of natural evolution. Chapter 2 of *Engines of Creation* placed the emergence of molecular manufacturing in a grandiose picture starting with cosmic order out of chaos then gradually evolving towards organization, then replications, and technology. Evolutionary principles guide Drexler's foresight exercises. They are supposed to determine what paths are open and possible as well as the limits of technological achievements. Drexler thus uses evolutionary biology in order to 'naturalize' the kind of technology that he encourages. In this respect he paved the way for Ray Kurzweil's prophecies of spiritual machines and universal intelligence.

For Ray Kurzweil, a staunch supporter of Drexler's program, and active promoter of Artificial Intelligence, nanotechnology is the means, but artificial intelligence is the end. Kurzweil uses evolutionary biology in order to 'naturalize' the kind of technology that he encourages. According to him, it is the evolution of life itself that tended to overcome the limitations of human brain by inventing computational technology and now presides over the building of nanobots. This vague notion of a process of hominization is all Kurzweil needs to establish himself as the prophet of a new era of spiritual machines. His argument rests on two postulates: (i) human technologies are the continuation of biological evolution; just as the flint chipper was an extension of the human hand, so the nanorobot extends the human brain; (ii) exponential growth is the feature of any evolutionary process of which technology is a primary example (Moore's law). The logical conclusion of this syllogism is this: the golden age of nanotechnology will come within a couple of decades as an unavoidable future. Because it is the continuation of the natural process of evolution, we have no choice over the matter. We must simply accept it and adapt our society to a world shared with nanobots.[7]

To sum up this section, Drexler and his supporters have developed a concept of machine that combines an old mechanistic model inherited from Cartesian mechanics – a passive matter moved by external agents – with a more recent computational model of machines inherited from cybernetics. Both the mechanistic model and the cybernetic one rest on the

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[7] This is the conclusion of Kurzweil's Testimony quoted above. Technology has always been a double-edged sword, so we simply need to implement 'defensive technologies' against self-replicating nanobots in the same way as our society is defending itself against computer viruses. See also, Kurzweil 1998.

assumption of a blind mechanism operating without intentionality under the control of a program. Biological evolution itself is conceived of as a blind mechanism operated and controlled by an all-powerful algorithm.

4. The Dynamic Model

A quite different perspective is conveyed by the chemists who vigorously criticized Drexler's model of machine. George Whiteside's frequent use of the term 'art' in his papers on nanotechnology epitomizes their approach to the field.[8] Nanostructures belong to 'art' both in the Aristotelian sense of *technê*, or design for specific purposes, and in the sense of skill, since they require the invention of astute and unconventional methods of nanofabrication. For chemists, the age of nanotechnology is not exactly a radical break. After all, building molecular architectures is what chemistry has done for many centuries and chemists took inspiration from living structures before the term nanotechnology became fashionable. In 1978, for example, bio-inspiration led to the creation of a new branch of chemistry – supramolecular chemistry – whose aim is to obtain molecular recognition without the help of genetic code through chemical processes that mimic the selectivity of biological processes. According to Jean-Marie Lehn, who coined the term 'supramolecular chemistry', "it is one of the major chemist's motivation to see that biology successfully made highly complex properties on a molecular basis."[9]

In their bio-inspiration, materials chemists are less concerned with genetic programs and genetic engineering than with the stuff of which living things are made. Their main purpose is to understand what is unique about biological materials both in their structure and in the dynamics of their development and morphogenesis.[10] Living organisms are models for nanodesign first and foremost because they present materials adapted, by design, to a set of performances.

Like Drexler, materials scientists and engineers have shaped an artificialist view of nature. For them, biological evolution is a kind of engi-

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[8] See for instance Whitesides 1998, Whitesides & Love 2001.

[9] Lehn 2004, see also Lehn 1995.

[10] See for instance Sarikaya & Aksay 1995.

neer designing efficient systems. Unlike Drexler and Kurzweil, however, they assume that nature is an insuperable engineer. Nature is not so much a model of order as a model of ingeniosity (*ingenium*). It is a wizard, an astute designer playing tricks with nature's laws. For instance, Richard Smalley, who was awarded the Nobel Prize for the discovery of C_{60}, describes the works of nature with superlative and playful terms:

> Nature has played the game at this level [the nanoscale] for billions of years, building stuff with atomic precision. Every living thing is made of cells that are chok-full of nanomachines – proteins, DNA, RNA, *etc.* – each jiggling around in the water of the cell, rubbing up against other molecules, going about the business of life. Each one is perfect right down to the last atom. The workings are so exquisite that changing the location or identity of any atom would cause damage. [Smalley 1999]

In trying to understand the tricks used by nature to solve her 'engineering problems', materials chemists received three major lessons from biology.

First, biomaterials are interesting because they are never homogeneous. Whereas engineered materials are usually processed for a single property, biomaterials are multifunctional composite structures. The interest of material scientists, especially chemists working on high performance composites, is to learn something about the art of associating heterogeneous structures from nature itself. In their effort to design composite structures at the molecular level, they either turned their attention to such familiar materials as wood, bone, or mucus, or to mollusk shells, insect cuticles, spider-silk, *etc.* These composite structures – associating hard and soft, combining inorganic and organic components, and capable of high performance – appeared to be ideal models for human technology for various reasons. They are models of functional diversity, being adapted for a variety of tasks including growth, repair, and recycling. Unlike Drexler's machines with rigid parts each of them designed for one specific function, biological nanomachines may not be mechanically robust and they may not have optimal performances, but they offer a good compromise between properties for different environments. The key to success of living organisms does not lie in a single engineered building block that concentrates all the instructions or information for operating the machine. Rather, biology teaches chemists that success comes with improving the art of mixing heterogeneous components and working out elegant solutions to complex problems. Consequently, the focus is less on the ultimate components of matter than on the relations between them. Interfaces and surfaces are crucial because they determine the properties of the components of composite materials and how they work together. Nanochemistry distinguishes itself from the culture of purity and high vacuum chambers by advancing an impure process of composition and hybridization that mimics natural materials. Biology does not provide a model of highly concentrated information as suggested by Feynman's famous talk. It is a model of interaction and composition. Nature challenges nanomaterials scientists to design a composite displaying more properties than the sum of the properties of its components. In this case biology provides a model of emergence.

The major objections raised by Whitesides and Smalley concern Drexler's view of universal assemblers. Drexler saw in enzymes the model of universal assemblers, a sort of molecular hands capable of moving parts to the right position for assembly. This assertion has provoked the skepticism of chemists who are well aware of the constraints of atoms' reactivity. Smalley (2001) raised two objections: not only would 'molecular fingers' obviously take up too much space and prevent the closeness needed for reactions at the nanoscale (the 'fat fingers' problem); but they would also adhere to the atom being moved, making it impossible to move a building block where you want it to go (the 'sticky fingers' problem). Drexler replied to these objections in an open letter:

> My proposal is, and always has been to guide molecular synthesis of complex structures by mechanically positioning reactive molecules, not by manipulating atoms. This proposal has been defended successfully again and again, in journal articles, in my MIT doctoral thesis [...]. [Drexler 2003]

He complained that Smalley attempted to undermine his scientific credentials and that for positioning reactive molecules no computer-controlled "Smalley fingers" are required. Smalley responded by asking, "So, if the assembler doesn't use fingers, what does it use?" If there is some kind of enzyme or ribosome in self-replicating nanorobots, he reasoned, then there should be water inside because enzymes and ribosomes can only work in water where they find all the nutrients necessary for living systems. Since there is no possibility of fine chemistry without solvent, Smalley denied that nanorobots working in high-vacuum are chemically plausible. As Philip Ball (2003) noticed, "It is becoming increasingly clear that the debate about the ultimate scope and possibilities of nanotech revolves around questions of basic chemistry".

For Whitesides, Drexler's program to force chemical reactions by placing the reagents in the right position is useless. "Fabrication based on the assembler is not, in my opinion, a workable strategy and thus not a concern. For the foreseeable future, we have nothing to fear about the grey goo." (Whitesides 2001, p. 83) Materials chemists simply dismiss Drexler's scenario because their main objective is to dispense with assemblers, by self-assembly. The top of their 'art' consists in making heterogeneous components *spontaneously* converge in the right location and assemble into larger aggregates without any external intervention. In fact, neither manipulating the molecules nor programming the machines requires outside intervention because the components move by themselves. A fascinating perspective was opened up by George Whitesides (1995):

> Our world is populated with machines, non living entities assembled by human beings from components that humankind has made [...] In the 21st century, scientists will introduce a manufacturing strategy based on machines and materials that virtually make themselves; what is called self-assembly is easiest to define by what it is not. A self-assembling process is one in which humans are not actively involved, in which atoms, molecules, aggregates of molecules and components arrange themselves into ordered, functioning entities without human intervention [...] People may design the process, and they may launch it, but once under way it proceeds according to its own internal plan, either toward an energetically stable form or toward some system whose form and function are encoded in its parts.

To be sure, Whitesides provides here only a negative definition of self-assembly, but this does not mean that it would be an obscure process that chemists do not understand. Many processes are explored to make variants of nature's highly-directional self-assembly. Chemists use templates such as mesoporous silica or they conduct synthesis in compartments

(Ball 2002, pp. 25-26). They take advantage of all possible resources of chemistry and thermodynamics in an effort to mobilize all sorts of interactions between atoms and molecules. Instead of using covalent bonds like traditional organic chemists, they make use of weak interactions such as hydrogen bonds, Van der Waals, and electrostatic interactions. They use microfluidics and surfactants in order to produce self-assembled monolayers which, in turn, permit them to move from atomic and molecular level structure to macroscopic property.

Self-assembly presupposes that the instructions for assembly are integral to the material components themselves or that they are embedded in their relations. Matter can no longer be viewed as a passive receptacle upon which information is imprinted from the outside because self-assembly rests on spontaneous reactions between materials. Molecules have an inherent activity, an intrinsic *dynamis* allowing the construction of a variety of geometrical shapes (helix, spiral, *etc.*). It is not an obscure and mysterious vital force, a breath, or animus that would come from the outside to give life to inanimate matter. It is more like Claude Bernard's inner force guiding phenomena generated by physico-chemical causes. But ironically, it is the reductionist approach of molecular biology – the understanding of the mechanisms of molecular recognition as well as the process of morphogenesis – that eventually allowed chemists to develop such emergentist views of molecular architectures.[11]

A third contrast between the chemists' and Drexler's views of nanomachines resides in their attention to complexity. Here, this term is taken in a weak sense, referring to non-linear processes. Complexity became a problem when chemists started to examine the behavior of single molecules instead of dealing with Avogadro numbers of molecules. How do molecules cooperate to produce the average properties and behavior of familiar macroscopic chemicals, became a puzzling question (White-

[11] Emergence here should be understood in thermodynamic terms as the production of higher order out of lower order, which according to Norbert Wiener was the major characteristics of machines and living organisms as well. Self-assembly is a process leading from less ordered to higher thermodynamically ordered ensembles of molecules or macromolecules. The resulting aggregates have new properties that could not have been predicted from the characteristics of individual components. A major difference lies in the fact that aggregates formed in a laboratory environment are in a state of equilibrium, whereas in living beings most of them are out of equilibrium.

sides & Ismagilov 1999). In fact, chemists had suspected that nanoparticles behave differently than macroscopic chemical substances long before the coming of nanoscience.[12] Gold, usually characterized by its yellow color, becomes red when processed in nanospheres. More generally, the color of metal and semiconductor nanoparticles depends on their size, a property commonly used in the glass industry. Today, it is also used to design magnetic materials with iron/platinum colloids, an application that has rendered colloid synthesis a highly sophisticated and promising domain of nanochemistry (Evans & Wennerstrom 1999). Given this long-standing attention to size-sensitive properties, the discovery that the semi-conductor behavior of bulk graphite can be modified into metallic behavior according to the size and geometry of carbon nanotubes did not come as a revelation in theoretical chemistry. Chemists were prepared to admit that elements have special properties and behavior when processed at the nanoscale. Unlike computer scientists, who are eager to replicate conventional machines at the nanolevel, materials scientists focus mainly on size-sensitive properties. Their work comprises the entire hierarchy of structures in living systems, from large molecules that assemble at the nanoscale to form organelles, to cells, tissues, and organs that ultimately compose unique organisms. Therefore, they cannot rely on a uniform view of nature as being the same at all scales. While it is true that the laws of nature are universal, chemists do not assume that they apply equally to all scales.

To sum up, chemists working on the design of nanomaterials seem to rely on a specific underlying view of machines that revives a number of anti-mechanistic notions. They do not deprive matter of spontaneity or *dynamis*; instead of assembling prefabricated building blocks, they play with composition and interfaces; instead of inferring from the macro to the nanoscales, they assume a hierarchy of structures. While Drexler's efforts are aimed at eliminating chemistry in order to work under the

[12] This phenomenon was observed in metal colloids or hydrosols by Michael Faraday in the mid-19th century and became known as the 'Tyndall effect' after Tyndall extended Faraday's earlier observations. Suspended particles that are small relative to the wavelength of visible light (with radii of approximately 20 nm) are brilliantly colored in red, green, and violet because the interaction with the incoming light is a combination of absorption and scattering (Arribart 2004, p. 363).

strict control of a program, they mobilize all possible resources of chemistry, of kinetics and thermodynamics.

5. Historical Roots

Clearly engineers and chemists have two irreconcilable views of nanomachines. So striking is the contrast that it raises the question: are there two cultures within the field named nanotechnology? In their revolutionary claims, Drexler and his followers never mention earlier attempts at taking inspiration from life. His emphasis on the bottom-up approach creates a discontinuity with more traditional materials processes. Moreover, thanks to the reference to Feynman, nanotechnology seems to be rooted in quantum physics thus proceeding from a 'noble' theoretical science rather than from 'dirty' experimental physics or materials engineering. However this was not the first biomimetic. There had been many previous attempts at mimicking living organisms at the macro and the microlevels.

Biomimetism has been a leitmotif in technology from mythical attempts – the wings of Daedalus – up to the more recent examples like velcro. In many technological areas, such as aeronautics, architecture, and textiles, mimicking living things has been a current practice that has lead to some brilliant results[13]. Biomimetism is more than a handful of occasionally successful bio-inspired inventions. It became a research program in the 20th century initiated by Darcy Thompson, a zoologist who applied mathematics to the study of living shapes and physics to the study of their growth. In *On Growth and Forms* (1992 [1942]) he argued that the different parts of an organism are optimally shaped. This book was the root of a joint approach of living organisms by biologists and engineers. Bionics (literally, 'units of life') was an attempt to evaluate the efficiency of an organism or a machine, to measure the structures and

[13] Vogel 1998, pp. 249-75. Among the most famous examples of successful copies are the Crystal Palace designed by Joseph Paxton whose roof allegedly copied a giant water lily; the spinneret for extruding textile fibers inspired by the organ of silkworms; barbed wire; and the velcro invented by the Swiss engineer Georges Mestral on the model of the hooked burs that clung to his socks.

processes by which the 'purposes' or ends of the system were fulfilled[14]. In the postwar period, biomimetism benefited from strong support from the US army, Naval research, and the National Institute of Health. The term 'biomimesis' was introduced in 1961 at the second symposium on bionics by Warren S. McCulloch, a neuroscientist member of the Research Laboratory of Electronic at MIT, as a generic concept. Taking the term in its most extensive sense, "the imitation of one form of life by another", McCulloch (1962) included the mimetic strategies to avoid enemies or catching preys that are predetermined in the genes of insects. McCulloch divided biomimesis into two distinct fields, cybernetics and bionics. Cybernetics, he argued, deals with control functions rather than with mechanical work.[15] It is mainly concerned with regulation mechanisms and feedback control. By contrast, 'bionics' was defined "as an attempt to understand sufficiently well the tricks that nature actually uses to solve her problems, this enabling us to turn them into hardware" (*ibid.*, p. 393). According to McCulloch the latter requires more than interdisciplinarity, new skills. He called for a novel science and a new organization of scientific research because: "one has to have a reasonable knowledge of both engineering and biology in his own head" for the purpose of understanding living systems. First he called logicians to join the program because new skills in logic and mathematics are necessary to understand the complex organization of living systems. Second, he called for increasing work on the thermodynamics of open systems because the major development that he saw coming was the understanding of natural processes that go on along with ever-increasing entropy: how order evolves from the inside instead of being forced upon a material after torturing it. In bionics the emphasis was on the holistic structure of living organisms. For instance, in an introductory paper entitled 'Bio-logic', Heinz von Foerster argued that the fundamental principle in life was 'coalition' rather than self-reproduction.

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[14] See for instance Howland 1962.

[15] According to McCulloch, cybernetics emerged from the steam engine, when Julian Bigelow pointed out that it was only the information concerning the outcome of the previous act that had to return.

> What I call coalition is an aggregate of elements which jointly can do things which all of them separately could never achieve. It is characterized by a superadditive nonlinear composition where the whole is more than the sum of the measure of the parts. [Foerster 1962]

Finally McCulloch identified a third, but minor trend of biomimesis: the design of artificial organisms that are capable of evolving and learning. At this time, it was just a small group interacting with the community, but it should become extremely fashionable in Materials Science and Engineering over the past decades. Materials scientists look at Nature as an insuperable designer of optimal, multi-functional, and self-repairing structures (Bensaude-Vincent *et al.* 2002). They are trying to understand 'the tricks that nature actually uses to solve her problems', and to mimic them in order to solve their own problems.

Beyond McCulloch's dual genealogy of biomimetism, the current divorce between two paradigms of nanotechnology resonates with an older philosophical problem. The current trend generates serious 'epistemological risks'. The mechanistic model may have a heuristic power for some time as it had, for instance, in the history of medicine. However, its epistemic relevance as a simplifying model may lead to epistemic obstacle because it ignores inner dynamics and power at work both in living organisms and in technological systems. Moreover, as George Canguilhem suggested in a paper on 'machine and organism', the mechanization of life is inseparable from a project of instrumentalization of life and control over nature. Descartes' theory of animal-machines rested on a systematic depreciation of animals in order to legitimize their utilization as tools by humans (Canguilhem 1952, p. 111). Ethical and epistemological issues are closely intertwined.

At this critical point, it may be helpful to go back to the ancient Greek notion of *technê*.[16] It is well-known that, while Aristotle defined *technê* as a *mimesis* of nature, he did not hesitate to draw analogies from arts to describe nature as a craftsman displaying the ingeniosity associated with mechanics. There is nothing new in the current artificialization of nature. Already in antiquity, there were two different and occasionally conflicting views of technology. On the one hand, the arts or *technai* were con-

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[16] See for instance Schiefsky (forthcoming) and Staden (forthcoming).

sidered as working against nature, as contrary to nature. This meaning of the term *para-physin* provided the ground for repeated condemnations of mechanics and alchemy. On the other hand, the arts – especially agriculture, cooking, and medicine – were considered as assisting or even improving on nature by employing the *dynameis* or powers of nature. In the former perspective, the artisan, like Plato's *demiurgos*, builds up a world by imposing his own rules and rationality on a passive matter. Technology is a matter of control. In the latter perspective the artisan is more like the ship-pilot at sea. He conducts or guides forces and processes supplied by nature, thus revealing the powers inherent in matter.[17] Undoubtedly the mechanicist model of nanotechnology belongs to the demiurgic tradition. It is a technology fascinated by the control and the overtaking of nature.

Nanotechnology and biotechnology are mainly concerned with the control of nature at the most basic level, *i.e.* the level of atomic building blocks. It does not really matter whether the control of the molecular machinery is in the hands of humans or in the hands of posthuman cyborgs. The grey goo scenario is just the continuation of a long tradition of mythologies and fictions – ranging from Prometheus to Faust and Frankenstein. Yet there remains an alternative future that could make nanotechnology more akin to agriculture or traditional medicine. Susan Linquist from MIT Whitehead Institute once said: "About 10,000 years ago, [humans] began to domesticate plant and animals. Now it's time to domesticate molecules." (quoted in Zhang 2003, p. 1177) In this case, blurring the boundary between life and matter invites neither reductionism nor dreams of control. On the contrary, nanoscientists dealing with isolated molecules cannot adopt the standard subject-object relation. Isolated molecules tend to become more like individuals or partners whom science and technology try to domesticate. If scientists and engineers were ready to behave more like farmers relying on plants and animals or like pilots in relying on winds to guide their sea boat, our future might be less tragic as it seems today. Sailors know that all journeys are risky, that

[17] On the contrast between the two definitions of technology in the case of genetically modified organisms, see for instance Larrère 2002.

their jobs require many precautions because they have to negotiate with natural elements, necessarily involving a good deal of uncertainties.

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CHAPTER 2

THE DREXLER-SMALLEY DEBATE ON NANOTECHNOLOGY: INCOMMENSURABILITY AT WORK?

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In a recent debate, Eric Drexler and Richard Smalley have discussed the chemical and physical possibility of constructing molecular assemblers – devices that guide chemical reactions by placing, with atomic precision, reactive molecules. Drexler insisted on the *mechanical* feasibility of such assemblers, whereas Smalley resisted the idea that such devices could be *chemically* constructed, because we do not have the required control. Underlying the debate, there are differences regarding the appropriate goals, methods, and theories of nanotechnology, and the appropriate way of conceptualizing molecular assemblers. Not surprisingly, incommensurability emerges. In this chapter, I assess the main features of the debate, the levels of the emerging incommensurability, and indicate one way in which the debate could be decided.

1. Introduction

Many debates about nanotechnology emerge from particular visions of the field. We find, for example, visions of a future dramatically changed by the new technology, with the production of materials and objects with atomic precision in a remarkably short time by self-replicating nanobots (Drexler 1986); but we also find the fear that nanotechnology will quickly run out of control, leaving us powerless behind (Joy 2000). As with most extreme views, it is unlikely that any of these scenarios is completely correct. However, particularly in less radical forms, they may capture something right about certain developments of the field.

In this chapter, I examine a recent debate in nanotechnology, which was also motivated by different visions of the field. But, in this case, the different visions involved distinct ways of conceptualizing what is (and is not) feasible in the area, and even alternative standards of assessment of such feasibility judgments. In the debate, we find all the interesting features of scientific debates more generally: curious arguments (and often not unproblematic ones), powerful images, unexpected conceptual shifts, the use of diverse standards, and a good bit of rhetoric. What emerges from the exchange examined here is an interesting perspective on how scientific debates can be conducted and interpreted – and why, sometimes, it is so hard to settle them. Nanotechnology, even at the metalevel, never stops to be intriguing.

The debate involves two significant characters. On the one hand, we have Eric Drexler, one of the visionaries of nanotechnology. He clearly conceived of a world completely transformed by the developments in the area. A crucial component of his view takes central stage in the exchange below: the notion of a *molecular assembler*. According to Drexler, such an assembler would be able to build virtually anything with atomic precision and no pollution. His vision was first presented in the 1980s, in *Engines of Creation* (Drexler 1986), with the more technical details articulated later in the early 1990s, in *Nanosystems* (Drexler 1992). Drexler is the chairman and cofounder of the Foresight Institute, an institution that aims to help prepare society for advances in technology, with particular emphasis on nanotechnology. Drexler's main background is in engineering, and as we will see, it is from the perspective of an engineer that he approaches nanotechnology. As will become clear below, this explains important features of his vision of the field.

On the other hand, we have Richard Smalley. University Professor of chemistry, physics, and astronomy at Rice University, Smalley was awarded the 1996 Nobel Prize in chemistry for the discovery of fullerenes. His current research is deeply immersed in nanotechnology, focusing, in particular, on the chemistry, physics, and potential applications of carbon nanotubes. With his main background in chemistry and physics, Smalley approaches nanotechnology with an eye for what can actually be implemented and controlled in the laboratory. His approach is not only informed by the relevant chemical and physical theories, but it relies deeply on the actual chemical and physical *practices* to determine the feasibility of proposed views.

What is the issue in the debate between Drexler and Smalley? Briefly put, the question is whether *molecular assemblers* are possible. As conceived of by Drexler, molecular assemblers are "devices able to guide chemical reactions by positioning reactive molecules with atomic precision" (Drexler 2003a, p. 38). More specifically, the issue is whether it is *physically* and *chemically* possible to construct such assemblers; *i.e.*, whether the construction of a molecular assembler is *compatible* with accepted physical and chemical principles. Drexler claims it is.[1] In his picture, molecular assemblers are basically *mechanical* devices, controlled by computers to "guide the chemical synthesis of complex structures by mechanically positioning reactive molecules" (Drexler 2003a, p. 38).[2] Smalley disputes the viability of this mechanical picture, challenging the possibility of obtaining the precise control of nanophenomena presupposed by Drexler. According to Smalley, the required control cannot be had – not even in principle.

2. The Debate

The debate starts with Smalley questioning Drexler's proposal with two arguments: the so-called *fat fingers* and *sticky fingers* objections. Smalley's point is that it is not possible to pick up and place *individual atoms* with the precision required by Drexler: computer-controlled 'fingers' will be too fat and too sticky for that (Smalley 2001). The talk of fingers in this context may seem strange, given that, literally, there are no at the nanoscale. However, as we will see, this talk plays an important rhetorical role in Smalley's argument, which can be seen as a kind of

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[1] Of course, Drexler has actually not constructed a molecular assembler. The question of the *possibility* of constructing such a device would be irrelevant if the device had already been constructed. It is enough for Drexler's purpose to establish the *theoretical possibility* of such a construction, sketching how it *could be performed in principle*. If no known physical and chemical laws are violated in the construction, the resulting process is, at least, theoretically possible – even though we may not have the slightest idea of how to *implement* the process and thus *actually construct* the assembler.

[2] Note that, according to Drexler, molecular assemblers will *not* manipulate individual atoms, but only *reactive molecules*. I will return to this point below.

reductio of the mechanical features of Drexler's conception. What Smalley wants to highlight with this language is the difficulty of *actually implementing* Drexler's vision, according to the standards set by Drexler himself. I will consider each argument in turn.

The *fat fingers* objection takes seriously the *mechanical* nature of Drexler's conception of molecular assemblers, and attempts to show that the unfeasibility of the conception is ultimately due to the mechanical assumptions it requires. As we saw, for Drexler, an assembler will "*mechanically* [position] reactive molecules" with "*atomic precision*", and in this way, it will be able to "guide the chemical synthesis of complex structures" (Drexler 2003*a*, p. 38, italics added). What happens if we take literally the idea of *mechanically* locating each atom with atomic *precision*? This would require, according to Smalley, nanobots with *manipulator arms* – this is the point where the mechanical features are taken at face value. But given that the fingers of the nanobot arm must themselves be made of atoms, there would not be enough room at the nanometer scale to allow the control required to *precisely* locate each atom. After all, to have *complete control* of the chemistry, too many fingers in too many arms would be needed. And there is simply not enough room for that. In Smalley's own words:

> Because the fingers of a manipulator arm must themselves be made out of atoms, they have a certain irreducible size. There just isn't enough room in the nanometer-size reaction region to accommodate all the fingers of all the manipulators necessary to have complete control of the chemistry. [Smalley 2001, p. 77]

According to the *sticky fingers* objection, the precise control over the positioning of atoms required by Drexler cannot be achieved, given that the atoms of the manipulator arms will interact with *other* atoms in unintended ways. Just by positioning an atom in a given place is not enough to guarantee that it will interact *only* with the atoms *we* want it to interact with. As Smalley points out:

> Manipulator fingers on the hypothetical self-replicating nanobot are [...] too sticky: the atoms of the manipulator hands will adhere to the atom that is being moved. So it will often be impossible to release this minuscule building block in precisely the right spot. [Smalley 2001, p. 77]

With these two arguments, Smalley thinks that Drexler's mechanical case for molecular assemblers is fundamentally flawed.

However, Smalley also raises an additional worry. In his view, Drexler needs *self-replicating* molecular assemblers to implement his vision; otherwise, the rate of production would be too slow. A single *non*-replicating assembler would take a long time to produce only a mole of something:

> Imagine a single assembler: working furiously, this hypothetical nanorobot would make many new bonds as it went about its assigned task, placing perhaps up to a billion new atoms in the desired structure every second. But as fast as it is, that rate would be virtually useless in running a nanofactory: generating even a tiny amount of a product would take a solitary nanobot millions of years. (Making a mole of something – say, 30 grams, or about one ounce – would require at least 6×10^{23} bonds, one for each atom. At the frenzied rate of 10^9 per second it would take this nanobot 6×10^{14} seconds – that is, 10^{13} minutes, which is 6.9×10^9 days, or 19 million years.) [Smalley 2001, p. 76]

In contrast, *self-replicating* nanobots would be much more efficient. With the ability to self-reproduce, very quickly they could create a whole army of assemblers, which in turn would be able to produce things at a much faster rate.

> For fun, suppose that each nanobot consisted of a billion atoms (10^9 atoms) in some incredibly elaborate structure. If these nanobots could be assembled at the full billion-atoms-per-second rate imagined earlier, it would take only one second for each nanobot to make a copy of itself. The new nanobot clone would then be 'turned on' so that it could start its own reproduction. After 60 seconds of this furious cloning, there would be 2^{60} nanobots, which is the incredibly large number of 1×10^{18}, or a billion billion. This massive army of nanobots would produce 30 grams of a product in 0.6 millisecond, or 50 kilograms per second. Now we're talking about something very big indeed! [Smalley 2001, p. 76]

According to Smalley, the implementation of Drexler's vision requires more than just molecular assemblers; these assemblers need to *self-replicate* as well.

How does Drexler respond? First, with regard to the self-replication requirement, even though Drexler himself had an important role in forming the impression that self-replication was necessary for the success of nanotechnology (Drexler 1986), things have changed on this front. Drexler has recently been developing, in collaboration with Chris Phoenix, models that do *not* require self-replication to implement large-scale systems of productive nanomachinery (see Drexler & Phoenix 2004). The details of these models, however, still remain to be seen.

Second, with regard to the fat fingers and the sticky fingers objections, Drexler insists, as noted above, that his assemblers do *not* manipulate individual atoms. They manipulate *reactive molecules* (Drexler 2003a, p. 38). Given that Smalley's two main objections were based on the difficulties associated with manipulating *individual atoms*, they just miss the target.

In reply to Drexler's response, Smalley formulates a second version of the fat and sticky fingers objections, extending to reactive molecules the arguments that were initially couched in terms of individual atoms:

> The same argument I used to show the infeasibility of tiny fingers placing one atom at a time *applies also to placing larger, more complex building blocks*. Since each incoming 'reactive molecule' building block has multiple atoms to control during the reaction, even more fingers will be needed to make sure they do not go astray. *Computer-controlled fingers will be too fat and too sticky to permit the requisite control.* Fingers just can't do chemistry with the necessary finesse. [Smalley 2003a, p. 39, italics added]

Thus, the original complaint about the unfeasibility of controlling chemical processes with the needed refinement can be easily extended to reactive molecules as well. If anything, in Smalley's view, the second version of the 'fingers' objections is stronger than the first, given that the precise manipulation of a whole *reactive molecule* requires more 'fingers' to control the multitude of atoms involved than what is required by the manipulation of just a *single atom*. Thus, the initial difficulty comes back – now multiplied by each atom involved in the process.

In response, Drexler thoroughly rejects the talk of *fingers*. It is not only that this talk cannot be taken literally; there are simply *no* such fingers at the nanometer scale. As he points out:

> Like enzymes and ribosomes, proposed assemblers neither have nor need these 'Smalley fingers'. The task of positioning reactive molecules simply doesn't require them. [Drexler 2003a, p. 38]

In a curious way, both Smalley and Drexler agree on the nonexistence of such 'fingers', albeit for very different reasons. Smalley rejects these 'fingers' as part of his *reductio* of the *mechanical* approach to assemblers, which he correctly takes to be Drexler's view. Drexler, in turn, denies commitment to these (obviously nonexistent) objects as part of his attempt to defuse Smalley's objection.

But once this is clear, we can see the significance of Smalley's 'fingers' objection: it challenges Drexler to spell out *not* the mechanical, but the *chemical processes* underlying Drexler's conception of molecular assemblers. The objection ultimately disputes the feasibility of controlling the *chemical* reactions that would inevitably take place if a mechanical molecular assembler were ever produced. In this way, by skillfully shifting the issue from the mechanical to the chemical domain, the objection defies the viability of Drexler's proposal.

However, once it is agreed that there are no fingers at all at the nanoscale, Smalley raises a *new* challenge. If the process of placing reactive molecules does not involve fingers, and if molecular assemblers are to use enzymes and ribosomes in this process – as Drexler himself acknowledges (Drexler 2003*a*, p. 38) – further difficulties emerge. After all, we should now take seriously the need for describing the *chemical* processes involved in the implementation of a molecular assembler; in other words, the chemical details have to be articulated.[3] In particular, several points need to be spelled out. For example:

> How is it that the nanobot picks just the enzyme molecule it needs out of this cell, and how does it know just how to hold it and make sure it joins with the local region where the assembly is being done, in just the right fashion? How does the nanobot know when the enzyme is damaged and needs to be replaced? How does the nanobot do error detection and error correction? [Smalley 2003a, p. 39]

Without answering questions of this sort, it is unclear how a molecular assembler – with the particular type of control and precision required by Drexler's proposal – could actually be constructed, even in principle.

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3 Or, at least, before actually implementing a molecular assembler, presumably we would need to accommodate the chemical details needed in the theoretical description of the latter.

The outcome of these considerations is what can be called *Smalley's dilemma*. Supposing that Drexler's molecular assembler will use something like enzymes and ribosomes, then either the assembler is a water-based entity, or it is not. If it is a water-based entity, then it is limited in what it can achieve; for instance, it *cannot* produce anything that is chemically unstable in water. (And how will it then produce steel, copper, aluminum, or titanium?) If the assembler is *not* water based, then the chemistry that underlies it eludes us. In Smalley's own words:

> The central problem I see with the nanobot self-assembler then is primarily chemistry. If the nanobot is restricted to be a water-based life-form, since this is the only way its molecular assembly tools will work, then there is a long list of vulnerabilities and limitations to what it can do. If it is a non-water-based life-form, then there is a vast area of chemistry that has eluded us for centuries. [Smalley 2003a, p. 40]

In either case, according to Smalley, there is trouble. The first horn seems to bring major limitations to what could be achieved by a water-based assembler (*e.g.* nothing that is unstable in water could then be produced). The second horn, with a non-water-based assembler, requires a chemistry whose details we may not have completely mastered yet.

Interestingly enough, Drexler's response to the dilemma does not address any of the two horns.[4] Instead, he returns from *chemistry* to *mechanics*. Talking about Feynman's famous 1959 talk (Feynman 1960), Drexler insists:

> Although inspired by biology (where nanomachines regularly build more nanomachines despite quantum uncertainty and thermal motion), Feynman's vision of nanotechnology is *fundamentally mechanical, not biological*. Molecular manufacturing concepts [that is, Drexler's own approach] follow this lead. [Drexler 2003b, p. 40, italics added]

With the acknowledgment of Feynman, Drexler then rejects the need for accommodating the details of chemical processes that, *prima facie*, seem to be required for the implementation of his own vision. By emphatically

[4] Perhaps Drexler could have challenged the second horn, noting that there have been studies of several chemical and biological processes that are *not* water-based. But, in this case, it might not be so clear how Drexler could still maintain the *mechanical* nature of his assemblers, given that the relevant work would have to be done by the appropriate chemical and biological processes.

putting himself back into a purely mechanical world, he denies any role for biological or strictly chemical processes in his proposal:

> Nanofactories contain *no enzymes*, *no living cells*, no swarms of roaming, replicating *nanobots*. Instead, they use *computers* for digitally *precise control*, *conveyors* for *parts transport*, and *positioning devices* of assorted sizes to *assemble small parts into larger parts*, building macroscopic products. The smallest devices *position molecular parts* to assemble structures through *mechanosynthesis* – 'machine-phase' chemistry. [Drexler 2003b, p. 41, italics added]

Without a doubt, Drexler emphasizes here the mechanical features of his conception of assemblers, invoking conveyors, computers, and positioning devices to assemble structures. We are now miles away from any chemical understanding of a molecular assembler. This is perhaps the position Drexler wants to be in. Presumably, he sees it as a safe place from which to disarm Smalley's dilemma, given that the latter does not arise for a nonchemical conception of assemblers.

This may be so, but the move has its cost too. And as Smalley does not fail to point out in his final reply, instead of exploring the chemical details that need to the articulated for Drexler's conception to get off the ground, Drexler simply returned to his mechanical view, bringing back the same difficulties along the way. For Smalley, a purely mechanical conception of molecular assemblers is miles away from anything that could actually be implemented – even in principle – due to the unfeasibility of the required control. With noticeable disappointment, Smalley notes:

> I see you have now walked out of the room where I had led you to talk about *real chemistry*, and you are now back in your *mechanical world*. [...] Much like you can't make a boy and a girl fall in love with each other simply by pushing them together, you cannot make *precise chemistry* occur as desired between two molecular objects with *simple mechanical motion* along a few degrees of freedom in the assembler-fixed frame of reference. Chemistry, like love, is more subtle than that. You need to *guide the reactants* down a particular reaction coordinate, and this coordinate treads through a many-dimensional hyperspace. I agree you will get a reaction when a robot arm pushes the molecules together, *but most of the time it won't be the reaction you want.* [Smalley 2003b, p. 41, italics added]

However, with Drexler's return to the mechanical view, we are back to the main trouble: the level of control over reactive molecules that is presupposed by this view simply cannot be obtained. In the passage that follows, Smalley emphasizes just this point:

> Chemistry of the complexity, richness, and precision needed to come anywhere close to making a molecular assembler – let alone a self-replicating assembler – cannot be done simply by *mushing two molecular objects together. You need more control.* There are *too many atoms involved* to handle in such a clumsy way. [Smalley 2003b, p. 41, italics added]

However, if a purely mechanical approach to assemblers does not quite work, what is the alternative? Not surprisingly perhaps, Smalley's final conclusion insists on the need for returning to a *chemical* conception of assemblers, as a way to try to obtain, at least in part, some of the required control. As he insists:

> To control these atoms you need some sort of molecular chaperone that can also serve as a *catalyst.* You need a fairly large group of other atoms arranged in a complex, articulated, three-dimensional way to *activate the substrate and bring in the reactant*, and massage the two until they react in just the desired way. You need something very much like an *enzyme.* [Smalley 2003b, p. 41, italics added]

In other words, to get the control Drexler needs, it is crucial to appeal to a *chemical* understanding of the phenomena: instead of conveyors, computers, and positioning devices, we have catalysts, reactants, and enzymes. Even then, it is not entirely obvious that one can fully implement Drexler's overall vision. After all, chemical processes are often capricious, subtle, and delicate – in ways that repeatedly elude us.

3. A Partial Diagnosis: Incommensurability at Work?

After reviewing the main features of the debate, it is hard to resist the temptation of giving at least a partial diagnosis. Although I do not intend to be comprehensive, I want to highlight significant features that should help us understand some of the moves made above.

3.1. Different Conceptions of Molecular Assemblers

First, we clearly have here two *radically different* approaches to molecular assemblers. On the one hand, there is Drexler's *mechanical* conception, which is developed as an *engineer's* (conceptual) prototype. It examines, from a mechanical point of view and purely theoretically, in what way molecular assemblers are possible, by essentially formulating a theoretical model in which the relevant physical principles are not violated. The irony is that, as an engineer, Drexler only provides *theoretical* artifacts, rather than *physical* ones. For Drexler, however, this is not at all a problem. It is simply part of his *theoretical applied science* project, which does not aim at providing experimental results, but develops instead only a "theoretical analysis demonstrating the *possibility* of a class of as-yet *unrealizable* devices" (Drexler 1992, p. 489, the first italic is mine). Instead of producing physical devices, the aim is to generate theoretical results. In much the same way, the aim of interpreting a physical theory (say, quantum mechanics) typically is the formulation of *theoretical results* regarding the *possibility* of certain aspects of the world (on the assumption that the theory in question is true), rather than the generation of new experimental results. The activity of interpretation may not be the most typical activity in scientific practice, but it is a significant part of it nonetheless.

On the other hand, there is Smalley's *chemical* approach to molecular assemblers, which challenges the *feasibility* of Drexler's *mechanical* conception. As a chemist, Smalley insists on the production of *detectable* and *controllable* effects, emphasizing the need for accommodating the *actual, chemical* details that are part of the phenomena. (This is precisely what Drexler is unwilling to do.) However, as we saw, Smalley's challenge goes deeper, given that it disputes even the feasibility *in principle* of actually implementing anything like a mechanical molecular assembler, due to the difficulty of having the required control.

As a result, and very briefly put, we are faced here with a *disciplinary* clash (between chemistry and engineering), with different *conceptions* of the *nature* of molecular assemblers (chemical versus mechanical), and with distinct *practices* that may lead to their construction (effective implementation versus conceptual exploration). It is perhaps not surprising that we have hardly any agreement in the debate!

3.2. Different Levels of Incommensurability

Given the significant differences between the two approaches, the picture that emerges is one of *incommensurability* (see, *e.g.*, Kuhn 1970, Feyerabend 1981, Siegel 1980, Hoyningen-Huene 1993, and Sankey 1994). After all, there are no *common standards* to assess the adequacy of each conception. According to the standards that Drexler set out to himself – namely, to articulate theoretical artifacts – his approach is perfectly adequate. His criteria of adequacy require only the *mechanical feasibility* of molecular assemblers, in the sense that the phenomena in question are not incompatibie with any known physical (and perhaps chemical) principles – even though we may *not* have the slightest idea of how to *actually implement* and construct the devices under consideration. For Drexler, the process of actual construction will come later.

But we also saw that, in response to Smalley's challenge, Drexler's own conception seems to shift, back and forth, between mechanical and chemical representations of molecular assemblers. Due to the nature of these shifts, we clearly have here incommensurability of a *conceptual* nature. Drexler's considered view, however, seems to favor the *mechanical* conception, which makes his proposal undoubtedly open to Smalley's criticisms. Smalley challenges, in fact, even the *feasibility in principle* of such assemblers. Why?

Because Smalley criticizes the core of Drexler's approach: the requirement of positioning reactive molecules with *atomic precision*. That is, Drexler demands (a) a perfect control of the *position* where each reactive molecule will be placed, and (b) a perfect control of the *way* in which a given reactive molecule will interact with other molecules. Smalley challenges both assumptions. If we were to implement anything like Drexler's proposal in the lab, we would face insurmountable difficulties. Given the huge number of atoms present in the phenomena, we would not have the precise control to determine in which way a given reactive molecule would interact (against (b)). Thus, it would not be possible to position precisely the reactive molecule (against (a)).

Smalley, in turn, adopts a radically different *conception* of the nature of molecular assemblers. With his *chemical* conception, assemblers are subject to all the vagaries of chemical processes. And it is this conception that grounds Smalley's criticism of Drexler's idea of *atomic precision*. If the *chemical factors* involved in the interactions between reactive molecules are taken into account, it becomes clear that we cannot simply have the required control envisaged by the mechanical approach.

Smalley also challenges the *methods* used by Drexler to implement his proposal. The construction of theoretical artifacts – as the outcome of Drexler's theoretical applied science – is not enough to establish the feasibility of molecular assemblers as Drexler conceives of them. After all, any attempt to actually implement such assemblers (for example, by trying to construct them in the lab) will immediately face trouble, given the relatively limited control that we can actually have over chemical reactions at the nanoscale.

The points just made indicate that there are at least three levels of incommensurability here: cognitive, conceptual, and methodological (see, *e.g.*, Kuhn 1970, Laudan 1984, and Sankey 1994).[5] (i) *Cognitive* incommensurability emerges when there are no *common standards* to assess the *adequacy of certain theories* about the phenomena under examination. (ii) *Conceptual* incommensurability is the outcome of the lack of common standards to *adjudicate concepts* used to describe the phenomena. (iii) And finally, *methodological* incommensurability arises from the lack of common standards of *assessment of the reliability of the different methods used.* How do these levels of incommensurability bear on the present discussion?

(i) The debate here involves *cognitive* incommensurability in that each side adopts different theories to articulate the corresponding conception of assembler: mechanical theories in Drexler's case and chemical theories in Smalley's. Each of these theories is, of course, adequate *in its respective domain*, but given the dramatically different ways in which Drexler and Smalley conceptualize the domains (one mechanically, the

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[5] The literature on incommensurability is, of course, huge (see, *e.g.*, Kuhn 1970, Feyerabend 1981, Siegel 1980, Hoyningen-Huene 1993, Sankey 1994, and the references quoted in these works). But this is not the place to review it. For the purposes of this paper, I will only focus on the issues that are significant for the present debate.

other chemically), it is unclear how one could assess the *overall* adequacy of the theories without simply begging the question against the rival proposal.

(ii) The debate also involves *conceptual* incommensurability, given the radically different ways in which molecular assemblers have been conceptualized: Drexler conceives of them in basically mechanical terms, whereas Smalley is highly sensitive to the chemical features involved in the phenomena. But how could we assess the adequacy of such concepts without simply prejudging the nature of the assemblers themselves? Depending on the view of assemblers we adopt (a chemical or a mechanical view), we obtain very different answers regarding the adequacy of the concepts in question.

(iii) Finally, the debate includes *methodological* incommensurability as well, given that each view has a different method of articulation of molecular assemblers. Drexler's theoretical applied science approach insists that we should first develop theoretical artifacts, establishing the theoretical possibility of such assemblers. Smalley, in turn, with a chemically grounded view, highlights the need for controllable and detectable results before we could even talk *realistically* about the possibility of such objects. Unless we could, in principle, develop techniques of implementation of molecular assemblers – identifying the relevant operations to be performed in the lab – it is hard to judge how such assemblers are *technologically* possible. The fact that a device is *theoretically* possible (that is, its existence does not violate any laws of physics or chemistry) is not sufficient to guarantee that we can *construct that device*, and hence establish that it is possible in the *actual* world, given *our technology*. Drexler agrees, of course, with the distinction between *theoretical* and *technological* possibility, and in fact, theoretical applied science often moves ahead of technology (Drexler 1992). But for Smalley, without accommodating the *practical details of what actually goes on in the lab*, without taking into account the *technological* aspects of current chemistry, we cannot claim to have established even the *theoretical* possibility of the devices in question. We need more than lack of inconsistency with physical and chemical principles. The technology that goes on in the lab is as much part of science as the theories that are articulated there. Given that the production of a molecular assembler crucially relies on that technology, we need to consider the latter as well.

Note that the fact that Drexler and Smalley's views are incommensurable does *not* entail that they are incomparable. The absence of common standards of assessment only entails that evaluative judgments cannot be made without begging some questions, such as assuming the set of standards of one view to judge the adequacy of the other. Concepts, theories, and methods can, of course, be compared. We have been doing this all along. What may not happen is that we will be in a position to decide – without circularity – the adequacy of these concepts, theories, and methods, given the lack of a common standard of adequacy.

Why is it significant to identify the various kinds of incommensurability found in the debate between Drexler and Smalley? Because this helps to explain in which ways the debate has been inconclusive, and why it is inevitable to end up with the impression that Drexler and Smalley are simply talking past each other. With different conceptions of assemblers and with different methodological strategies to articulate such assemblers (*i.e.*, strategies that aim to show the feasibility of such assemblers and to sketch how the latter could, in principle, be constructed), it is not surprising that there is no agreement as to how the debate could be settled. Without common standards of evaluation, or common methods of assessment and construction of assemblers, it is hard to see how to resolve this debate without simply begging the question against one side or the other.

By highlighting the incommensurability involved in the discussion, we can also understand another feature of the debate: the many layers in which it takes place. As noted above, we find not only different *conceptions* of molecular assemblers (chemical versus mechanical), different *methods* of construction or implementation of such assemblers (actual implementation versus conceptual exploration), but also, more generally, different *goals* for nanotechnology research – given the different *visions* underlying Drexler's and Smalley's projects. As we saw, Drexler's vision for nanotechnology is one of atomic precision and perfect and complete control over molecular reactions. It is essentially an *engineer's* vision. Smalley's vision, in turn, insists on the production of detectable and controllable phenomena, and takes as a crucial part of scientific activity the manipulation and stabilization of the phenomena. This vision challenges the viability of a notion of *control* that is not grounded on what can *actually be performed* in the lab. It is essentially a *chemist's* vision. And, as was pointed out, in each of these levels, we have incommensurability.

3.3. An Alternative Way of Interpreting the Debate: Instruments at Work

The considerations just made implicitly suggest an alternative strategy to analyze the debate between Drexler and Smalley. Perhaps with some adjustments, this alternative could provide a way to 'settle' the dispute without (hopefully) begging any questions.

As is well known, Larry Laudan developed a very interesting framework to assess scientific debates: the reticulated model (Laudan 1984). The idea is that scientific practice is articulated in terms of three interrelated levels: goals, methods, and theories. The level of *goals* involves the aims and values shared by a particular scientific community. These goals include certain ways of assessing and structuring scientific research, for example, searching for and valuing empirically testable and informative theories over mere conceptual sketches of possible experiments. The level of *methods* deals with methods of theory construction and theory evaluation, as well as the particular experimental strategies used to implement, control, and stabilize the phenomena. Finally, the level of *theories* includes the various theories and theoretical assumptions adopted by a particular community to explain and predict the phenomena.

According to this picture, scientific change involves change on at least one of the three levels, but *never* changes in all of them at once. Thus, we could use the 'shared' level (say, the level of theories) to assess the adequacy of the remaining levels (say, goals and methods), and in this way, try to settle the debate. For instance, suppose that a given community has as one of its goals to construct a machine that accelerates objects with a speed faster than that of light. But if the community also accepts a theory that states that no object could travel faster than light, this would establish the unfeasibility of the goal. Thus, the community could invoke that theory to revise the goal.

Of course, this simple model does not cover all of the crucial elements of scientific practice. We also have, at least, the level of *scientific instruments* (for a fascinating and sophisticated account, see Baird 2004); and instruments cannot be identified with any of the three previous levels. (i) Although *theories* are often invoked in the construction and manipulation of instruments (including the *interpretation* of the results), instruments are, of course, much more than theories, and play a significantly different role in scientific practice. For instance, instruments provide the tools in terms of which experiments are possible, allowing scientists to probe details of the physical world that would otherwise be unavailable to them. (ii) Although the use of instruments require, of course, ingenuity and technique, the skills demanded go well beyond whatever *methodological rules* that may be adopted in scientific practice. Learning such skills involves special requirements and abilities, such as to be able to calibrate the instrument and to distinguish artifacts of the instrument from genuine information it provides. (iii) Finally, the *goals* and *values* of instrumental practice need not be the same as those of theoretical practice, given that the former is concerned with details of the instrumental apparatus that need not be the primary concern of the latter. Thus, instruments are a crucial *additional* level of consideration in scientific practice.

For simplicity's sake, let us consider scientific practice as involving certain *aims*, *methods*, *theories*, and *instruments*. Bearing this in mind, we can now return to the Drexler-Smalley debate and identify the levels in which it has been conducted. As noted above, there are differences in all of the first three levels. We have distinct *aims*: Drexler's theoretical applied science project is ultimately concerned with the production of *theoretical artifacts*, whereas Smalley insists on the need for the construction of *detectable and controllable phenomena*. There are different *methods*: Drexler invokes *theoretical exploration* to establish the possibility of certain devices, whereas Smalley insists on the *actual implementation* of the relevant phenomena in the lab. Finally, there are different *theories*: Drexler's *mechanical* approach to molecular assemblers emphasizes the *mechanical* features of the phenomena, whereas Smalley insists on the need for accommodating the relevant *chemistry*.[6]

Despite the disagreements at these three levels, the picture changes if we consider the fourth level, that of *instruments*. Here, at last, we find *agreement* between our authors. Both agree that the use of appropriate microscopy devices is crucial for the implementation of the phenomena in question, and *necessary* for the *actual* construction of a molecular assembler (assuming that it can be done). After all, it is through these instruments that the scientific community has the control it has over nanoscale phenomena. And it is *only* in terms of appropriate *instruments* that the community might be able to build an assembler. After all, given the size of such assemblers, the mediation of appropriate instruments is indispensable to control them.

With this minimal agreement, we can now work our way upward, and assess the debate from the point of view of instruments. Given that instruments are *indispensable* to the construction, stabilization, and control of phenomena at the nanoscale – and both sides of the debate agree on that – a *purely theoretical* approach to molecular assemblers that does *not* take into account the need for such instruments misses a *crucial point* of what needs to be accommodated. And Smalley's insistence on the need for the production of controllable and detectable devices can be seen as an emphasis on just the need for appropriate instruments.

In this way, we see how Smalley is ultimately justified in making the requirement he makes, without begging the question against Drexler. After all, *both parties share their commitment to the indispensability of appropriate instruments to control nanophenomena*. Smalley, however, articulates this commitment further, introducing the requirement that detectable results should be produced as part of the determination of the possibility of molecular assemblers. After all, given that instruments are

[6] This is a bit rough. Presumably, Drexler would agree on the relevance of chemical theories for his *overall* approach, which goes *beyond* his account of molecular assemblers (see Drexler 1992). However, if we focus only on Drexler's conception of *assemblers*, we get a more ambivalent picture regarding the role of chemistry. As we saw in his response to Smalley, Drexler shifts back and forth between a mechanical and a more chemical understanding of assemblers. However, given that Drexler's considered view seems to be the *mechanical* one, the crucial role is ultimately played by *mechanical* theories.

indispensable for the construction of such assemblers, to determine whether the latter are possible, it is crucial to be able, *at least in principle*, to produce detectable results. In this way, the overall proposal Smalley advocates seems more adequate.

Of course, this does not establish the adequacy of Smalley's *criticism* of Drexler. This is a separate issue, and is open to the incommensurability charge discussed above. For, as was noted, the criticism relies on concepts, methods, and theories that are *not* shared by Drexler. However, the emphasis on *instruments* indicates one way in which the debate could be decided. After all, there is a common perspective – the commitment to the indispensability of instruments – that is shared by both sides, and from which the overall adequacy of the two proposals can be determined, without assuming points that are contentious in the debate.[7]

4. Conclusion

As we saw, the debate between Drexler and Smalley has many levels and involves a variety of moves. Given the dramatic differences in concepts, aims, theories, and methods, and the difficulty of finding common standards of assessment of them, it is understandable that we are faced with many levels of incommensurability.

However, by exploring the shared commitment to instruments – as the basic source of stable information about the phenomena under consideration – it is possible to overcome, in part, the incommensurability and decide the debate. Not in the sense of conclusively settling the issue, which is not to be had in any case. But at least in the sense of appreciating what needs to be done to carry out the visions that underlie each proposal. By identifying the crucial role that instruments play in the articulation of these visions, we also see the role these visions can play in shaping nanotechnology.

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[7] The community of chemists typically also shares Smalley's commitment to the need for the relevant instruments as part of chemical practice. It is therefore not surprising that most members of that community will also accept Smalley's *critical* assessment of Drexler's proposal. This is expected, of course, given that the values, methods, and theories of that community are being assumed. Drexler, however, does not share them. This is another expression of the incommensurability involved in the debate.

Acknowledgments

My thanks go to Rick Adams, Davis Baird, David Berube, R.I.G. Hughes, Loren Knapp, Cathy Murphy, Alfred Nordmann, Chris Robinson, Joachim Schummer, and Chris Toumey for extremely helpful discussions. An earlier version of this chapter was presented at a workshop on the Drexler-Smalley debate at the University of South Carolina's NanoCenter. I wish to thank all those who attended for their contributions, and Joachim Schummer for his encouragement and help. The material is based upon work supported by a grant from the National Science Foundation, NSF 01-157, NIRT. All opinions expressed here are mine and do not necessarily reflect those of the National Science Foundation.

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CHAPTER 3

NOUMENAL TECHNOLOGY: REFLECTIONS ON THE INCREDIBLE TININESS OF NANO

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Technology stands for humanly initiated causal processes. Some have very detailed knowledge of how such processes unfold. Others can represent to themselves only the turn of a switch and a resulting action. In both cases, technical intervention is accompanied by an act of the imagination. But what happens when technologies elude the grasp of imagination? – The term 'noumenal technology' refers to envisioned nano- and biotechnological applications that revert from the domination, control, or rationalization of nature and produce instead a form of technology that is as uncanny as brute, uncomprehended nature itself. This perspective helps us understand some of the arguments and supposedly irrational anxieties that are associated with these technical developments.

1. Introduction

Noumena are distinct from *phenomena*. While the latter are the things as they appear to us and as we experience them, the *noumena* are the philosophically infamous and mysterious things-in-themselves.[1] The '*noumenal* technology' referred to in the title of this chapter would therefore appear to be a contradiction in terms: Technology is a human creation that involves human knowledge and serves human needs; this firmly

[1] Among Kant scholars, there is some debate as to whether *noumena* and the things in themselves should actually be equated. Whether or not there is a subtle distinction to be made here, does not affect the following discussion.

roots it in phenomena and it appears absurd to speak of technology that exists beyond human perception and experience among the things-in-themselves. The *noumenal* world is nature uncomprehended, unexperienced, and uncontrolled; it is nature in the sense of uncultivated, uncanny otherness. By speaking of '*noumenal* technology' this chapter argues that some technologies are retreating from human access, perception, and control, and thus assume the character of this uncanny otherness.

Three seemingly disparate reflections prepare the formulation of this thesis, and the remaining sections work to establish at least its plausibility.

2. The Emperor's New Guitar

Under the heading 'US-researchers play nano-guitar' the following brief notice appeared not long ago in a German newspaper:

> US-researchers struck the smallest guitar string in the world: The journal *Nature* reports that a nanocarbontube only a few millionth of a millimeter wide vibrates with an inaudibly high frequency. [*Frankfurter Rundschau*, 16 September 2004]

Too small to be seen, too high-pitched to be heard, this is clearly not much of a guitar. Indeed, one might wonder why anyone would call it a guitar in the first place. In fact, the *Nature* editorial does not refer to a guitar at all but likens the observed effects to "the strings of a violin" (Cleland 2004).[2] Since this does little to clarify matters, the article explains that the resonance frequency of the nanotubes can be tuned – and both, the notions of resonance and of tuning suggest the functional similarity to a stringed musical instrument. The analogy can now be extended to say that the functionality may lead to devices or instruments. Researchers may well begin to play on these instruments, though not to produce music but, for example, to amplify the instrument's informational state and thus to make it an "electronic detector – one that can

[2] Cleland's editorial comments regard a finding by Sazonosa *et al.* (2004). The authors of that paper refer in their abstract to "guitar-string-like oscillation modes of doubly clamped nanotube oscillators." Neither paper includes the now-popular picture of the 'nano-guitar'.

'hear' its own motions". The editorial concludes by expressing the hope that "[f]uture efforts may add multi-stringed instruments to the present device – and perhaps, in time, arrive at a full symphony orchestra" (Cleland 2004).

The nano-guitar adds further evidence to Joachim Schummer's thesis about the aesthetic origin of molecular nanotechnology. He argues that the technical functionality of molecules was suggested by a certain way of looking at molecules within supramolecular chemistry, where molecular structures became associated with artifacts like baskets, rotors, or chains (Schummer 2006). Assuming the position of the newspaper reader, however, we might go on and probe a little more deeply what it means to imagine as a familiar instrument like a violin or electric guitar something that is utterly remote to our senses, namely a carbon nanotube which is suspended between two gold electrodes and tuned by the variation of gate voltages.

3. Mastery of Nature

Francis Bacon's famous dictum that 'knowledge is power' ties the advance of theoretical understanding to the expansion of experimental control.[3] We know that we know when we can bring things about on the basis of our knowledge. It is worth asking whether the inverse holds and whether the advance of technical control is tied to representations of what we do. Do we have mastery of nature only to the extent that this mastery is rehearsed and reproduced in thought?

In recent years, the philosophy of instrument and experiment has pressed this issue by showing that experiments and technical constructions can have a life of their own, that is, independent of scientific theory (for example, Baird 2004). Accordingly, the general claim that technical control is accompanied by conceptual representations must be distinguished from the more specific, untenable claim that technical control consists in the application of theoretical knowledge. Once this distinction

[3] Though Bacon did not coin the phrase, he has become powerfully associated with it as the founder of modern science by Merchant (1980), Böhme (1993), Schäfer (1993), compare Soble 1997.

is kept in mind, the relation between power and knowledge can be formulated in a more innocuous and intuitive manner: Technology involves humanly initiated causal processes. Some have very detailed knowledge of how such processes unfold. Others imagine only the turn of a switch and a resulting action. Yet others have a largely intuitive and physical mastery of, say, their bicycle and equate the causality of stopping, turning, or adapting gear with the causal powers of their own, technically extended bodies. In all these cases, technical mastery is attended by representations of how this power is exercised.[4] Indeed, it appears inconceivable to say that we technically control nature without possessing at the same time some conceptual image – no matter how impoverished – of the causality that is implied by the very notion of control. This raises the question whether the nano-guitar or other technologies are such that we fail to form such a conceptual image even though we must do so in order to assert responsibility and control.

It is important to distinguish the case where we must, but fail to imagine the workings of a technology, from the familiar case where we need not do so and where, in fact, we do so only in a most rudimentary way. This familiar case goes under the name of 'black-boxing' and was described as early as 1919 by Max Weber in his 'Science as a Vocation':

> Excepting physicists who know the subject, those of us who take a streetcar have no idea how it sets itself in motion. We do not need to know this. It is enough to 'count' on the behavior of the streetcar, we orient our actions accordingly; but we know nothing of how one constructs a streetcar so that it moves. Savages know their tools incomparably better [...] Increasing intellectualization and rational-ization therefore do *not* imply increasing general knowledge of one's conditions of life. It implies something else, namely knowledge of or faith in the fact that, if *only one wanted to*, one *could* find out any time, thus that in principle there are no secret, incalculable forces entering in, that instead – in principle – the things can be *mastered through calculation.* [Weber 1988, 593ff.]

[4] Heidegger (1977) offers an account according to which technical control presupposes a causal picture of the world, one in which actions either poetically bring forth what lies dormant or instrumentally exploit a scheme of means-end relations.

Weber's case of the streetcar refers to a most impoverished but still existing connection between technical control and causal representation. In cases like these we represent our technical interventions in the world only as a generic causal relation between input and output: When I flip this switch, some action will commence or conclude even if I know nothing about the mechanism through which this is effected.

However, the nano-guitar or genetically modified foods, ambient intelligence, nanoparticulate sensors, and pervasive large technical systems raise the question whether technical control is decoupled far more fundamentally even from generic representations. In these cases, it might not help to look up in a book how the technology operates because all the explanations and illustrations in the world do not yield perspicuity. Indeed, these technologies may well become more unfathomable when we are asked to imagine their unimaginably intricate workings that lie beyond the reach of our senses. Also, for these technologies the notions of use or of a user and thus of control are meaningless to the innumerable non-users who find themselves conscripted into their technological networks. Technological interventions, like the nano-guitar, might be operating in the background, unknown and unknowable to us. They therefore do not become objects of experience – and what is no object of experience remains unrepresented and does not prompt the formation of a conceptual image of its working. To the extent that they remain in the unconsidered and unconceptualized background of our actions and lives, these technologies are much like brute and uncomprehended nature – instead of knowing them, we merely know of them. Their looming presence and potential efficacy does not appear as an extension of our freedom or our will, but as a mere constraint, even perhaps as a threat. Where technical and intellectual control come apart, the humanly induced workings of technology no longer signify mastery of nature but take on the character of nature itself.

This would further suggest that the novelty of these technologies is not the *Technisierung der Natur* (nature taking on the character of technology) which may be as old as agriculture but, instead, the *Naturalisierung der Technik* (technology taken on the character of nature).[5]

4. (Mis)Understanding Kant

In all our attempts to understand the philosophy of Immanuel Kant, we inevitably encounter the question regarding the 'thing-in-itself'. This question can be answered in a roughly correct and in a woefully incorrect manner. By speaking of '*noumenal* technologies', this chapter will be flirting with the incorrect one.

According to the roughly correct account, the things-in-themselves are nature unrepresented in experience – if it were possible to speak of this nature at all.[6] We do not and cannot know the things-in-themselves or nature 'as it is' (with the one tenuous exception, perhaps, of our own nature as free, intellectual beings). This unknowability of the *noumena* or things-in-themselves can be described as a limit to theoretical understanding. Put positively, it represents the characteristic effort of modernity to push back the alien and uncanny otherness of nature. How things appear to us as *phenomena* in experience is already structured by the mind, already subject to mathematization and intellectual control. As opposed to brute nature, the phenomena are already civilized.

Now, the woefully inadequate account goes something like this: If you want to know what *noumena* or things-in-themselves are, consider

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[5] For the notion of *Technisierung der Natur* (nature taking on the character of technology) see, for example, Ropohl 1991, pp. 70ff. Here, nature is considered in terms of machines or literally rendered machine-like in order to assimilate nature to culture and to the spheres of knowledge and control. In contrast, *Naturalisierung der Technik* (technology naturalized) considers nature an engineer for the purposes of conceiving technology as natural. The latter strategy was identified, for example, in Nordmann 2004, pp. 52f.

[6] Compare Kant's *Critique of Pure Reason*, especially pp. A 236-260 (B 294-315) where '*noumenon*' is defined as a problematic concept, that is, as a concept that contains no contradiction and is yet empty in that there is no means by which its objective reality could be ascertained (A 254, B 310, compare A 252). There is no contradiction in assuming that there are 'things in themselves' of which we only experience (phenomenal) appearances. But there is also no means to ascertain the objective reality of anything except by the way in which it appears to us. To posit the 'thing in itself' as beyond and in some sense prior to human experience (as brute nature) involves no contradiction but also does not allow us to speak of the 'thing in itself' as if we could know anything about it, including that it exists.

things like atoms or molecules. After all, we cannot directly experience them and yet our *phenomenal* world of experience is composed of them. This interpretation is obviously incorrect because we formulate and test scientific theories about atoms and molecules. These are therefore objects of knowledge and it was precisely for all objects of knowledge that Kant showed how we constitute them as *phenomena* in time and space, as subject to causality, *etc.* As far as science is concerned, atoms and molecules are definitely no things-in-themselves that are unstructured by our minds. As objects of knowledge they come with, they are part and parcel of our theoretical representations.[7] But perhaps, as far as technology is concerned and when the bond between understanding and technical control is severed, atoms and molecules might as well be things-in-themselves. *For all practical purposes*, that is what they are. In what follows, the nano-guitar and other examples will be recruited to suggest that nanotechnologies, in particular, are thought to act in ways that remain, quite literally, inaccessible and in a size-regime that despite all our scientific theories remains unknowable.[8]

5. *Noumenal* Technology

Taken together, the preceding remarks suggest the thesis or at least explain the title of this chapter: *Noumenal* technologies arise where the link between representation and control is broken, that is, when we successfully create artifacts and perhaps a technical agency whose presence and

[7] One cannot argue, for example, that chemical change has a 'deep structure' which is *noumenal* and that chemistry as a science should attend to this structure, see Stein 2004, especially note 1. If something can be conceived as a possible object of scientific experience, it is not *noumenal*. To be sure, the fact that process is not now the subject of chemical thought may reflect the conditions of possibility for chemical experience – whatever is meant by 'process' may not be intelligible, especially if it involves a notion of transmutation that violates conservation principles. If this were the case, there can be no knowledge of such processes, scientific or otherwise, and the notion of chemical process would then serve, at best, to elucidate the limits of chemical knowledge.

[8] It will become clear, however, that only a small and perhaps insignificant part of actual nanotechnology research concerns technologies that *act* at the nanoscale. The argument does not apply to the more familiar applications where nanostructured materials serve as a substrate or medium for macroscopic action – as in the case of a macroscopic desktop computer that includes nanostructured components, for example.

action are inscrutable to us and, in effect, indistinguishable from the presence and action of the natural processes that serve as an unconsidered background and framework of our lives.

In order to substantiate this thesis, it needs to be shown that with the nano-guitar and numerous associated technologies, technical intervention eludes imaginative or conceptual grasp. Indeed, Günther Anders has shown something very much like this half a century ago for nuclear technology.[9]

> As engineers, at least as engineers of nuclear weapons, we have become omnipotent – an expression that is little more than a metaphor. But as intellectual beings we do not measure up to this omnipotence of ours. In other words: by way of our technology we have gotten ourselves into a situation in which we can no longer conceive [*vorstellen*] what we can produce [*herstellen*] and do [*anstellen*]. What does this discrepancy between conception [*Vorstellung*] and production [*Herstellung*] signify? It signifies that in a new and terrible sense we 'know no longer what we do'; that we have reached the limit of responsibility. For to 'assume responsibility' is nothing other than to admit to one's deeds, the effects of which one had conceived [*vorgestellt*] in advance and had really been able to imagine [*vorstellen*]. [Anders 1972, pp. 73f; see also 33-40, 88f, 96-99].[10]

Anders reflects the incommensurability or absolute disproportionality between the scale of human action and the scale at which its effects unfold. In one size regime occurs a perfectly conceivable technical malfunction or a human reaction to a perceived threat, in quite another size regime there is the perfectly predictable, yet utterly inconceivable end of humankind. The nano-guitar, genetically modified foods, or pervasive technical system present a different kind of inconceivability, one that still needs to be characterized.

Rather than serve as an instrument for deliberate action in the world, such *noumenal* technology recedes into the uncanny otherness of nature

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9 I would like to thank Jean-Pierre Dupuy for drawing my attention to this.

10 Anders developed the distinction between *Vorstellen* and *Herstellen* in Anders (1956). He repeatedly placed it in the context of Kant's philosophy: Kant's critique has shown how our intellectual capacities are limited but the possible effects of nuclear weapons cannot be accommodated within the limits of the human condition but transgress or exceed it altogether (see Anders 1972, pp. 33f., 38, 73).

and resists our attempts to make it an object of experience and knowledge. Its elusive character can be characterized, perhaps, in reference to Gerhard Gamm's conception of technology as a medium that structures human action without being present in experience as a structuring device – somewhat like blood in our bodies or money in our economies (Gamm 2000).[11] As such, this technology is knowledge-based and yet no tool or instrumental application of scientific knowledge. By the same token, this technology does not prefigure the scientific manner of recruiting calculable effects of nature (compare Heidegger 1977). Instead, the mutual dependence of science and technology, of knowing and acting comes asunder in *noumenal* technology and Max Weber's story of progressive rationalization unravels.

By definition, science involves objects of knowledge and experience. To the extent that we see the world through the glasses of science, we remain – as Kant would say – the lawgivers of nature and consider *phenomena* in their causal or structural contexts. This is certainly true also of nanoscience and its understanding of nanoscale phenomena. In contrast, *noumenal* artifacts like the nano-guitar turn out to be in essential respects not even objects of science, even though they were discovered, controlled, and explained by scientists and engineers. Where technical artifacts are no objects of experience, the scientific and technical rationalization of the world and the disenchantment of nature give way to a celebration of magic and enchantment. Naturalized technology is a mere medium for action, so deeply embedded that it eludes reflection or deliberate use, let alone rejection. As technical control outstrips intellectual control, our progressively expanded technical reach might thus prove regressive as regards the mastery not only of nature but also of our own destiny.[12]

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[11] See also Bensaude-Vincent 2004. Gamm, to be sure, takes his thesis about technology as a medium to be more general than suggested here. With Bensaude-Vincent I would like not only to distinguish the peculiar characteristics of such *noumenal* technology but also trace how different technologies come to be no more than an intractable medium for human action. *Pace* Bensaude-Vincent, I insist on '*noumenal*' as opposed to 'immaterial' technology because – unlike rituals, bureaucratic procedures, or social codes – the 'nano'-dimensions of nanotechnology are not thought to be immaterial but, more fundamentally, fail to become material by failing to become an object of experience at all.

[12] Compare the discussion of Joy 2000 in Nordmann 2004, p. 50.

Genetically modified foods serve as a paradigm for this and, depending on how it develops, so may nanotechnology. They begin as purposeful interventions in nature (*e.g.*, pesticide resistance) but their effects cannot ordinarily be observed or tracked even as they propagate through human bodies. Rather than reduce anxiety by assimilating nature to culture and by rationalizing the world through technology, such *noumenal* technology heightens anxiety. It does so by implicating us in a pervasive technical environment that is just as uncanny as is nature with its imperceptible germs, viruses, or bacteria on the one hand, its disruptive and haphazard earthquakes, lightning strikes, or volcanic eruptions on the other. These technologies enter the sphere of rationality only when we assume the mostly fictitious vantage point of a user whose judgment is not based on immediate physical experience but on statistically mediated experiences of benefits relative to costs or risks. The farmers, for example, who choose to plant genetically modified crops may experience an increase in yield and they can thus articulate a rational justification of their choice. But even these farmers, of course, have no experience of the genetic modification when they are cooking and ingesting their crops, and even they may find the presence of this unexperienced modification uncanny.

This regressive rather than progressive aspect of *noumenal* technology in regard to the mastery of nature is of a different character entirely than the familiar problem of not being able to imagine all the consequences of some technical intervention. Indeed, even where we have technical control with attendant representations, inadvertent effects may well get ahead of our imaginative abilities – as happens in the case of the 'sorcerer's apprentice' and whenever the effects of our actions get 'out of hand'. Here the limits of imagination consist in a computational inability to think through easily representable but highly complex pathways and interactions. In contrast, *noumenal* technologies and *phenomenal* (scientific) representations are incommensurable from the beginning since essential features of the technology cannot enter into phenomenal representations at all. Again, Günther Anders was perhaps the first to carefully distinguish the practical inconceivability of the infinitely long chain of effects that follows upon any human action, from the absolute inconceivability of the infinite magnitude of the single, perfectly predictable, and immediate effect of a nuclear attack (see Anders 1972, p. 34). The *noumenal* technologies discussed here involve a similar incommensurability. It results from the fact that the indefinitely near- or medium-term agency of certain technologies is shielded from our sensory modalities. To the seismic movements of nature that may eventually produce an earthquake, human engineering is adding further causal processes that operate behind our backs with possibly catastrophic consequences.

6. The Absolute Smallness of Nano

The elaboration so far of the thesis has shown that its plausibility hinges on the claim that the nano-guitar is not an object of science, even though it was presented, discussed, and even though its construction and workings were explained by scientists in the journal *Nature*. This apparently paradoxical claim needs to be elucidated and, ideally, justified. Here is the argument in a nutshell: As a nanotechnological artifact the nano-guitar is essentially small. Its 'incredible tininess' and ability to perform defined functions at the nanometer scale is its very point and apparently the point of much (though by no means all) nanotechnology.[13] If something is so small that we cannot imagine its size and if yet we feel that we must imagine its size in order to grasp its essential feature as a nanotechnological artifact, we will be attempting and failing to grasp something *noumenal*, namely how small or large something really is. In contrast, like everything *noumenal*, absolute size is never a feature of objects of science or knowledge. These objects are constituted and represented as they phenomenally appear to us and our measuring apparatus, that is, as relatively large or small, as measuring so much on some scale, as comparatively smaller or larger than something else. In other words, we can know and imagine a great deal about the nano-guitar, but we cannot know at least one of its essential features as a nanotechnological artifact. The nano-guitar therefore demonstrates simultaneously the expansion of technical control and the limits of human understanding, and because of

[13] "The Incredible Tininess of Nano" is the heading of a section in IWGN (1999, p. 3). I am taking this heading literally: The tininess of nano is not just amazing but incredible - impossible to be known, believed, or imagined. Of course, the brochure goes on to ask of us what cannot be done, namely that we imagine this incredible tininess.

this it is an object of technology that is not at the same time an object of science.

What is represented in the journal *Nature* is the nano-guitar as a *phenomenon*, namely as it appears to scientists by way of their representational tools and within their traditions and conventions of representing states of matter and motion. The readers are told how the guitar is constructed and how it works, they can learn to understand the relation of the parts to the whole, and they can refer its interesting properties to a rather general theoretical account of atoms and molecules. In other words, the readers of *Nature* will know quite a bit about the nano-guitar and in respect to this knowledge, the nano-guitar is clearly an object of scientific, though not ordinary experience. There is one feature of the nano-guitar, however, which is not represented to the scientists and which alone makes it a specifically nanotechnological device, and that is its size. We see in images and print a perfectly macroscopic representation that appeals to our sensory modalities. For the most part this image of the world at the nanoscale is to be taken quite literally: in this world, if you produce an electrical impulse here, you will observe some oscillation there. But like all scientific articles, this one does not (and need not) tell us how small this world really is. We are simply informed, for example, that 1 centimeter in the image before our eyes corresponds to 1 nanometer. Here, there is no literalness but a translation of sorts – the nanoworld has been scaled up for the purposes of human perception and understanding. As long as the scientists realize that nanometers are greater than angstroms and smaller than micrometers, that they are considering molecular rather than atomic or astronomic scale, all is well. Scientists are not required to correct for this scaling effect or to somehow subtract in their minds the magnification that was provided by their instruments.

Accordingly, it is not just a lay audience that has to deal with the incredible tininess of nano but also nanoscientists who learn to manipulate individual atoms, including the creator of nanoscience's most conspicuous accomplishment regarding the positioning of atoms at will. Don Eigler used 35 xenon atoms to spell the letters 'I B M' with all three letters spanning less than 3 nanometers, and yet he declares fifteen years later: "If you can imagine anything that's a billionth of anything else, you are way of ahead of me".[14] Put another way, as far as Don Eigler is concerned, the grouping of xenon atoms measures precisely 2 to 3 nanometers across and at the same time is unimaginably small. The first half of this statement refers to relative size as measured at the nanometer scale, the second half of this statement refers to absolute size and how small something really is.

Eigler's nanotechnological achievement draws attention to an incommensurability that goes entirely unnoticed in science and that does not require our attention in regard to most technology. While a scientifically trained intelligence can imagine the world at the nanoscale, it cannot and need not imagine the length of a nanometer. For science, it is not important and perhaps even an absurd undertaking to imagine the length of a nanometer. In this respect, the 'problem' of imagining the length of a nanometer is no different from trying to imagine the length of a meter.

Indeed, it would be quite absurd to assume that to the question 'how long is a meter?' there should be an answer in terms of absolute size. Clearly, the meter is a perfectly arbitrary unit and, as such, the best answer provides a mere definition in terms of some non-deformable physical units. It has been an interest of science to provide the terms for such a definition. Also, it is of interest to science that there is a reliable standard of measurement. Beyond that, to ask about the length of a meter is not a scientific question. Not long ago, the questioner would have been referred simply to the 'standard meter' in Paris – the length of a meter was defined by the length of that object which served as the international standard. One way or another, the scientific definition involves only relative size, either relative to certain physical operations or to the standard object in Paris. And if one wanted to how long a meter was in terms of human experience, the approximate answer would refer to the human being and the gesture that a meter is about so-and-so long relative to our body in space.

The nanometer is not so defined. There is no 'standard nanometer' on display in some vault that provides visual comparison, and there is no gesture indicating that it is roughly so-and-so small. Since the nanometer

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[14] Don Eigler during a presentation at the conference *Images of Science*, Amsterdam, December 7, 2004.

is a billionth of a meter, this is no problem for science. The size of nanoscale objects is perfectly secure relative to other size scales. But the scientific definition does not satisfy the demand for another, more intuitive grasp of how long a nanometer is. Since even scientists cannot imagine the billionth of anything else, we apparently need to find a way of imagining the nanometer in a way that is not relative to the meter and that substitutes for the absence of any physical relation to human gestures or sensory modalities. Since the length of the nanometer and the relation of a billionth to a whole are beyond the realm of appearances, this amounts to a demand for an intuitive grasp or absolute knowledge of how long a nanometer really is. This demand is given expression in countless introductory presentations and publications of nanotechnology. Those that are addressed to scientific peers and those that reach out to a general audience usually begin with more or less impressive, more or less desperate attempts to illustrate how long a nanometer is.

Any request to know what is *noumenal* or is a property of the things as they are themselves must, by necessity, fail. This holds true also for the request to illustrate and imagine how long a nanometer really is. According to Kant, objects of experience are constituted not only in time and space or the framework of causality but also in terms of magnitude and quantity. As Kant shows especially for infinitesimals, this means that we do not apprehend size as such and how large or small things are in and of themselves (compare Kant 1997, A166ff.). Instead, infinitesimals are represented in a continuum of intensities and effects and thus only in so far as they contribute to human experience. It would be nonsensical to imagine infinitesimals as such or independent of the calculus. Extending Kant's argument, Ludwig Wittgenstein tells us that it would be a similar mistake to take 'meter' or 'nanometer' for anything but grammatical.[15] We use these terms to relate things to one another but they have no na-

[15] Wittgenstein (1997, remark 50): "There is *one* thing of which one can say neither that it is one meter long, nor that it is not one meter long, and that is the standard meter in Paris – But this is, of course, not to ascribe any extraordinary property to it, but only to mark its peculiar role in the language-game of measuring with a meter-rule." – To ask how long a meter is would be akin to asking what 'being' is. The verb 'to be' serves the grammatical purpose of predication, the terms 'meter' and 'nanometer' belong to the grammar of measuring, that is, of establishing commensurability among things within a given or among different size regimes.

tures or properties of their own. It would be nonsensical, therefore, to ask how small or large a nanometer is, especially in the absence of any physical rituals or gestures that can serve as symbolic substitutes. What we have, instead, are only the rituals of taking us to the limits of our imagination: "To see a nanometer would be like seeing a postage-stamp from half way across the earth" – which says no more or less than that we cannot do it, that we can neither see nor imagine it. And yet we attempt again and again to imagine the unimaginable, running up against the limits of comprehension. Take this famous anthologized reflection on the large and the small from Kenneth Ford's 1958 introduction to *The World of Elementary Particles*:

> On the submicroscopic frontier of science (as well as on the cosmological frontier) man has proceeded so far away from the familiar scale of the world encompassed by his senses, that he must make a real effort of the imagination to relate these new frontiers to the ordinary world...One of the best ways to try to visualize the very great or the very small is by analogy. For example, to picture the nucleus, whose size is about 10^{-4} to 10^{-5} of the size of an atom, one may imagine the atom expanded to, say, 10,000 feet (10^4 feet) or nearly two miles. This is about the length of a runway at a large air terminal such as New York International Airport. A fraction 10^{-4} of this is one foot, or about the diameter of a basketball. A fraction 10^{-5} is ten times smaller, or about the diameter of a golf ball. A golf ball in the middle of New York International Airport is about as lonely as the proton at the center of a hydrogen atom. The basketball would correspond to a heavy nucleus such as uranium. [Ford 1991, pp. 18, 21f.][16]

Ford sets out to relate the ordinary to the extreme. This gesture is repeated again and again in the context, for example, of nanotechnology. The relation of 1 nanometer to 1 millimeter, we are told, is like the relation of the distance between New York and Boston to the distance be-

[16] Similarly, it has been suggested that we can imagine a billionth (10^{-9}) of something else because our experience ranges across 10^9 orders of magnitude from millimeters (10^{-3}) to 1000 kilometers (10^6). However, even if we could therefore imagine the relation of 1 millimeter to 1000 kilometers (along the lines of imagining a basketball in JFK airport), we could not therefore transfer that imagined relation to the different relation of one nanometer to a meter.

tween earth and sun.[17] These analogies present relative magnitudes and succeed at communicating the loneliness of the golf ball in the middle of today's John F. Kennedy Airport in New York. They help us imagine the world at the atomic or molecular scales, a bit like helping people imagine a foreign country or exotic culture. At the same time these analogies strain and fail to acquaint us with the size of these worlds, their distance from us. Ford exemplifies this when he develops his airport-analogy further and thereby exposes its absurdity:

> To arrive at the number of atoms in a cubic centimeter of water (a few drops), first cover the earth with airports, one against the other. Then go up a mile or so and build another solid layer of airports. Do this 100 million times. [Ford 1991, p. 22]

Of course, to imagine our solar system filled up with airports is just as impossible as imagining the number of atoms (all 10^{16} of them) in a cubic centimeter of water. It also does not help to be told that "if the airport-construction rate were *one million* each second, the job could have been finished in the known lifetime of the universe (something over 10 billion years)". All these descriptions say the same thing, namely that we cannot imagine these magnitudes or sizes. All scientific knowledge of relative sizes, all technical control does not yield a sense of absolute size, except to say that this or that is 'incredibly small'.

There is nothing surprising about this failure from a Kantian point of view. What is all the more surprising, therefore, is that we keep trying. Kenneth Ford demands that we "must make a real effort of the imagination to relate these new frontiers to the ordinary world" – why must we?

7. Intractable Agency

For the purposes of scientific understanding we do not ordinarily need to represent the size of things – indeed, science probes from within the limits of theoretical understanding and thereby fosters a sense of curiosity and wonder at that which remains unexplained: It is thought to be marvelous even that all the mechanisms identified by science are actually

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[17] See the brochure *Große Chancen im Nanokosmos – Nanotechnologie in Hessen*, 2004 (the brochure takes Frankfurt-Kassel as the distance of reference).

taking place in and around us.[18] We arrive at these moments of wonder when we run up against the limits of what we can imagine. And where this is not marvelous, we can safely refrain from imaging or imagining it. (So, you don't think that it is marvelous that your body is host to millions and millions of incredibly tiny parasites? Don't imagine it then!) Science aims for explanations of interesting perceived regularities, and only the most zealous of scientific realists care whether the unobservables that occur in these explanations correspond to anything real.[19] In daily life and for purposes for acting successfully in the world, there is no need for complete scientific understanding. This holds also for the probe microscopist who understands the theories of probe microscopy, who moves, even feels individual atoms, but who does not and cannot imagine the smallness of those atoms.

In contrast, we are obliged to form representations of our deliberate actions in the world. Where humans act purposefully, these actions are set off from the unconsidered or black-boxed background environment in which these actions unfold. Whether one thinks of technology as applied science or of science as applied technology, technology is purposeful intervention in the world. We therefore ought to develop a representation, no matter how impoverished, of how the technology works. If we fail to do this, this is a failure not only of imagination but also of morality or responsibility. Günther Anders' work is an indictment of just such failure:

> *The reach of our responsibility extends as far as the immediate and mediate effects of our actions, our omissions, or our deeds.* At least we should try to extend it this far and to assume the magnitude of that which we bring about in the world [...] Today's '*malum*' is essentially different from that which has dominated the European tradition, namely the Chris-

[18] Philosophical expressions of this wonder include Kant's introduction to the *Critique of the Power of Judgment* and Wittgenstein's "not how the world is, is the mystical, but that it is" (Wittgenstein 1922, remark 6.44).

[19] For science and the search for explanatory accounts, it is heuristically useful to assume their real existence. In the course of scientific research, the unobservables become real for all practical purposes of experimentation and instrumentation. But this is true, of course, also of 'magical' explanations: If I tell myself that the room has been cleaned by fairies, I assume – of course – that they must really exist since otherwise they could not have performed such a tangible feat.

> tian conception of 'evil'. [...] *What makes us bad is that as agents we do not measure up to the products of our deeds* [...] *The gap* is therefore not that between mind and flesh but *between product and mind.* Example: We can produce the bomb. But we appear to be incapable of imagining what we have become as owners of our products and what we can do and have already done as their owners [...] This difference is unique in history, and thus unique also in the history of ethics [...] Due to this being a failure of the imagination, what is 'weak' here is the 'mind'. [Anders 1972, pp. 34-36][20]

In the case of absolutely disproportionate effects[21] and in the case of technological agency absolutely below (or above) thresholds of human perception and imagination, to keep up with the effects of one's actions involves the effort to imagine the magnitude of things. Where we must engage in this effort and must by necessity fail, we are confronted with *noumenal* technology. While the case of nuclear arm signifies the abandonment of the effort and thus a moral failing from the very start, the case of nanotechnology is characterized by the persistent pursuit of the unattainable goal to imagine the unimaginable; it thus expresses a moral ambition to take responsibility beyond the human capacity to responsibly track the consequences of technical intervention.[22]

As we saw, for purposes of scientific understanding there is no imperative to imagine the size of things. For the purposes of taking responsibility for technical interventions, this depends upon the specific character of the technology and whether or not it is *noumenal*, engaging us in an impossible feat of the imagination. And this specific character is determined in part by our beliefs regarding the causal agency of the technology.

Desktop computers, for example, are clearly not *noumenal* even though we cannot represent to ourselves the speed and complexity of operations, let alone the site or spatial and temporal extension of a par-

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[20] The novelty of this ethical situation is therefore that it is not the flesh that is weak: "the element of 'nature' that up to now always contributed to a definition of the '*malum*' drops out of the picture."

[21] "*End of the Comparative* [...] but what is supplied *transcends* our needs, it consists of things that we *cannot* desire; it is *absolutely* too big" (Anders 1972, p. 99).

[22] This moral ambition finds expression also through early engagement with ethical, social, and legal aspects of nanotechnology.

ticular inferential step. We can black-box these particulars and are left with a device that relates macroscopic inputs to macroscopic outputs. In contrast, ambient intelligence, distributed or ubiquitous computing may well become a *noumenal* technology as this technology creates a quasi-natural, though now 'intelligent' environment that structures human action without transparency and individual control. In this case, when we black-box the unimaginable we are left with nothing, but a nothing that somehow acts upon us. Whether radios, cell phones, or fluoridated drinking water are *noumenal* technologies depends entirely on whether one believes that fluorine is an 'active ingredient' or that radio waves produce environmental effects. Regarding the radio, for example, we are told and for the most part believe that it is controlled by its switch, that its use is closely coupled to our representations of how to manipulate power and volume, and how to seek out stations. At the same time most people hold that the pervasiveness of radio waves serves only as a passive medium that enables the transmission of signal, and therefore we do not ordinarily imagine these waves along with the macroscopic device that is subject to our control. What defines opponents of cell-phones or of fluoridization is that they view these same technologies as being *noumenal*. They insist on the need to imagine unimaginable effects and are therefore prone to discern a vaguely generalized danger that blends in with and contaminates the background effects of nature itself (water, air, soil).[23] For them, these pervasive technical interventions change the things-in-themselves, the world not as we know it but where we rely on it unknowingly. This view is reinforced rather than weakened by the fact that we have no sensory experience of these pervasive changes.[24]

This same ambiguity applies to genetically modified foods as the paradigm case for *noumenal* technology. It is the paradigm case because the technical intervention remains essentially inconspicuous to human

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[23] See Todd Haynes' 1999 film *Safe* as an excellent analytic case study of the perceived uncanniness of such and similar technical systems.

[24] I am here focusing on smallness but it is worthwhile to extend the argument to large and even just largish technologies. (To be sure, ambient computing or radio technology should be considered not simply for the invisible smallness of their physical implementation but also as large technical systems.) For example, should we consider as an example of *noumenal* technology the fully automated climate control of an office building, if only because it cannot be surveyed or controlled by individual users?

senses as well as natural selection. The genetic modification may produce visible as well as invisible phenotypic traits, and these phenotypic traits whither away or become consumed. However, the genetic modification may also persist and continue to act as it passes through our bodies to some untraceable place in the environment. Here, there is no represented proportionality between intervention and effect. Largely due to the smallness of the intervention, the effect is thought to escape our attention and control, meandering on indefinitely, perhaps producing a surprising large effect when and where we least expect it.[25] Finally, little reassurance comes from reading up on genetic engineering. The more we learn to understand and even admire its technical capabilities, the less transparent the world becomes for the individual consumer of genetically modified foods and the harder to maintain a sense of ownership, empowerment, responsibility, and control. Genetically modified organisms appear uncanny because they operate like nature itself. We can learn how they work, in principle, but we cannot know for any particular genetic modification where, when, and for how long it acts. All the while, however, it is easy to understand why it is that not everyone defines genetically modified foods as an uncanny, *noumenal* technology that necessarily implicates us in a failure to responsibly track its workings. Many scientists deny, after all, that the genetic modification should be considered biologically active. If its action exhausts itself and terminates in a single phenotype that is otherwise a plant or animal like all others, there is no need to imagine or take responsibility for the modification. In that case, we would simply take responsibility for creating the macroscopic phenotype and thereby remain within the bounds of phenomenal technology.

Similarly, while the effects of a nuclear worst case scenario exceed by far our imaginative capacities, the 'normal working' of nuclear technology is not necessarily uncanny. Though we cannot imagine the size of the nuclei of uranium and plutonium, nuclear weapons or reactors are perfectly macroscopic parts of our ordinary world of experience, operated by switches, interfaced through output devices and monitors, relying on a lot of scientifically described, though for the most part black-boxed

[25] This description may not be true to GMOs as we know them. But it captures why this technology is thought by many to be so uncanny.

knowledge of physical mechanisms. As with our desktop computers, it is irrelevant for questions of responsibility and control just how big or small the smallest components of a nuclear plant or nuclear weapon are. Significantly, however, the most troubling or uncanny aspects of nuclear technology concern the possibility that it might revert to quasi-natural conditions. First among these is the fear of accidental nuclear war as complex systems begin to 'act on their own'. This further amplifies the gap between the smallness of the occasion and the unfathomable magnitude of the effect (see Anders 1972, p. 89). Related to this is the fear of a decision-maker gone mad or the fear of radioactivity as an invisible, yet persistent and pervasive source of environmental contamination.

The discussion so far leaves quite open whether or to what extent nanotechnology will assume the character of *noumenal* technology. Nanostructured surfaces, material properties, or components in larger devices do not amount to *noumenal* technologies. When we black-box the incredible tininess of nano we are left with a sufficiently rich conception of how these operate and what it means to take responsibility for their mostly mundane effects. Freestanding nano- to microscale devices such as sensors and distributed components of networked computers are far more likely candidates for *noumenal* technologies, depending also on whether or not other technologies will allow us ultimately to detect, monitor, and track these devices. Of course, any device with biological properties, such as artificial bacteria for environmental clean-up can be considered *noumenal*, as would the legendary assemblers and nanobots of whom hardly anybody believes as of yet that they will actually come to pass.

8. The Meanings of Failure

By way of conclusion, it is now possible to identify the deeper significance of the apparently pointless attempts to illustrate again and again the smallness of a nanometer.

From a theoretical point of view, atoms and molecules are phenomena. Indeed, theories are the instruments by which we learn to know things that we cannot know as they are by and of themselves. With the help of theory, science makes images of things, stabilizes them in experiments, and creates models to exhibit them. The deliberate use of theory serves to remind scientists that they are creating certain kinds of pictures; it marks these pictures as aides to the imagination. From the point of view of theory, then, it is as a matter of course that these pictures stay within the bounds of imagination and do not convey any true reality of absolute size or the like. The repeated failure of visualization or illustration thus serves as a meaningful reminder of the reliance on scientific theory to establish patterns of relatedness among phenomena. Accordingly, that we cannot imagine the size of molecules is no problem at all: The hapless stories about the incredible tininess of nano underscore that the business of science is to relate things to one another and not to grasp an absolute reality. By dramatizing inconceivability, science highlights the unbridgeable difference between *noumena* and represented phenomena and sides emphatically with the latter.

From the technological point of view, however, these hapless stories have a different meaning in that they strain to accomplish something that needs to be accomplished even where we lack the theoretical and imaginative resources to do so. It is a virtue of theory that it marks the impossibility of moving from scientific representations and how we imagine things to reality as such. Technical interventions, however, engage reality. The moral ambition to keep up in thought with the reach and workings of our technical interventions does not respect limits of knowledge if the interventions themselves reach beyond these limits. The ritual of attempting to illustrate the size of a nanometer thus serves as the constant reminder of an insoluble dilemma.[26] It is an expression of the moral ambition to take responsibility for nanotechnology, and its failure demon-

[26] It would be far too simplistic to introduce a variation on the Kantian theme of phenomena vs. *noumena* by associating on the one hand science with nature and the deterministic representation of phenomena, on the other hand technology with freedom and the expansion of our action as free, rational and responsible (noumenal) beings in the world. This move interprets '*noumena*' primarily in terms of human freedom (rather than in regard to unknowable things in themselves as limits of knowledge). The insoluble dilemma would thus be associated with the Kantian dilemma that we are free only as *noumenal* but causally determined as phenomenal beings. If we were to follow this suggestion, *noumenal* technology would be technology unadulterated. This contrasts starkly with my suggestion, however, that *noumenal* technology is regressive and tends to diminish human autonomy in that it withdraws from the mastery of nature by giving technology the character of uncomprehended nature.

strates that some technologies systematically outpace our moral ambition. The exhibition of our failure of imagination thus dramatizes meaningfully the challenge and moral demand to reintegrate *noumenal* technology within the spheres of reason, responsibility, and control.

It is therefore not at all pointless to try what cannot be done. The ritual of repeatedly failing to imagine the smallness of a nanometer reveals the *noumenal* character of at least some envisioned nanotechnologies. Such 'freestanding' nanotechnologies that are thought to act below the thresholds of perception and responsibility provoke a mixture of abhorrence, awe, and fear that does not fit into the calculus of rationality. One of our oldest and perhaps deepest fears is the fear of brute, arational nature that has not been cultivated, rationalized, tamed, domesticated.[27] If an advance in technical control produces a type of technology that eludes sensory perception and human responsibility, this technology turns out to be regressive in that it casts us back into a state of nature. We cannot trust a *noumenal* technology. In order to earn our trust the various nanotechnologies will have to move beyond the incredible tininess of nano to become credibly integrated with human experience.

Acknowledgments

I would like to thank Michael Hauskeller for provoking this paper, Jean-Pierre Dupuy, George Khushf, Joseph Pitt, Joachim Schummer, Alexei Grinbaum, and Pieter Vermaas for commentary and criticism.

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[27] Baird (2004) and the history of nanotechnology remind us that these four terms should not be equated: by stabilizing phenomena through intuitive knowledge and control of system behaviors technology can 'tame' nature without therefore 'rationalizing' it. Just to the extent that this is true, however, we are confronted with the problems described in this paper. Indeed, the demand that *noumenal* technologies be integrated with human experience is premised on the notion that sensory experience and a 'feeling' for the technical intervention are sufficient to place the technology into a framework of deliberate and responsible human action.

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CHAPTER 4

NANOTECHNOLOGY AND NATURE: ON TWO CRITERIA FOR UNDERSTANDING THEIR RELATIONSHIP

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Two criteria are proposed for characterizing the diverse and not yet perspicuous relations between nanotechnology and nature. They assume a concept of nature as that which is not made by human action. One of the criteria endorses a distinction between natural and artificial objects in nanotechnology; the other allows for a discussion of the potential nanotechnological modification of nature. Insofar as current trends may be taken as indicative of future development, nanotechnology might increasingly use the model of nature as a point of orientation, while many of its products will continue to be clearly distinguished from nature.

1. Introduction

The relationship between nanotechnology and nature does not presently admit of uniform description. By way of an introductory presentation of the problem, I would like to sketch a provisional characterization based upon central aspects of nanotechnological and natural objects respectively. Nanotechnological objects rank among those technically produced objects that emerge from processes "that exhibit fundamental control of the physical and chemical attributes of molecular-scale structures" (Stix 2001, p. 9). Nanotechnology brings with it the possibility of a precisely projectable alteration of nature on the scale of molecules. Nanotechnology comprises not only the manipulation of natural molecules, but also the creation of molecules not found in nature. In this sense, molecules or other objects are natural if they are not produced through human action.

The multifariousness of the relationship between nanotechnology and nature is expressed in the fact that some nanotechnological objects are clearly distinct from comparable natural objects, while others are identical to natural objects. I shall begin with some examples of non-natural nanotechnological products, recognizable – as is the case with other products of human action – by their obviously artificial origin.

- For medical purposes, certain molecules are synthesized that are designed to direct medicine to particular parts of the body, and which – as far as is known – do not exist in nature.
- The production of materials by means of nanotechnology is of interest to the materials sciences because these materials possess characteristics (*e.g.* firmness) that make them more suitable for the fabriccation of macroscopic products than those made from natural substances.
- Miniscule electrical and mechanical systems are to be constructed analogously to larger systems utilized today, which are not modeled upon natural patterns.

Nano-products that do not exist in nature form an artificial world whose relationship to nature is problematic. On the one hand, uncontrolled releases from such nano-objects could constitute a new dimension of life-threatening pollutants. On the other hand, it cannot be ruled out that even the controlled insertion of non-natural nanoproducts into nature – particularly into the human body – may entail substantial risks. In both cases these dangers would be linked to the extreme minuteness and to the reactivity of these products. They may enter biotic systems deeply and irreversibly, affecting life functions not positively but deranging or destroying them with lethal effects. Compared to previous conventional macroscopic technologies, nanotechnology relates differently to nature inasmuch as it can affect the functionality of natural systems on the smallest scale.

Nanotechnology, however, does not only create an artificial world that is distinct from nature. It also relates to natural processes and materials in a new way.[1] In this respect it is difficult to separate it from nature. Here, too, I would like to give some examples.

- There is hope that the development of nanotechnology may not only permit the production of artificial made-to-measure materials, but also improve conditions for the perfect artificial reproduction of substances that can only be derived from nature through difficult procedures.
- In the bottom-up-production of materials, nanotechnology already uses techniques of self-organization – which are similar to processes that appear in nature (*e.g.* the spontaneous creation of GaAs-quantum points).
- On the product level, there are nanotechnological systems in which objects of biotic origin are used. Since the functions of such objects are partly independent of their origins, the characterization with which we began is a problematic basis for distinguishing between nature and nanotechnology. DNA-molecules, for example, are utilized in electronic components. Other nano-products are to have new kinds of biocompatible (*e.g.* coatings of artificial joints) or bio-analogue (*e.g.* hydrophobe) features.

Nanotechnological products and techniques that are closely related or even identical to natural materials and processes may cause just as much harm to nature as those that are clearly distinct from nature. For instance, the degree to which an artificially produced substance is life threatening is not clearly related to the degree of its structural similarity to natural substances. To mention another example, the introduction of artificially produced nature-identical substances into natural cycles can lead to considerable interferences of these cycles. But despite justified objections to the use of the model of nature as a point of orientation, there is still hope that the dangers of nanotechnology could be reduced by an increasing proximity to nature.

The practical relevance of the dangers to life processes that might emerge from nanotechnology constitute probably the most important mo-

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[1] "Nanotechnology [...] can be oriented either to reproduce natural things or processes, exhibiting different features, or to produce new objects or materials" (Negrotti 2002, p. 4).

tivation for investigating the relationship between nanotechnology and nature. But, with respect to a technology that permits the synthetic production of nature-identical objects and that is able on demand to execute minute changes in nature on the molecular scale, the question of its relationship to nature emerges also in theoretical terms. Is it at all possible to distinguish between nature and technology if nature has already become technologically malleable at the level of molecules? Can nature – if it is distinguishable from technology at all – set limits to technology? Against the background of Western culture, where nature is conceived through its opposition to technology, the importance of these problems cannot be overestimated. While technology as a human creation is regarded as completely transparent, a separate reality is ascribed to nature. The contrast between technology and nature is to be considered most obvious in the case of living nature – organisms are paradigmatic of a nature not produced by human beings. Up to now, the concept of nature has had a central function in shaping the Western worldview, which would be undermined if it became impossible to maintain its difference from technology.

But can these questions be answered if the relationship between nanotechnology and nature is itself manifold? One could be tempted to assume that a restriction of the term nanotechnology would lead to a more unequivocal statement. But this suggestion is rendered implausible by the fact that nanotechnological research is still in its early stages. According to the unanimous judgment of its analysts, most disciplines of nanotechnology have not yet reached the stage of producing functioning technology, but are still researching their object fields.[2] There are endeavors underway in various disciplines to shed light on the scarcely analyzed structures of the nanoworld. Thus, a specification of this term would only conditionally restrict the variety of disciplines belonging to it. Nor is a reduction of the scope of the concept of nature likely to clarify the different ways in which nano-objects are related to nature. The concept of nature that I proposed earlier corresponds – as I aim to show – to the common and justifiably used conception of nature in nanotechnology. It allows different relations to nanotechnology in general and in

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[2] *E.g.* Siegel *et al.* 1999, p. 11-12, Stix 2001, Jopp 2004, p. 36.

specific areas. Therefore, I would argue that under the present circumstances the relationship between nanotechnological and natural objects cannot be described in uniform terms.

But the diversity of the relations between nanotechnology and nature does not necessarily imply a diversity of the criteria for describing these relations. Rather, I would assume that the various relations can be characterized by a single set of criteria that make it possible to give initial answers to the aforementioned questions. In so doing, one cannot rely on the philosophical discussion of nanotechnology, which until now has been poorly developed.[3] The proposed concept of nature forms a proper starting point, as it makes it possible to develop two basic criteria for characterizing the relationship between nanotechnology and nature.

- First, the concept of nature as that which is not produced by human beings suggests a criterion for distinguishing between natural and artificial nanotechnological objects (Section 3).
- Secondly, this concept of nature makes it possible to formulate a criterion for delimiting the scope of nanotechnology (Section 4).

The most important point in the discussion of the relationship between nanotechnology and nature is the contrast between nanotechnology and living nature. None of the known laws of nature excludes the possibility that life could in the future be produced artificially by means of nanotechnology. If the difference between the objects of nanotechnology and those of living nature were to be dissolved, it would be the most fundamental conceivable change in the relationship between nanotechnology and nature (Section 5).

Before I expound these criteria, I would like to elucidate the concept of nanotechnology with which I began in order to clarify what aspects of it enter into a relationship with nature.

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[3] The philosophical discussion focuses mainly on issues of ethics, without making a problem out of the relationship between nanotechnology and nature. *Cf.* the Nano-STS Bibliography of University of South Carolina (www.cla.sc.edu/cpecs/nirt/bibliography.html), which "includes scholarly publications in the history, philosophy, and sociology of nanoscience and technology", as well as Baird *et al.* 2004. One exception is Lee 1999, who grounded the distinction between the natural and the artificial upon an ontological basis and defended it against the nanotechnological possibility of its nearly complete effacement. Schiemann 2004 provides a philosophical discussion of the concept of nature, wherein he makes reference to the public presentation of nanotechnology.

2. On the Definition of Nanotechnology

The initial understanding of nanotechnology is only a part of a definition proposed by Mihail C. Roco, according to which nanotechnological materials and systems have the following 'key properties': "they have at least one dimension of about one to 100 nanometers, they are designed through processes that exhibit fundamental control of the physical and chemical attributes of molecular-scale structures, and they can be combined to form larger structures" (Stix 2001, p. 9).[4]

Nanotechnology is the application of scientific knowledge for the purpose of producing such materials and systems. In the present phase of investigating elementary conditions of production, technological and basic scientific research are merging. Wherever I do not explicitly differentiate between nanotechnology and nanoscience, the term 'nanotechnology' includes nanoscience.

I want to adopt Roco's definition and make two additions. The first concerns the origin and purpose of nanotechnology. Nanotechnology is – as all technology – a human affair. In this respect, the relation of nanotechnology to nature is reduced to the relation of human beings and their actions to nature. As a human affair, nanotechnology is a cultural-historical phenomenon that uses appropriate and knowledge-based ability in pursuance of objectives. The concept of nanotechnology can only be used in an analogous or metaphoric manner to describe non-human nature; strictly speaking, there are no nanotechnological processes or products in nature. The next section, however, will give some examples that show why not all nanotechnologists would agree with this view.

My second addition concerns the relation of nanotechnology to other technologies. By 'fundamental control' of attributes, I understand a realization of desired attributes that goes beyond the manipulation of already existing attributes. Here the definition distinguishes nanotechnology from gene- and biotechnology,[5] which frequently deal with objects of a

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[4] The currently relevant definitions of nanotechnology are discussed at length in Schmidt *et al.* 2003.

[5] Biotechnology means in general the technical utilization of advances in the methods and instruments of the biological sciences. Genetechnology can be understood as a subarea of biotechnology and molecular biology.

size above nanoscale. The attributes of gene- and biotechnological objects are not produced but, rather, modified by exerting influence. Without this distinction between disciplines, it would be impossible to differentiate between the transfer directions of nanotechnology and biotechnology.

The definition does not rule out that biotic materials or living beings could be produced in the future by means of nanotechnology, nor does it deny the already existing transitions and contacts between nano-, gene- and biotechnology. Its application to current technological possibilities leads, however, to a division into the mainly abiotic products of nanotechnology on the one hand, and the mainly biotic products of gene- and biotechnology on the other. In this respect, current nanotechnology is clearly distinct from a nature that includes living beings.

3. Nature as That Which Is Not Produced by Human Action

As in the natural sciences and in most other technological fields, fundamental categories like the concept of nature are not a subject of discussion in nanotechnology. When they are explicitly used, it is normally only in publications that address a broader audience or the audience of other disciplines – and therefore somewhat vaguely. The concept of nature takes on various meanings in these contexts, which I assume are also relevant in scientific practice. I have chosen three representative and electronically accessible publications as examples and scanned them for appearances of the term 'nature': the brochure *Nanotechnology. Shaping the World Atom by Atom*, published by the National Science and Technology Council (NSTC) in the US in 1999; the volume *Understanding Nanotechnology*, compiled by the journal *Scientific American* in 2001; and the *Springer Handbook of Nanotechnology* (Bhushan 2004.

An adjectival and a substantival usage can be differentiated as the two primary meanings in these texts. These also correspond to the two meanings of nature given in *The New Oxford Dictionary of English* (without being labeled as such). The adjectival usage describes "the basic or inherent features of something, especially when seen as characteristic of it". A typical example is, for instance, "the wave nature of electrons" (NSTC 1999, p. 1) or "the cyclic nature of this process" (Bhushan 2004,

p. 156). Since this meaning does not refer to specific properties and can only be understood contextually, I will ignore it here.

The substantival usage is divided into an extensional and an intensional meaning. Both can also be found in *The New Oxford Dictionary of English*, although they are not labeled as such. In its extensional meaning, nature refers to "the phenomena of the physical world collectively [...] as opposed to humans or human creations"; in its intensional meaning, it is "the physical force regarded as causing and regulating these phenomena". The extension demarcates the scope of the concept negatively – namely, through the contrast to human action. The intension, on the other hand, cites properties – such as a physical force – by way of a positive characterization.[6]

A typical example of the extensional understanding is the reference, which appears in all three publications, to "nature's own nanotechnology, which emerged billions of years ago when molecules began organizing into the complex structures that could support life" (NSTC 1999, p. 1; similarly, *Scientific American* 2001, p. 9; Bhushan 2004, p. 2). This understanding gives rise to a distinction between natural and synthetic objects. Hence, we learn, for example, "that nature constructs its objects" (Bhushan 2004, p. 246), or that an artificially established function is "unprecedented in nature" (Bhushan 2004, p. 283). The intensional usages differ from the aforementioned encyclopedic notion in that the characteristics given also include human action and their products. Thus, the NSTC brochure quotes from Richard Feynman's famous speech 'There's Plenty of Room at the Bottom' (1959): "But we must always accept some atomic arrangement that nature gives us" (NSTC 1999, p. 4). In the same vein, Michael L. Roukes refers to the concept of nature by stating, "Nature has already set the rules for us" (*Scientific American* 2001, p. 32).

These examples are the product of an intuitive technological understanding of nature, according to which nature is a resource for the realization of human purposes. With respect to conceptual precision – which,

[6] The term 'extension' means the object class that a concept refers to, 'intension' means the class of features that appear in a complete conjunctive definition of a concept. *Cf.* Schiemann 2005 for a more specific definition of the extensional and intensional senses of the concept of nature.

admittedly, is not decisive in the context of these publications – it leaves much to be desired. Part of the terminological haziness is also due to the ambiguity of the concept of technology, which is not consistently opposed to that of nature but, rather, partly transferred to natural processes. Furthermore, relations between intensional and extensional meanings of nature are not taken into account, and there is no criterion for distinguishing between natural and artificial objects. These desiderata can be attained by specifying more precisely the concept of nature I proposed earlier.

The concept of nature that I am going to elaborate follows the intuitive understanding of nature by assuming a positive characterization not of nature, but of human purposes: nature is that which is not made by human action. This concept is distinct from traditional definitions, which attribute positive attributes to nature – such as self-movement in Aristotle, or expansion in Descartes.[7] I use the expression 'not made by human action' in a narrow and in a broad sense. While the narrow sense refers to objects whose existence does not originate in human action, the broad sense describes the empirical content of laws of nature – which is not at humans' disposal[8] – and thus comprehends predetermined conditions to which human action is subjected. In this section I focus on the narrow, in the next section on the broad sense.

In view of the sophistication of today's technology, scientific methods are required to determine whether an object owes its existence to human action. Thus, I would like to introduce an epistemic criterion according to which an object is natural if it is impossible with all scientific methods available at a given time to detect that it was produced by human action; alternatively, an object is to be defined as artificial if it can be scientifically demonstrated that it was produced by human action. This criterion makes the distinction between natural and artificial objects

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[7] Historically, the definition of 'nature' as that which is not produded by humans first became significant in the 19th century. Mill 1874 was particularly influential. For a more recent formulation, see Passmore 1974.

[8] The extension of the term 'nature' in the narrow sense can be defined either intensionally by the property of not being produced by human action, or extensionally by listing the objects to which it refers. In its broad sense, it can be defined only intensionally by the empirical content of the laws of nature, which refer to reality in its entirety (the extension in the broad sense).

an empirical matter, subject to experimental methods of assessing the naturalness of technological products – similar to the Turing-test of artificial intelligence.[9] An artificially produced object would therefore belong to nature if all scientific methods available at a given time could not succeed in distinguishing it from an identical natural object. This application of the criterion presumes of course all knowledge about existing natural objects.[10]

I want to elucidate this criterion by appealing to some examples: according to this criterion, the atoms dealt with in nanotechnology are natural if they stem from natural substances or if it becomes impossible scientifically to ascertain their artificial origin. Insofar as natural substances are designed differently in nanotechnology than in nature, nanotechnological products are always hybrids of nature and art. The criterion does not challenge the naturalness of an object merely if it is influenced by human action. Thus, atoms do not lose their naturalness because they must first be isolated in order to be assembled in a different pattern. As for this assemblage, it is possible to distinguish several ways in which an influence can artificially be exerted. A weak form of influence would be to create the appropriate conditions under which a process of synthesis would run independently. Processes of self-organization in the production of quantum points are a good example of this form of influence.[11] Production that requires a special operation at each step represents a stronger form of influence. This applies, for example, to the movement of atoms, which M. Eigler used in 1989 to produce the IBM-logo in nanoscale.

The criterion can be applied to all of the examples that I mentioned earlier in order to illustrate the difficulty of distinguishing between natural and artificial objects. According to the criterion, if nanotechnology succeeds in constructing perfect replicas of naturally existing molecules,

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[9] The Turing-test investigates the ability of computers to imitate human intelligence: a person interviews two invisible objects, one of which is a human being, the other a computer. The person is to determine whether there are specific differences in the respective answers.

[10] The criterion must be supplemented to make sure that synthetic molecules produced on earth would not cease to be considered artificial in the unlikely event that they were found to exist extra-terrestrially.

[11] Wevers & Wechsler 2002, p. 11.

they should be considered natural the moment when their artificial origin ceases to be demonstrable (*e.g.* when mingled with the corresponding natural molecules). Each component of self-organizational processes that are used in the production of nano products and each property of completed nano products can be assessed to determine whether it is natural or artificial. Nonetheless, the application of the criterion is not unproblematic. Artificial properties may, for instance, unknowingly be added to a substance when it is extracted from its natural environment.

It may appear odd that nanotechnological objects, *e.g.* synthetic molecules, should lose their artificial character the moment they cease to be (scientifically) distinguishable from natural objects. However, this not only corresponds to traditional concepts of nature[12] and to current linguistic conventions in nanotechnology (as discussed above), but also reveals the point where the distinction between human-made products and nature becomes senseless.

I suspect, though, that most nanotechnological objects are still distinguishable from natural objects and will continue to be in the near future. I see three reasons why the artificial character of nanotechnological objects should remain apparent for the time being. First of all, the focal point of nanotechnology is to produce artificial objects that are more useful for human purposes than natural ones. Since these objects are intended to differ in their effects from natural objects, they can be expected to remain distinguishable from them. Secondly, the scientific methods of revealing an object's artificial origin are so sophisticated that they would probably still be able to identify an artificial object even if it were very similar (not identical) to equivalent natural objects. Thirdly, there is still a clear difference between nanotechnological and natural processes, as I shall illustrate in Section 5, where I discuss the example of living nature

This epistemic criterion builds upon the narrow understanding of nature as that which is not produced by human action. It inquires into the genesis of any produced object, but unfolds its efficacy only when it becomes problematic to ascertain an object's artificial origin. Nanotech-

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[12] For Aristotle, for instance, certain parts of a sick human body take on natural status the moment they are healed. According to Aristotle, medical treatment of diseases is actually technological. Physicians are technicians, who produce artificial states in the body that lead to health and thus back to nature (*cf.* Schiemann 2005).

nological objects provide characteristic examples. By having the greatest possible influence on the properties of its materials, nanotechnology can blur the traces of its interventions to the most comprehensive extent.

4. The Lawfulness of Nature in the Nano world

In this section, I will return to the broad sense of the term 'nature'. It does not necessarily refer to the genesis of objects, but generally to those regular properties that are beyond human influence, and which sciences express as laws. Natural laws represent the universally valid expression of the conjunction of conditions under which an event or a state regularly obtains.

As revisable, mostly mathematical constructions, natural laws are human-made. True observational statements, however, which are predicted by these laws and constitute their empirical content, refer to the natural prerequisites of human action. Hence, their truth does not depend on the specific experimental conditions under which the corresponding phenomena are produced or discovered. The empirical content of the laws of nature delimits the scope within which nanotechnology can unfold its potential.[13]

Between nature in this sense and nanotechnology, there is a certain tension, which has recently been the subject of discussions about the potential of human constructions on the nanoscale. Particularly at issue are physical and chemical laws, which must be taken into account in planning nanotechnological constructs. In the following, I will focus on physical laws, which *present* plans have to take into consideration. In the next section I will move to discussions of technological constructs (*e.g.* Eric Drexler's assemblers) whose *future* conditions of realization are controversial.

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[13] The relation of the broad sense of the concept of nature to the narrow sense, which is only defined negatively by reference to human action (*cf.* Section 3) is of tensional character inasmuch as the lawful structure of nature can be understood as a positive (scientific) characterization of nature. Laws, however, can always be formulated in negation (*cf.* Popper 1935, p. 39), in which case nature emerges as a limit to possible human actions. One example is the theorem of energy conservation, taken as a postulate of the impossibility of constructing perpetual motion machines of the first kind.

A large portion of the current projects in nanotechnology are designed to advance the miniaturization of technology. This tendency is especially strong in electronics (Fahrner 2003, p. 1-3). Nanotechnological constructions are to reproduce traditional electronic components (switches, diodes, transistors, *etc.*) on a nanoscale. One main goal of this effort is to open up new dimensions of data processing, namely through the storage of large amounts of data in the smallest possible space (*e.g.* the British Library in a sugar cube). These plans are countered by the assertion that new laws have to be expected at the nano level, which emerge from the fact that this field lies between the atomic and subatomic quantum phenomena on the one hand, and the continuous phenomena of systems with large numbers of atoms on the other. Because of the intermediary position of the nanoscale, it is also called 'mesoworld'. In this world, not only known quantum phenomena appear (*e.g.* the uncertainty principle or the tunnel effect), but also the known phenomena of continuum physics (*e.g.* heat flow). There are even some new regularities that emerge, like the quantization of electrical and thermal conductance. The quantization of electrical conductance has already turned out to be a fundamental feature of the smallest structures of conductors. The quantum nature of heat flow was first observed in 2000 in narrow silicon nitride bridges, constituting a fundamental lower limit of this flow in minute objects that can conduct heat (Roukes 2001a, 2001b).

These phenomena restrict technology's ability to maneuver on the nanoscale (Fogelberg & Glimell 2003, p. 18. The question whether a quantized current flow is technologically utilizable remains problematic; the quantum nature of heat flow could hinder the necessary cooling of electronic and mechanical nano building components. Roukes comments on the novel regularities discovered in the mesoworld as follows: "The nanoworld is often portrayed by novelists, futurists and the popular press as a place of infinite possibilities. But this domain is not some ultra miniature version of the Wild West. *Not* everything goes there; there are *laws*" (Roukes 2001a, p. 26).

Corresponding to the tension between nature as the lawful constitution of reality and nanotechnology, there is a conflict between scientists' interest in knowledge and engineers' interest in applications. Roukes represents the scientific position, stating that understanding laws is a precondition for technological applications: "Much exotic territory awaits exploration. As we delve into it, we will uncover a panoply of phenomena that we must understand before practical nanotechnology will become possible" (Roukes 2001a, p. 21). Engineering technology, in contrast, is less interested in the clarification of lawful coherence than in its utilization for technological purposes. P. Chaudhari of IBM Watson Research expresses this position by stating the following: "The engineers were not so much concerned with understanding the laws of nature but rather in using them to build something useful for mankind" (Chaudhari 2001, p. 78).

5. The Relationship Between Living Nature and Nanotechnology

Up to the present, living nature has been considered the epitome of that which is not human-made. As much as the organic structures of living beings have been changed through human intervention, human beings have not yet succeeded in producing life itself. Life processes occur in dimensions that are so complex and minute as to be only conditionally accessible. At this level, nanotechnology promises to open up new opportunities. It is among the disciplines that develop means to create life artificially – be it as a reconstruction of existing forms of life or as a construction of a differently designed artificial form of life.

Against this background, it is striking that not only current nanotechnological research but also the most boldly futuristic visions of nanotechnology are confined to non-living constructions. Correspondingly, artificial life is mentioned neither in Eric Drexler's futurist books (Drexler 1986, Drexler *et al.* 1991) nor in connection with nanotechnology in the optimistic report *Converging Technologies for Improving Human Performance* (Roco & Bainbridge 2002).

In my view, the restriction of nanotechnology – both in current practice and in futuristic visions – to the construction of non-living systems reflects a gap between technological and biological objects, which also exists at the nano level. Following Stuemper-Jansen 1994, I have compiled some of the characteristic differences between technological and biological systems in Table 1. I want to underscore the abilities of organisms to self-replicate and to self-repair, which have not even begun to be realized in abiotic technological systems. Moreover, whereas metabolic processes in living organisms produce energy by degrading endogenous substances, technological systems depend upon energy usually supplied from outside. The comparatively low efficiency of technological systems makes it necessary that they be cooled.

Eric Drexler believes that the difference between living nature and non-living nanotechnology originates from the fact that living nature must submit to the struggle for survival even at the lowest level of the generation of its products. He quotes Ralph Merkle approvingly: "It's both uneconomical and more difficult to design a self-replicating system that manufactures every part it needs from naturally occurring compounds. Bacteria do this, but in the process they have to synthesize all twenty amino acids and many other compounds, using elaborate enzyme systems tailored specifically for the purpose. For bacteria facing a hostile world, the ability to adapt and respond to a changing environment is worth almost any cost, for lacking this ability they would be wiped out" (Drexler *et al.* 1991). Under the conditions of the struggle for survival, organisms have developed an adaptability, which is normally not inherent in technologically produced systems designed to serve human purposes. As Merkle – referring to the example of machines – puts it: "The machines made by human beings bear little resemblance with living systems, and this is most likely to be true for molecular production systems. [...] Machines do not have this marvelous adaptability of living systems" (Merkle 2001, p. 184).

As a property that distinguishes organic beings from nanotechnological products, adaptability is one example of the application of the epistemic criterion for distinguishing between natural and artificial objects. For the time being, the lack of adaptability of the latter attests to a human origin. Nanotechnological development of adaptable products, *e.g.* the context-dependant adaptation of a substance's surface properties, constitutes a step toward dissolving the difference between nature and technology.

The difference between living nature and non-living nanotechnology has also provided the backdrop for a controversy in the past few years, mainly between Richard E. Smalley and Eric Drexler, regarding the future possibilities of technology on a nanoscale. The subject of the argument has been, above all, the question to what extent nanotechnological production will be possible without reference to already existing biological processes. Drexler follows Richard Feynman's program, according to which nanotechnology is "fundamentally mechanical, not biological" (Drexler 2003). Drexler's plans envision computer-programmed robots on a nanoscale, so-called assemblers, that assemble single molecules with atomic precision in order to produce themselves or other objects. Smalley, on the other hand, considers such nano-scale mechanical self-replication and production of objects to be physically impossible. According to Smalley, moving single molecules does not suffice to produce stable chemical compounds. In his opinion, the entire reaction scale has to be controlled. For this purpose even the smallest robot would be too big (Smalley 2001, Whitesides 2001, Jones 1995). Moreover, the molecules to be moved would adhere to the arms of the robots (Smalley 2001, 2003). Smalley concludes that "such a nanobot will never become more than a futurist's daydream" (Smalley 2001).[14]

Smalley's arguments illustrate the application of the second criterion, which refers to natural laws. This criterion is not conducive to distinguishing among objects, but it defines the scope that natural laws set for potential nanotechnological object design. In Smalley's view, the production of nanobots contradicts physical laws and is therefore impossible.

Smalley believes that the fabrication of products on a nanoscale would require "something very much like an enzyme". "Any such system will need a liquid medium. For the enzymes we know about, that liquid will have to be water, and the types of things that can be synthesized with water around cannot be much broader than the meat and bone of biology" (Smalley 2003). According to Smalley, the limits posed by natural laws compel nanotechnology to orient itself toward the model of existing biological systems. George M. Whitesides sees a larger scope for nanotechnology. He, too, assumes that there is presently a difference between biological and nanotechnological systems, and considers the realization of Drexler's assembler vision impossible. In his view, only two possibilities remain for the production of nanomachines. "The first is

[14] Jones 1995 provides an additional argument related to the concept of entropy.

to take existing nanomachines – those present in the cell – and learn from them. [...] The second is to start from scratch and independently to develop fundamental new types of nanosystems. [...] It will be a marvelous challenge to see if we can outdesign evolution. It would be a staggering accomplishment to mimic the simplest living cell" (Whitesides 2001). However, since this approach is much more difficult than the first one, he considers it unlikely to be implemented. Therefore, it also seems reasonable to him for nanotechnology to assume the model of existing biotic nature.

Table 1. Characteristic differences between technological and biological systems

	Typical realization in technological systems	Typical realization in biological systems
production process	- top-down (bottom-up, self-organization only in nano- and biotechnology) - technological methods for large amounts	- bottom-up, self-organization processes (incl. self-replication and self-repair) - slow growth of functional units on the molecular level, connection to larger systems
controllability	- possible only in small parts at atomic or molecular levels or as statistical ensembles	- by means of numerous specialized systems combining in a network on the molecular level
materials	- generalized building set (wide range of elements and compounds with various properties)	- flexible basic building set (few classes of bio-materials, optimized for various functions)
energy input	- high (often in high temperature range), comparatively low efficiency, loss through cooling	- low (highly efficient transformation chain with chemical substrates, but therefore also with molecular by-products)
environmental sustainability	- frequently problematic	- bio-degradable products, usually unproblematic under natural conditions
durability, stability, changeability	- technological solutions over a broad scale of environmental conditions (*T, p, pH, etc.*) - usually stable long-term; but, no self-repair, inflexible	- comparatively susceptible - but: renewable, flexible, able to regenerate, natural degradation processes, self-correcting

The controversy among Drexler, Smalley, and Whiteside illustrates two positions with respect to the divergent directions in which nanotechnology may be developed in the future: Nanotechnology could develop independently or follow the model of nature. The first way would mean the creation of an increasingly artificial world apart from nature; the second a new dimension of connection between technology and nature. Both scenarios would clearly be distinct from the traditional relationship between macroscopic technology and nature. The latter is characterized by the fact that while it admits of a distinction between technology and nature, it also interrelates the two. In the future, either the element of interrelation, with increasing artificiality, or that of distinguishability, with the establishment of a new dimension of connection between nanotechnology and nature, may become less relevant.

6. Conclusion

I have defined nanotechnology as a human affair. The human origin of nanotechnological methods clearly distinguishes them from nature insofar as nature is not produced by human action. But this distinction does not necessarily apply to the relationship between nanotechnological and natural objects. Nanotechnological objects are designed to serve human purposes. Nanotechnologically produced substances, which are appropriate as industrial materials, are just as unlikely to be found in nature as nanoelectrical switches and nanomechanical gears. On the other hand, nanotechnology offers unique ways of using natural processes and rebuilding natural objects, or of substituting equivalent alternatives. Large molecules can be assembled from naturally occurring atoms in such a way that they become indistinguishable from molecules of natural origin. Since both of these aspects presently play a role in the relationship between nanotechnology and nature, this relationship cannot be characterized uniformly.

The multifariousness of the relationship between nanotechnology and nature, however, does not prevent the application of uniform criteria for characterizing it. In order to show this, I considered a conception of nature that is common among nanotechnologists. This notion conceives of nature as that which is not made by human action. I distinguished two senses of this concept. While the narrow sense refers to objects that do not originate in human action, the broad sense describes the empirical content of laws of nature, which is not at humans' disposal.

Building upon the narrow sense, I proposed an epistemic criterion according to which an object is natural if it is impossible – using all available scientific methods at a given time – to ascertain that it was produced by human action. This criterion makes it possible to distinguish – analogously to the Turing-test of artificial intelligence – between natural and artificial components of most nanotechnological processes and products. Given the multifariousness of the relationship between nanotechnology and nature, there are cases where it becomes problematic to distinguish between the two. I assume, however, that these cases are exceptions. Nanotechnological objects are mostly hybrids of nature and art; only in a few cases would they be said to be wholly natural because their artificial origin could no longer be confirmed.[15]

The broad sense of the concept of nature led to a criterion for the scope of current and future nanotechnology. Whatever the future development of the relationship between nanotechnology and nature might be, nanotechnology will be subject to a reality that is structured by the laws of nature. The empirical content of laws refers to that which precedes human action. Nature in this sense is already relevant for nanotechnology, because present developmental prospects depend on the still poorly researched laws of the mesoscale between quantized and continuous phenomena. It is possible that a more precise determination of these laws may considerably restrict technology on a mesoscale. Just as there are areas in the macroscopic world that are rather unsuitable for human life (such as mountains, icy or sandy deserts, deep seas *etc.*), the mesoscale could turn out to be an area whose structures are only conditionally useful for technological purposes.

The relationship between the two criteria can be formulated in the following way: While the narrow sense of the concept of nature permits the determination of variable demarcations between natural and artificial properties in nanotechnology, the broad sense denotes invariable proper-

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[15] As long as nanotechnology does not use atoms made of non-natural elementary particles, its products will not be completely artificial.

ties of nature, which are preconditions for nanotechnology. The first criterion deals with the dynamic boundaries of the natural world, the second with the static limits imposed by nature. The one describes what is possible within the scope of the other.

An important example to which both criteria can be applied is the relationship between nanotechnology and living nature, which I discussed in the last section. Currently, life is the part of nature most distinct from technology in general. The possibility that nanotechnology may in the future produce artificial life, similar to or distinct from existing living nature, cannot in principle be ruled out. The present discussion of future possibilities indicates that technology on a nanoscale will probably be modeled after living nature in order to have the best possible conditions for producing artificial products to serve human purposes.

Acknowledgments

My thanks to the two anonymous referees for their useful comments, as well as to Katja Plaisant and John Michael for their translation.

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CHAPTER 5

SMALL, BUT DETERMINED: TECHNOLOGICAL DETERMINISM IN NANOSCIENCE

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Analysis of technological determinism by historians, sociologists, and philosophers has declined in recent years. Yet understanding this topic is necessary, particularly in examining the dynamics of emerging technologies and their associated research areas. This is especially true of nanotechnology, which, because of its roots in futurist traditions, employs unusual variants on classical determinist arguments. In particular, nanotechnology orients much more strongly to the past and future than most traditional disciplines. This non-presentism strongly colors its proponents' articulation of the field's definition, purview, and likely development. This chapter explores nano's non-presentism and suggests ways to further explore nano-determinism.

1. Introduction

Is (nano)technology a product of society, or is society a product of technology? Do social groups construct what counts as 'progress' in the development of a technology, or do artifacts and systems evolve according to their own, internal rules? These are the questions that once sparked vigorous debate over 'technological determinism'. Yet in the past few years philosophers, historians, and sociologists of technology have largely steered away from these thorny issues. Stark versions of determinist thinking, such as Lynn White's (1962) claim that feudalism was a product of the stirrup and the heavy plow, or, for that matter, Marx's

(1963/1847) remark that "the hand mill gives you society with the feudal lord; the steam mill society with the industrial capitalist" today seem too oversimplified even to provoke scholarly discussion. As one of the last important contributions to this debate, the edited volume *Does Technology Drive History?* (Smith & Marx 1994), answered its eponymous question – 'not really'.

One of the problems with sustaining analysis of technological determinism is that there is little agreement about what it is. Indeed, in the decade between 1985 and 1995, there briefly flourished a cottage industry devoted to splicing apart the various threads of determinist thought, giving them names, and associating them with different schools of philosophy and history.[1] As Bruce Bimber (1994) pointed out in a landmark article, technological determinism "exists in enough different incarnations that the label can easily be attached to a range of views". Within this range, one can find a spectrum from 'strong' to 'weak' determinism – for some, technology may be *the* driving force of social change, while for others (most notably Thomas Hughes) a technological system may seem to have an autonomous, extra-social 'momentum' (Hughes 1983, 1994) that drives social change only because society itself provides the soil to grow networks of power, standards, institutions, and artifacts that entrench the system by enrolling vast numbers of stakeholders.

Thus, much of the attraction of determinist representations of technology's development and effect on society may lie in the interpretive flexibility of applying both 'technology' and 'determinism' to any particular case. Yet, though marking out the different senses latent within technological determinism was an important project, it has tended to end rather than provoke debate. For the purposes of this chapter, therefore, I wish to point to conceptual territory that may lie beyond the parsing of definitions. To do so, I will rely on a two-handed definition of technological determinism borrowed from Bijker (1995). In Bijker's summary, technological determinism encompasses *both* the idea that technological development proceeds via an autonomous, internal logic (a logic determined only by a unidirectional calculus of engineering considerations,

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[1] See, among others, Bijker & Pinch 1987, Bijker & Law 1992, Bimber 1994, Mackenzie 1996a, 1996b, Misa 1988.

rather than a dense weave of contradictory aims that are both 'social' and 'technical') *and* the idea that technology determines the social organization of a society (and therefore pushes rather than pulls societal change). As Bijker points out, though, the two notions are intertwined. Because technology is seen as prior to, rather than an upshot of, society, it is easy to think of technological choices as having their own, pure logic; and because technological changes are thought to accumulate under their own power (and simultaneously provide the motive force for societal change), it is almost axiomatic (at least in North America and many other Western societies) that technical development can be used as a (or usually *the*) yardstick in measuring how 'advanced' a culture is.

The advantage of this particular definition is that it highlights elements of technological determinism within both mainstream, popular ideology, and academic philosophy and history. To be sure, outside of technology studies circles determinist talk is still alive and well. Popular representations of technology, as well as policy statements by proponents and opponents of particular artifacts and systems, paint technologies as possessing autonomy, as developing along ineluctable pathways, and as being the core around which society is structured and measured. Indeed, this provides its own fodder for analytical debate as historians and sociologists examine how advocates' and opponents' *representations* of technology as autonomous shape both the design of artifacts and the social order surrounding them in ways that recursively give the technology a deterministic social reality. As historians Gabrielle Hecht and Michael Thad Allen argue,

> [I]nstead of continuing to ask 'Does technology drive history?' we should ask questions such as 'When or why do historical actors believe or argue that technology drives history?' Addressing such questions leads us to view technological determinism – and other beliefs about the relationships between technology and social change – as political practices. [Hecht & Allen 2001, p. 14-15]

Though determinist talk of all stripes – strong and weak, nuanced and simple – is ubiquitous, it is often easiest to capture and analyze pronouncements made about *emerging* technologies. This may seem counterintuitive; after all, emerging technologies are thinly connected to networks of people and institutions, are easily reconstrued as new participants have their say, and continually face the specter of failure and disappearance. Unlike many entrenched technologies, emergent systems usually spawn a variety of contradictory voices. Yet, though these voices differ, they still often reinforce a technologically determinist worldview by laying out a determined path for the technology's development and a means by which the technology will ineluctably reshape society. The strong association between emergent technologies and determinist talk seems less paradoxical, though, if we see such statements as *performative*, rather than reflective, of a determinist viewpoint.[2] Technology's advocates build networks of people and institutions *through* determinist talk and action, and in doing so they conjure up the thick social ties that make such determinism plausible.

Few of today's emerging technologies fit this model better than nanotechnology. Nano's proponents, in particular, are not shy about saying that current research will inevitably generate a brave new world that will look completely different from pre-nano society. In engaging analytically with such promises, scholars of science and technology have a tremendous opportunity. Nano represents a scientific and technological movement in the making (or, perhaps, unmaking). Nano should be viewed as an exquisite field site for testing our ideas about how people generate knowledge and artifacts; how they integrate new technologies into their practices and organize themselves around new kinds of artifacts; and, indeed, how they use emerging technologies to push the limits of human instrumentality.

For these reasons, nano is fertile ground for sharpening historical, philosophical, and sociological analysis of technological determinism. Yet, nano, as currently constituted, also displays a number of wrinkles on classical determinism that make it interesting as more than a mere test case. Most fascinating and analytically useful is its proponents' cultivation of it as a simultaneously scientific and technological endeavor. Nanoists routinely mix scientific and technological registers in their talk; and in their practice, they devise experiments that can easily be construed both/either as generating interesting scientific knowledge and/or useful

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2 For an interesting take on the performative aspects of Moore's Law, see Mackenzie 1996a.

technological artifacts. Interestingly, nanoists often project this synthesis far back into the past and forward into the future by, for instance, saying that nanoscience has been gathering steam (perhaps unnoticed) for a very long time in the guise of research in fields such as chemistry and materials science, or that nanotechnology has long been present in practices such as glass-making and blacksmithing where craft knowledge can produce striking nanoscale effects.

Moreover, they say, nature (or 'biology') has been doing nanotechnology for billions of years; every virus, bacterium, and cell is a nanomachine of enormous complexity. Indeed, it is around this point that some nanoists invoke a complex but strong form of determinism. After all, nature's nano-achievements show us that nanomachines are possible, and nature's version of nano has completely restructured the earth and produced human life, culture, and consciousness. The progress of science, they say, means that it will inevitably be possible for us to understand and mimic nature's nanomachines; once we have done so, our own nanomachines will develop in a way determined by biology, chemistry, and engineering design; and as they do develop, our inventions cannot help but revolutionize our world just as much as nature's nanobots did.

Thus, nano – and the determinist rhetoric that surrounds it – plays with and synthesizes distinctions between science and technology in interesting ways. This makes nano ripe for the kind of analysis that extends almost a century-long tradition of using the philosophy, history, and sociology of science and technology to cast light on each other. The strands of this tradition that I will draw on here begin with Dewey and Heidegger, and pass through Bachelard and Wittgenstein and Kuhn, but have taken on many colors with the advent of the science and technology studies literature in the late 1970s.[3] Indeed, today scholars as diverse as Don Ihde, Trevor Pinch, Gabrielle Hecht, Ian Hacking, Peter Galison, and Bruno Latour have used our understanding of science to sharpen analysis of technology *and* vice versa.[4] Of these post-Kuhnian literatures, this chapter draws most heavily on the social construction of technology (or

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[3] Representative works include Heidegger 1977, Dewey 1958, Kuhn 1996, Polanyi 1962, Bachelard 1984.

[4] Representative works include Ihde 1991, Pinch 1986, Hecht 1998, Hacking 1983, Galison 1997, Latour 1983.

SCOT) model associated with Bijker and Pinch (1987).[5] SCOT is particularly appropriate here since the model cut its teeth in the 1980s on the debates over technological determinism. In particular, by showing that there is 'interpretive flexibility' in the way engineering choices are made (and therefore no wholly autonomous logic of design is possible) and that technologies are continually reshaped and reinterpreted as new social groups become relevant to them (and therefore technology cannot straightforwardly 'impact' social organization), SCOT countered most (strong) determinist arguments and contributed to the shift away from the debate on technological determinism.

The lessons of SCOT and other post-Kuhnian literatures are many, but a few are key in examining the role of determinism in the relationship between nanotechnology and its constituent communities of practice.[6] First, whatever the metaphysical nature of reality, the sciences as they are actually constituted deal almost exclusively not with the 'real world' but with a world that has been appropriated for human action. That is, scientists engage with a world that they manufacture to be more amenable to the generation of knowledge, and then they learn what they can about *that* world. They clean this reconstituted world, they filter it, they abstract it, they mold it into model systems, and they stimulate it to produce and be populated by some entities rather than others. Thus, the scientific world is inherently technological, and scientists create knowledge by piecing together generative relationships between different *made* objects – microscopes, accelerators, electrons, lab rats, *etc.*[7]

Hence, different regions of science and engineering have quite different epistemic materials and therefore quite different practices and bodies of knowledge.[8] Different disciplines and subdisciplines have a certain autonomy because of their arcane knowledge of how to tame the world in their peculiar way and learn something about it. Thus, the knowledge of

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[5] For later amendments to the SCOT program, see Bijker 1995a, Kline & Pinch 1996, Rosen 1993, and Mody 2000.

[6] For an introduction to the communities of practice literature, see Wenger 1998.

[7] I find the following useful in thinking about the 'made world' of science: Knorr-Cetina 1992, Hacking 1992, Amann 1994.

[8] I draw the idea of 'epistemic materials' from Rheinberger 1997. For a nice analysis of the epistemic and cultural disunity of scientific disciplines, see Knorr-Cetina 1999 and Galison & Stump 1996.

one science should not be seen as reducible to the knowledge of another, nor should the work of engineers in creating a world that is amenable to their technological expertise be seen as a mere 'application' of any scientific discipline's body of knowledge. From this also follows the Kuhnian point that these crafted worlds make scientific progress difficult to measure. Disciplines change their world-creating practices over time, and hence the knowledge of one era relates to a set of entities that is, in some sense, incommensurable to the knowledge of another era. By the same token, this line of reasoning problematizes notions of technological determinism. Fine-grained studies of scientific practice show that new laboratory technologies do not fit unproblematically into ongoing research communities; rather, the technologies have to be reworked and made compatible with the community's practices. Thus, the design of a technology does not determine its use, and there is no determined relation between a research community's organization and the technologies it employs.

Yet, technologies *can* travel between communities, different disciplines clearly *can* communicate with each other, and different kinds of practitioners *can* harmonize their practice. What is required for this are bits of crafted world – 'boundary objects' (Star & Griesemer 1989) – that can be passed as tokens and made the focus of work that is sufficiently, but not completely, harmonized between different kinds of practitioners. Again, this way of looking at things brings out many of the most conspicuous characteristics of nanotechnology. Like any of the traditional big scientific disciplines, nanotechnology is a community of communities – it contains an overlapping yet mixed bag of surface scientists, probe microscopists, semiconductor physicists, supramolecular chemists, molecular biologists, computer scientists, electrical engineers, materials scientists, UV and electron lithographers, micro-electromechanical systems experts, and so on.[9] Unlike the traditional disciplines, though, there has been little attempt to claim, so far, that the expertise of the constituent parts of nanotechnology is fully commensurable. Policy specialists, practicing scientists and engineers, and sociologists and philosophers of science and technology have all had tremendous difficulty even arriving

[9] See Schummer 2004.

at a coherent *definition* of nanotechnology, much less a common jargon for all of the knowledge created by self-described nanotechnologists.

Several of the constituent communities of nanotechnology are drawn from the engineering sciences – materials science, electrical engineering, mechanical engineering, fluid dynamics, computer science, MEMS, *etc.* Since the 1970s, these subdisciplines have spawned their own literature in the science and technology studies tradition, a literature that has consistently engaged and critiqued technological determinism in ways that will be helpful in understanding nanotechnology. Scholars such as Ed Layton, Ed Constant, Walter Vincenti, Ron Kline, Eda Kranakis, and Thomas Hughes have shown that engineering has its own practices, its own kinds of instrumentation, theories, and heuristics, and a body of knowledge that cannot simply be reduced to physics.[10] Moreover, these scholars have demonstrated that rhetorical repertoires of 'science' and 'technology' or of 'pure' and 'applied' science are historically situated and closely connected to struggles over the disciplinary identity and autonomy of the engineering sciences (Kline 1995, 2000). The historical sensibility these authors provide is useful in considering nanotechnology as merely the latest in a long line of attempts to provide a heuristic and organizational umbrella over different patches of the engineering disciplines, and the rhetoric of nanoists as performative in the construction of their umbrella.

Nano also has a strong constituency from scientific subdisciplines, especially those currently housed in traditional chemistry departments. Even before Dalton and atomism, chemists knew their discipline dealt with very small objects, and modern chemistry is the birthplace of canonically nanotechnological 'artifacts' such as the nanotube, the buckyball, and the DNA computer. In the past, because of the reductionist bent of certain kinds of logical empiricism, and because of the social prestige of physics, chemistry was often overlooked by sociologists and philosophers; there were very good histories of chemistry, such as the classic Guerlac (1961), but little exploration of how the epistemics and social practice of chemistry differed from physics. As with the engineering sci-

[10] See Layton 1971, Constant 1980, Vincenti 1990, Kline 1992, Kranakis 1997, Hughes 1983.

ences, though, there is now a burgeoning literature showing that chemists have their own kind of relationship to instrumentation, that they treat issues of purity and contamination in their own (epistemically significant) way, and that they have a different kind of bodily engagement with their experiments and representations than other scientists.[11] Most importantly, this literature draws out the sense in which chemistry is the consummate science of *making* 'epistemic things' – materials that provide a stage for ongoing experimental work and that yield up some small part of the world for scrutiny. The purview of chemistry *is* the making of molecules, integrated with the equipment, concepts, and processes that allow chemists to simultaneously generate knowledge and nanoscale objects.

2. Drexler and Non-Presentism

Engineers and chemists both bring a thing-making orientation to nanotechnology. What is perhaps new for chemists, though, is the idea that the *epistemic* materials they are making should be construed primarily as *technological* artifacts (or parts thereof). It is this process of recasting that has provided much of the hype of nanotechnology, as well as some of the internal frictions of the nano community. It is not immediately obvious in what sense molecules or supramolecular assemblies should be viewed as technological artifacts; and those who have made that leap have sometimes attracted criticism for doing so. This is true of no one more than Eric Drexler, the popularizer of the term 'nanotechnology' and one of the most influential visionaries of the field. It is worthwhile examining Drexler's rhetoric, and his evolving place in the nano community, to understand how this synthesis of chemistry and engineering can yield new forms of technological determinism.

Interestingly, Drexler's background is as a futurist, rather than as a practitioner of any of nanotechnology's constituent communities. During his undergraduate education at MIT in the late 1970s, he became a protégé of space travel visionary Gerard K. O'Neill and artificial intelligence futurist Marvin Minsky.[12] At the same time, he kept close track of

[11] Examples include Francoeur 1997, Baird 1993, Reinhardt 2004, Mody 2001.
[12] I have used biographical details from Regis 1995 in analyzing Drexler's futurist roots.

the dramatic changes in molecular biology and genetic engineering of the day and began developing his own ideas about how artificially engineered biomolecules could be used to further his mentors' dreams of space exploration and artificial intelligence. By 1981 he had begun publishing his vision under the label of 'nanotechnology' – a vision in which very small 'assemblers', modeled on biological machines (cells, ribosomes, viruses, *etc.*), could reconstitute raw materials into almost any physically possible artifact (Drexler 1981).

In 1986, Drexler and his wife, Christine Peterson, along with a group of like-minded friends, moved to Palo Alto to found the Foresight Institute, an organization dedicated to predicting and planning for the dramatic changes caused by nanotechnology. At this time, Drexler formed personal and intellectual links with other futurists in the Bay Area, particularly Stewart Brand, founder of the *Whole Earth Catalog*, that helped legitimate Drexler's project and provided a model for the niche he began to fill.[13] This tradition of futurism, with roots going back through Werner von Braun and Arthur C. Clarke to at least as far back as H.G. Wells and Jules Verne, has left a profound imprint on nanotechnology. All nanotechnologists – whether supporters or critics of Drexler – must deal with his legacy, even if he can no longer fully control his bequest; and that legacy bears the mark of the futurist community.

This futurist inheritance ought to spur particular kinds of analytical discussions of nanotechnology. Historians and sociologists, for instance, will have to place Drexler and nanotechnology in this visionary tradition and delineate the linkages between different kinds of futurism latent in his work. Philosophers, meanwhile, should investigate the unusual time horizons that govern nanotechnological work. It may be useful, for example, to develop a concept of 'presentist' and 'non-presentist' disciplines. Physics and chemistry, for instance, have a more or less presentist orientation. Results generated in the now are drafted into a body of knowledge that is conceived as applying regardless of date. Except for sub-fields like cosmology and geochemistry, the past and future are con-

[13] For some historical and ethnographic detail on Bay Area futurism, see Turner (forthcoming) and Brooks 2003.

ceived as being essentially like the present, so that the present is the only arena of experimentation that matters.

Nanotechnology, on the other hand, seems decidedly non-presentist. Most traditional disciplines restrict their focus to the materials and instruments (the 'made world') presently available to them. As Drexler and other nano elites often point out, though, nanotechnology came of age at the same time as widespread, powerful computing. Thus, nanotechnology is intensely grounded in computer simulations, and much of the 'made world' of nano has a virtual, yet-to-be-realized quality (Lenhard 2004). Nanotechnologists work as much in this future world as in the present. Drexler himself nicely sums up this orientation and its debt to the futurist tradition:

> Scientists are encouraged by their colleagues and their training to focus on ideas that can be tested with available apparatus. The resulting short-term focus often serves science well: it keeps scientists from wandering off into foggy worlds of untested fantasy [...] [E]ngineers share similar leanings toward the short term [...] [S]cientists refuse to predict future scientific knowledge, and seldom discuss future engineering developments. Engineers do project future developments, but seldom discuss any not based on present abilities. Yet this leaves a crucial gap: what of engineering developments firmly based on *present science* but awaiting *future abilities*? [...] Imagine a line of development which involves using existing tools to build new tools, then using *those* tools to build novel hardware (perhaps including yet another generation of tools) [...] Recent history illustrates this pattern. Few engineers considered building space stations before rockets reached orbit [...] Similarly, few mathematicians and engineers studied the possibilities of computation until computers were built. [Drexler 1990, pp. 46-7, italics in original]

Currently, nano experiments often yield *knowledge* that is siphoned into the experimenter's home discipline (physics, chemistry, *etc.*); but the epistemic *value* of the experiment for nano itself is that it provides a 'proof of concept' for some process or mechanism that – in the future – can be integrated into a more complex nanomachine. That is, nano results are framed in terms of how they contribute to an envisioned path of engineering evolution that necessitates small, cumulative design advances along the way.

To flesh out the roots of nanotechnology's non-presentist orientation, it is worth doing a close reading of Drexler's first popular book, *Engines of Creation: The Coming Era of Nanotechnology*. This is the book that first pushed nanotechnology into the public consciousness, and, through its influence on policy makers, science fiction writers, journalists, and practicing scientists, continues to shape the practice of the field. It lays out Drexler's vision of atomically-precise technology, then jumps from one staid futurist topic to another (space travel, artificial intelligence, immortality, new media) demonstrating that nanotechnology will revolutionize each of them. The basic points on which the book's argument hinges are unabashedly determinist and non-presentist: nanotechnology is inevitable, and when it comes it will change everything.

> Assemblers will take years to emerge, but their emergence seems almost inevitable: Though the path to assemblers has many steps, each step will bring the next in reach, and each will bring immediate rewards. The first steps have already been taken, under the names of 'genetic engineering' and 'biotechnology' [...] Barring worldwide destruction or worldwide controls, the technology race will continue whether we wish it or not [...] To have any hope of understanding our future, we must understand the consequences of assemblers, disassemblers, and nanocomputers. They promise to bring changes as profound as the industrial revolution, antibiotics, and nuclear weapons all rolled up in one massive breakthrough. To understand a future of such profound change, it makes sense to seek principles of change that have survived the greatest upheavals of the past. [Drexler 1990, p. 20]

The reason nanotechnology is inevitable is that we have a model for how to proceed: natural, biological nanoscale 'machines'. According to Drexler, we are on the verge not only of understanding these biomachines, but of mimicking them:

> [S]imple molecules make up passive substances. More complex patterns make up the active nanomachines of living cells. Biochemists already work with these machines, which are chiefly made of protein, the main engineering material of living cells [...] [P]rotein machines are unusually flexible. But like all machines, they have parts of different shapes and sizes that do useful work. All machines use clumps of atoms as parts. Protein machines use very small clumps. Biochemists dream of designing and building such devices, but there are difficulties to be overcome

> [...] When they combine molecules in various sequences, they have only limited control over how the molecules join. When biochemists need complex molecular machines, they still have to borrow them from cells. Nevertheless, advanced molecular machines will eventually let them build nanocircuits and nanomachines as easily and directly as engineers now build microcircuits or washing machines. Then progress will become swift and dramatic. [Drexler 1990, p. 6]

Why will progress be swift and dramatic? In *Engines of Creation* and his more technical sequel, *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, Drexler makes an exact, systematic analogy between biological 'nanomachines' (and their parts) and macroscale engineering artifacts (and their parts). In Drexler's view, nanotechnology will inevitably progress by translating the principles of macroscale engineering into their nanoscale equivalents:

> The similarities between nanomachines and macromachines are pervasive and fundamental. At the analytical level, systems of both kinds can be described by applying classical mechanics to objects that occupy space, exclude other objects from that space, and resist deformation. At the design level, systems of both kinds must apply forces, guide motions, limit friction, and so forth [...] Because functions at the system level can usually be implemented in many different ways at the component level, the parallels between macro and nanoscale systems can be even stronger than those between their components. Accordingly, many of the lessons of macroscale mechanical engineering can be applied directly. When nanomechanical designs are drawn at a scale and resolution that omits atomic detail, they can be almost indistinguishable (save for dimensioning labels) from designs for macromachines. [Drexler 1992, pp. 315-6]

Reading Drexler's technical work can be a bit like flipping through Diderot and d'Alembert's *Encyclopedie* – he introduces all the classical machines and their parts, and then offers simulations of their nano-equivalents. Note, for instance, the sub-headings of sections 10.5 through 10.7 in *Nanosystems*, in which he describes a series of simple machines made from small numbers of atoms: 'Nuts and Screws', 'Rods', 'Springs', 'Bearings', 'Spur Gears', 'Helical Gears', 'Rack-and-Pinion Gears and Roller Bearings', 'Bevel Gears', 'Worm Gears', 'Belt-and-Roller Systems', 'Cams', and 'Planetary Gear Systems'.

In articulating his argument, Drexler relies on a form of technological determinism that Wiebe Bijker (1995b) calls the 'autonomous logic of technological development' variant. That is, Drexler sees nanotechnology unfolding in a stepwise, progressive fashion, where each step is related to the next by an inherent design rationale – a rationale that can be made visible through the analogy to macroscale technological systems built up from individual machines that are themselves composed of simpler components. Note, though, how Drexler's vision for the evolution of nano-design relies on an *historical* analogy to the evolution of macro-design. The quaintly Enlightenment character of Drexler's nanomachines is symptomatic of a pervasive, forward- *and* backward-looking non-presentism in his writing. Hardly a page goes by in *Engines of Creation* without a pronouncement about a myriad of pasts. Sometimes, Drexler presents nanotechnology as a radical break with these pasts:

> [M]odern technology builds on an ancient tradition. Thirty thousand years ago, chipping flint was the high technology of the day. Our ancestors grasped stones containing trillions of trillions of atoms and removed chips containing billions of trillions of atoms to make their axheads [...] The ancient style of technology that led from flint chips to silicon chips handles atoms and molecules in bulk; call it *bulk technology*. The new technology will handle individual atoms and molecules with control and precision; call it *molecular technology*. It will change our world in more ways than we can imagine. [Drexler 1990, p. 4, italics in original]

At other times, Drexler offers views on a past that can be mined for lessons in organizing this new molecular technology. Indeed, a central – and often overlooked – part of Drexler's argument is that nanotechnology has a long, long past that demonstrates the inevitable success of efforts in the present:

> Simple molecular devices combine to form systems resembling industrial machines. In the 1950s engineers developed machine tools that cut metal under the control of a punched paper tape. A century and a half earlier, Joseph-Marie Jacquard had built a loom that wove complex patterns under the control of a chain of punched cards. Yet over three billion years before Jacquard, cells had developed the machinery of the ribosome. Ribosomes are proof that nanomachines built of protein and RNA can be programmed to build complex molecules. [Drexler 1990, p. 8]

Ribosomes are 'proof', and a three billion year old proof at that; here and elsewhere, we see that Drexler's nanotechnology possesses an epistemic frame in which 'proof' is not a demonstration of certain knowledge about the present state of nature, but rather a performance of a new kind of relationship between how things once were and how they will, inevitably, come to be.

3. Non-Drexlerian Echoes

Though he made the term 'nanotechnology' current, and continues to profoundly influence the debates surrounding it, Drexler is by no means the only voice for the field. Indeed, at least since the founding of the US National Nanotechnology Initiative (NNI) in 2000, Drexler's perspective has continually faced challenges from all of the other stakeholders in the enterprise. Those who seek to make nanotechnology a coherent, well-funded, publicly-supported discipline in the present have tried hard in the past few years to separate the field from its futurist past. Above all, this means separating it from Drexler, and both prominent and ordinary nanotechnologists have participated in his ritual expulsion in an attempt to mainstream their discipline.[14] Debates between Drexler and his critics often center on his non-presentist, determinist reasoning. Some of his critics find his analogy between humanly engineered nanomachines and biological 'machines' unconvincing; therefore, they do not accept the three billion year old proof that molecular assemblers can work; hence, they do not see nanotechnology traveling down the path of progressively more complex nanomachines that Drexler lays out; and, therefore, they find Drexler's vision of how the world will be transformed by nano unbelievable.

These objections to Drexler's framing of a non-presentist, determinist nanotechnology can be seen in his well-known debate with Nobel Prize-winning chemist Richard Smalley. The crux of the debate is the so-called 'fat fingers, sticky fingers' issue – the idea that molecular assemblers will be unable to pick up and precisely release atoms (as Drexler envi-

[14] For some analyses of ritual expulsion and boundary work, see Gieryn & Figert 1986, Gieryn 1999, Sullivan 1994.

sions) because chemical bonds are too 'sticky' and because any assembler will be unable to choose exactly which of many atoms it will interact with (its fingers are too 'fat'). We will return to the image of nano-fingers and nano-limbs later in this chapter, but for now it is important to note that Smalley's critique centers on the conspicuous features of Drexler's reasoning that I have outlined above:

> You [*i.e.* Drexler] write that the assembler will use something 'like enzymes and ribosomes' [...] But where does the enzyme or ribosome entity come from in your vision of a self-replicating nanobot? Is there a living cell somewhere inside the nanobot that churns these out? There must be liquid water present somewhere inside, and all the nutrients necessary for life [...] Biology is wondrous in the vast diversity of what it can build, but it can't make a crystal of silicon, or steel, or copper, or aluminum, or titanium, or virtually any of the key materials on which modern technology is built [...] If the nanobot is restricted to be a water-based life form, since this is the only way its molecular assembly tools will work, then there is a long list of vulnerabilities and limitations to what it can do. If it is a non-water-based life-form, then there is a vast area of chemistry that has eluded us for centuries [...] You cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler-fixed frame of reference. [Baum *et al.* 2003, pp. 39-40]

Yet these key modules of Drexler's argument appear again and again in nano discussions, from supporters and critics alike. For example, his likening of genetic material to a computer punch tape that 'instructs' organelles (like some miniscule Turing machine) taps into a broad usage that has old roots in fields such as postwar genetics, information theory, and cybernetics that have branched into nanotechnology.[15] Drexler's more general, and exact, analogy between those nanomachines that are old and biological and those that are new and artificial is also ubiquitous in nano circles.

> Imagine a motor measuring a few hundredths of a thousandth of a millimeter, running on and on. Or a data storage device squeezing the equivalent of five 'high-density' floppy disks into a thousandth of a millimeter [...] We are talking about complicated and highly efficient machines

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[15] As examined in, for example, Kay 2000.

> having a size of only a few millionths of a millimeter. Unbelievable? Not at all, for evolution solved these problems more than a billion years ago. The motor mentioned above is already in existence – it is a system mainly consisting of the proteins actin and myosin, and serves to power our muscles. The data store, or chromosome [...] determines your genetic identity. [Gross 1999, pp. 3-5]

Drexler's next conclusion, that the bio-to-nano analogy allows nano design to proceed quickly and progressively because the principles of macroscale design can simply be translated down, has met more resistance. Yet, the practice of nanotechnology shows that many in the field have accepted this point. Nanotechnology journals are filled with news about the latest nanogears, nanomotors, nanotrains, nanoabacuses, nanoshovels, and other macroscale machines and devices replicated on the nanoscale. The epistemic frame of nanotechnology relies heavily on 'simulations' of all sorts – not just mathematical models, but physical, miniaturized 'models' of macroscale artifacts. Often, these simulations take Drexler's translation from biological to mechanical at face value; for instance, in one well-known experiment (Soong *et al.* 2000), researchers bonded an adenosine triphosphate 'motor' protein to a substrate and used it to spin a small metal bar – an ATP 'engine' much like what Drexler describes. These physical simulations 'prove' new processes or techniques, yield components that can eventually be added together to form complex systems, and signpost nano's travel down a mechanically evolutionary, more or less Drexlerian, pathway. As George Whitesides describes this experiment, "at the very least, such research stimulates efforts to fabricate functional nanostructures by demonstrating that such structures can exist" (Whitesides & Love 2001).

Even Drexler's critics (such as Whitesides) often accede to this part of his thesis while pointing out that biology may offer lessons unknown to macroscale engineers – as in this recommendation by a prominent science editor and analyst:

> Why copy nature? Biomimetics has become such a popular buzzword that there is a risk of it becoming its own justification [...] Yet there is little in the history of chemistry, materials science or engineering to show that this need be so. The steam engine, internal combustion engine, jet engine, and rocket engine owe no debt to inspiration from nature [...]

> [Meanwhile m]icroelectronics continues its incredible shrinking act with only the barest hint of any weakening of Gordon Moore's 'law' [...] This reduction in scale brings engineering down to length scales comparable with the dimensions of cells or subcellular constituents. There are two ways in which one could respond to this situation. One could regard the coincidence in scale as irrelevant, since engineering's traditional methods and materials have nothing in common with those of the cell [...] The other option is to realize that the cell faces many, if not most, of the same challenges as we do [...] The ideal position lies, as ever, somewhere in between. I feel that the literal down-sizing of mechanical engineering popularized by nanotechnologists such as Eric Drexler – whereby every nanoscale device is fabricated from hard moving parts, cogs, bearings, pistons and camshafts – fails to acknowledge that there may be better, more inventive ways of engineering at this scale [...] On the other hand, we should remember that the cell's objectives are not necessarily the engineer's. [Ball 2002, pp. 13-16]

Note how this author, like Drexler, references everything about nano to an instructive past and a future shaped by rules such as Moore's Law.

Note, too, though, how the author uses law-like observations about the evolution of science and engineering in the past to define a particular purview for nanotechnology now and in the future. Interestingly, though they share the use of this trope, Drexler and his critics disagree about how to apply it in defining the field. Drexler sees the history and practice of engineering as providing *analogical* design cues for how to build things with atoms once we have mastered their precise control, and as giving a systems perspective that allows us to make enormous complexes of nanoscale machines work in coordinated ways – so-called 'nanofactories' that work almost exactly like macroscale factories, with conveyor belts and assembly lines and computer control. Yet, for Drexler there is little or no *genealogical* connection between traditional engineering's march of miniaturization (the so-called 'top-down' approach) and molecular nanotechnology's atomic precision (the 'bottom-up' approach).

Non-Drexlerians, and some Drexler associates, though, describe engineering's unstoppable march *down* in length scale as converging with chemistry's and molecular biology's journey *upward* in the size of the entities they can comprehend. This convergence gives nano its character, and makes a unified study of the nanoscale a necessity. As Heini Rohrer, Nobel Prize-winning co-inventor of the scanning tunneling microscope, puts it,

> While solid-state science and technology have moved down from the millimeter to the nanometer scale, chemistry has simultaneously and independently progressed from the level of small, few-atom molecules to macromolecules of biological size [...] The nanometer age can thus be considered as a continuation of an ongoing development: for example, miniaturization in solid-state technology [and] increasing complexity in chemistry. [Rohrer 1995, p. 3]

Compare this with a very similar passage from a prominent Foresight Institute participant:

> In the years that followed [Feynman's 1959 talk], chemists and biologists focused on untangling the molecular structures that constitute materiality from the 'bottom up', while physicists and electrical engineers devoted their efforts to building ever smaller machines from the 'top down' [...] The recent confluence of these two monumental efforts has produced an epochal cross-fertilization of knowledge – and the inevitable conceptual turbulence of two colliding world views [...] Nanotechnology arises out of this confluence and aims at building complex, atomically precise machines by the trillions. [Crandall 1999, p. 21]

Rohrer, Crandall, and others who write in this vein almost always include charts and graphs that correlate the two key variables of nanotechnological determinism: length scale and time. Rohrer, for example, includes a diagram with length on one axis and year on the other showing two converging lines: one for steadily *decreasing* size of the smallest structures that can be included in the 'made world' of engineering (microelectromechanical systems, semiconductor chip features, *etc.*); and the other for steadily *increasing* size of the largest molecules that make up part of the made world of chemistry (dendrimers, nanotubes, buckyballs, and so on).

Many writers frame nanotechnology with a chart describing conspicuous features and characteristic entities of length scales from the humanly familiar (usually one meter or centimeter – represented by a familiar animal such as a bee or a cat) to the sub-nanoscopic (one angstrom – represented by a hydrogen atom) and everything in between. Often, these writers juxtapose the chart of length scales with a chart of significant nanotechnological achievements and their dates; usually, such events include the birth dates of the more artificial epistemic materials in the length scale chart (*e.g.* buckyballs or integrated circuits), as well as the dates of invention of new ways to handle or characterize these materials (*e.g.* the electron or scanning tunneling microscopes). Almost always, though, this timeline includes exquisite outliers that make the history of nanotechnology unfathomably deep; for instance, the first two items in a nano-timeline from *Scientific American* are "*3.5 billion years ago* the first living cells emerge" and "*400 B.C.* Democritus coins the word 'atom'" (Stix 2001, p. 36).

This is one of the most pervasive and interesting characteristics of nanotechnology, common to Drexlerians and non-Drexlerians alike. Drexler and his allies tend to focus on the very ancient *biological* precursors of nanotechnology, since this helps them make the analogy between biological and artificial nanomachines, and because Drexler has worked hard to limit the scope of 'nanotechnology' to only those activities that involve precise positioning of individual atoms. This is a more limited scope with fewer precursors in human history than that offered under, for example, the National Nanotechnology Initiative's definition of the field. Those outside the Drexler camp, meanwhile, are more likely to point out very old *craft* activities that would today count as 'nanotechnology':

> The process of nanofabrication, in particular the making of gold nanodots, is not new. Much of the color in the stained glass windows found in medieval and Victorian churches and some of the glazes found in ancient pottery depend on the fact that nanoscale properties of materials are different from macroscale properties [...] In some senses, the first nanotechnologists were actually glass workers in medieval forges rather than the bunny-suited workers in a modern semiconductor plant. Clearly the glaziers did not understand why what they did to gold produced the colors it did, but we do now. [Ratner & Ratner 2003, pp. 13-14]

The last part of this quote shows some of the epistemic consequences of nanotechnology's non-presentism. Nano, in this formulation, produces new *knowledge* that maps onto old *practice*. What makes nano new is that it brings *understanding* where before there was only *doing*. Though nanodots in stained glass are an extreme example, the epistemic shyness of nano, and its strong predilection for creating knowledge by creating *nano-things*, does encourage nanoists to mine past work for present results. Indeed, in one of nano's most important constituent communities, surface science, researchers are exploring practices that in the past they rejected specifically because they yielded non-epistemic materials.

> [Surface scientists] were interested in understanding the science base of what was necessary in order to grow materials of interest to the electronics community [...] You had to understand the surface in a lot of detail, how you grew the thin film on top of it and kept a very fine, smooth surface. A tremendous amount of work had to go into the preparation of the surface, understanding how things settled down, what structures were there, how you varied the process and conditions to get it. One of the amusing things to me was that for many decades the people who were trying to grow these superlattices worked very hard to get these perfectly smooth surfaces, which they needed. So anytime they found conditions in which you got a non-flat surface, they would turn around and run the other direction. Which was appropriate at the time. Now when we get into the nano, what they've discovered is that some of those things they were trying desperately to avoid back then were giving them 'ordered nanostructures'. Which was killing them at the time, but now becomes of a high degree of interest [...] Some of the things that were the poison back then now become the candy that you can go back and say 'ooh, yeah!' We turned and ran the other direction back then, but let's go back and try 'what happens if we push harder, can we now enhance that growth rate and give us these little pyramidal islands?'[16]

I can only make exploratory gestures toward a better understanding of nano's orientation to the past here, but it seems so unusual and so central to the current framing of nanotechnology that it deserves more intensive study. It is possible that nano shares this kind of rhetoric with other non-presentist fields like astronomy, where participants orient explicitly to pre-scientific ancestors of the modern discipline (and even occasionally use the work of those ancestors to better understand the history of the objects of study).

It is also possible that these kinds of statements are necessary *now*, when nanotechnology is being defined and woven into a coherent discipline. For instance, rhetoric of this sort certainly helps nano proponents convince various publics that nano has a long and hence non-threatening

[16] From an interview with a government scientist, July 6, 2000.

lineage. This is similar to attempts by biotechnology companies to persuade the public that genetic engineering is simply the latest variant of an ancient tradition of plant breeding, animal husbandry, and beer-making, rather than the dawn of a scary new Frankenstein-era.[17] The need for boundary-drawing and credence also seems to be at the root of nanoists' constant search for prominent researchers of the past who can be recast as heroes of proto-nanotechnology. This is especially true of Richard Feynman, whose obscure after-dinner speech from the 1959 American Physical Society meeting, 'There's Plenty of Room at the Bottom' (Feynman 1999), has been taken up as a herald of all aspects of the new field. The phenomenon is by no means limited to Feynman, though – icons like Einstein, Schrödinger, and von Neumann are also routinely invoked as having done nano before there was nano.

Nanoists carry their boundary-drawing struggles to the past in other ways as well. It is difficult, for instance, to find a description of nanotechnology that does not call it 'the next' X or Y. Even the official slogan of the National Nanotechnology Initiative is that nano is the "second industrial revolution" (Anonymous 2002, p. 3). Different participants cast around for different historical models and different kinds of lessons to draw from them. Drexler, for one, usually points to fields – such as space travel, computing, or aviation – with individual, visionary founders (Goddard, Babbage, da Vinci) who were unsuccessful in their own time but eventually proven correct. For investors, or those trying to attract capital, the relevant examples are the rise of the biotech industry, the dot-com boom and bust, or the law-like progress of semiconductor manufacturing. Finally, those who are trying to build national infrastructures *for* nanotechnology, or who are trying to make nano part *of* the global economy, often draw analogies to the giant technological systems of the past.

There is a curious, though surely quite common, mixing of technological and social determinism in this way of arguing. On the one hand, it is clear that nano is not completely determined on its own merits; societies have some choice in molding it to look more like some historical models than others. Yet, proponents and critics both seem to say that

[17] My thanks to Steve Hilgartner for discussions on this topic.

once we figure out whether nano looks more like the computer industry or the electricity industry or the biotech industry then we can predict how it will proceed. Societies have some choice at the highest level (do we do nano at all?), but once they dip their toes in the water they will be swept along; and if they do not jump in the river now, their competitors will quickly outdistance them. Take, for instance, this assertion from a supporter of the US "21st Century Nanotechnology Research and Development Act":

> From the dawn of modern agriculture to aerospace to the launching of the Information Age, government support has been a powerful catalyst to drive basic research and accelerate technology from the laboratory to the marketplace. In industry after industry, one sees the same pattern: federal dollars encourage early discoveries in a new technology, which then attracts private investment, which then grows into a successful industry, with large employers and many jobs [...] We are now at a critical juncture in our technological evolution, and timely passage of this bill will go far to assuring American leadership in the global economy [...] We see other governments of the European Union and East Asian nations investing heavily in major nanotechnology research and development centers. The hard reality is that the worldwide race for preeminence in nanotechnology is on, and America must push to stay in the lead. [Swami 2002]

Indeed, this is exactly the sort of reasoning Drexler uses to motivate the founding of the Foresight Institute and his continuing efforts to describe the inevitably coming, but still able-to-be-influenced, nano-future:

> Some force in the world (whether trustworthy or not) will take the lead in developing assemblers; call it the 'leading force'. Because of the strategic importance of assemblers, the leading force will presumably be some organization or institution that is effectively controlled by some government or group of governments [...] Design-ahead can help the leading force prepare, yet even vigorous, foresighted action seems inadequate to prevent a time of danger. [Drexler 1990, p. 182]

Drexler and his critics agree, then, that nano is on its way whether we choose to be part of it or not. They agree, too, that when it arrives, everything will be different; society will have to adapt to nano much more than the other way around. Drexler's vision of the post-nano world is perhaps the more sweeping, and it has clearly influenced the vivid, exquisitely imaginative depictions of science fiction writers such as Neal

Stephenson and Kathleen Ann Goonan (Milburn 2002). Interestingly, though, Drexler originally wrote in *Engines of Creation* that a post-nano future would leave us *free* from technological determinism; we would inhabit a world made so radically malleable by nano that we could be liberated from the constraints of any one technological system:

> [The modern technological] system now sprawls across continents, entangling people in a global web. It has offered escape from the toil of subsistence farming, lengthening lives and bringing wealth, but at a cost that some consider too high. Nanotechnology will open new choices. Self-replicating systems will be able to provide food, health care, shelter, and other necessities. They will accomplish this without bureaucracies or large factories. Small, self-sufficient communities can reap the benefits. One test of the freedom a technology offers is whether it frees people to return to primitive ways of life. Modern technology fails this test; molecular technology succeeds. As a test, imagine returning to a stone-age style of life – not by simply ignoring molecular technology, but while using it. [Drexler 1990, p. 235]

As Stefan Helmreich (1998) has pointed out, this theme of radical liberation made possible by new technologies is common in futurist circles: whether freedom from the earth (space travel), from the body (artificial intelligence and artificial life), or from death (Drexler's most-cherished application of nano is to allow frozen corpses to be reanimated and healed, allowing immortality for anyone born today). The freedom enabled by the massive changes brought on by nano is not particular to Drexler alone, though. For instance, some of his staunchest critics among practicing nanotechnologists and policy makers promote the idea that nano is the key to a transhumanist future, in which the very definition of human capabilities will have to be redefined. Even a die-hard Drexler-skeptic like George Whitesides sees a nano-future that bears little resemblance to today:

> [N]anoscale machines already do exist, in the form of the functional molecular components of living cells [...] What are the most interesting designs to use for future nanomachines? And what, if any, risks would they pose? [...] [A]s for ravaging the earth: in a sense, collections of biological cells already have ravaged the earth. Before life emerged, the planet was very different from the way it is today. Its surface was made of inorganic minerals; its atmosphere was rich in carbon dioxide. Life rapidly

> and completely remodeled the planet: it contaminated the pristine surface with microorganisms, plants and organic materials derived from them; it largely removed the carbon dioxide from the atmosphere and injected enormous quantities of oxygen. Overall, a radical change. Cells – self-replicating collections of molecular nanomachines – completely transformed the surface and the atmosphere of our planet. We do not normally think of this transformation as 'ravaging the planet', because we thrive in the present conditions, but an outside observer might have thought otherwise. So the issue is not whether nanoscale machines can exist – they already do – or whether they can be important – we often consider ourselves as demonstrations that they are – but rather where we should look for new ideas for design. [Whitesides 2001, pp. 78-79]

4. Nano and Special Varieties of Technological Determinism

This quote from Whitesides sums up all three of the arguments used by nanoists of all stripes that fall well within classic notions of technological determinism: that nano is inevitable; that it will develop with its own progressive, internal logic (though we have some choice whether to follow the logic of biology or engineering); and that nano *itself*, beyond the control of society, will completely transform the world. Indeed, with regard to the latter, Whitesides plays with fears of the so-called 'grey goo' problem – a catastrophic scenario in which nanomachines become so completely autonomous and uninfluenced by social considerations that they run amok and destroy life as we know it (perhaps the most extreme form of technological determinism imaginable).

Whitesides also displays some of the peculiarities in the way nanoists handle determinist arguments, particularly in his consistent non-presentism – it is difficult to imagine other sciences where events of billions of years ago would so consistently be invoked unless those events were themselves the objects of study (as is the case in geology or cosmology but not in nanotechnology). I conclude by examining two more tropes that nanoists have applied as technologically determinist arguments, but that they have applied in such unusual ways that they tell us a great deal about the field's epistemic and practical frame.

The first, which has been discussed much more thoroughly elsewhere by Alfred Nordmann (2004), might be called the trope of manifest destiny. Nordmann points out that much of the epistemic shyness of nano research comes from practitioners' conceptualization of the field as focused on a space (the nanoscale) rather than a characteristic set of materials or practices or concepts. Nano is oriented much more to expanding human *control* over larger areas of the nanoscale and the entities that inhabit it than to learning anything fundamental about 'nature' or 'reality'. As we have seen, control over the nanoscale has long been an aim of some of nanotechnology's constituent communities, such as chemistry or surface science; but in those disciplines *control* was seen as a means to generating fundamental knowledge about a few characteristic materials (*i.e.*, about creating an epistemically amenable 'made world'), rather than (as in nanotechnology) as an end unto itself.

Nanoists often represent their relation to this new place, the nanoscale, as one of dominance and entitlement – it is their manifest destiny to explore, control, and remake this undiscovered country.[18] Roots for this trope can clearly be found in Drexler's original formulation of the field; after all, the futurist tradition, particularly with regard to space travel, has long been obsessed with creating new 'final frontiers' where technological achievement necessitates the outward expansion of control and exploration. Nano, at least in the United States, is merely the latest effort to engage what David Nye has called the 'American technological sublime' (Nye 1994) – the attempt, so central to America's self-conception, to create something transcendent and beyond humanity *through* artificial structures.[19] Drexler's early work radiates the technological sublime, with his talk of immortality, space travel, and radical transhumanism made possible by molecular assemblers. Moreover, his description of the imminent development of the nanoscale closely resembles a narrative of American frontier expansion: from the first sighting of land (the imaging of atoms with a scanning tunneling microscope), to interactions with 'natives' (biological nanomachines), to the appropriation of some technologies from those natives and the wholesale importation of simple non-native technologies (nanoscale bearings, gears, *etc.*), and finally the im-

[18] My thanks to Astrid Schwarz for discussions on this topic.
[19] See also Nye 2003 for Nye's take on the role of technology in the ideology of manifest destiny and westward expansion.

position of state control over the lawless nanoscale and widespread industrialization through the proliferation of nano-factories.

Non-Drexlerians, too, see just as certain a manifest nanodestiny. After all, the US National Nanotechnology Initiative calls its founding document 'Small Wonders, Endless Frontiers' (Anonymous 2002) – a combination of the technological sublime, frontier expansion into the nanoscale, and a postwar American tradition, going back to Vannevar Bush's (1945) *Science, the Endless Frontier*, of seeing science as the next arena for the nation's manifest destiny. Nanoists perform this destiny in a variety of ways in their research practices. For instance, in coming of age at the same time as widespread computing, nanotechnology has made much more extensive use of computer graphics than any traditional discipline. When they can, nanoists use this software to render images of their made world as breathtaking landscapes of wide-open vistas, often portrayed in the coloring of the deserts of the American West. Often, such images possess a great deal of visual *éclat*, but are more difficult to integrate with theory than more traditional, non-perspectival representations. At the same time, nanoists often stake a claim to these landscapes by literally writing their ownership right into the material itself – through various nanolithography techniques they can, and do, inscribe their names, their favorite phrases, and, inevitably, a series of flags, maps, and patriotic proclamations. Again, this goes to the epistemic heart of nanotechnology – it is a field where 'proof' can be achieved just as readily by writing one's name as by more traditional methods for assuring the rigor of knowledge. It is necessary only to show that one *owns* a patch of the nanoscale to have contributed to nano's body of knowledge.

The second, related, trope stems from nanoists' predilection for what I have called elsewhere 'nanopresence' (Mody 2004). Nanopresence is, basically, the endowment of nano-objects with familiarity, tangibility, and even personality – the creation of a sense that they can be touched, that they are ordinary and quotidian objects of interaction. As the name implies, nanopresence owes some debt to Heidegger's thoughts on the nature of technology and his distinction between ready-to-hand and present-at-hand (Heidegger 1962). In Heidegger's formulation, technological artifacts have two quite distinct phenomenological casts – one we experience when we regard the artifact as an object, something that can be theorized about, that can be thought about apart from the act of actually using it; the other is the artifact as we experience it when we are using it, when we and the tool become extensions of each other and we cannot pause to consider the tool apart from how we actively engage with it.

Nanotechnology can, in many respects, be seen as the coordinated attempt to recast nanoscale objects as ready-to-hand tools, to move past the theories and epistemic pretensions of nano's constituent communities and instead use their knowledge to actively engage with the nanoscale. Interestingly, 'handedness' has a very long history in nanotechnology. In Richard Feynman's original 'There's Plenty of Room at the Bottom' speech, he lays out a vision of miniaturization in which he imagines a linked chain of progressively smaller 'hands' that allow us to make progressively tinier bits of the world 'ready-to-hand'.

> How do we make such a tiny mechanism? [...] [I]n the atomic energy plants they have materials and machines that they can't handle directly because they have become radioactive. To unscrew nuts and bolts and so on, they have a set of master and slave hands, so that by operating a set of levers here, you control the 'hands' there, and can turn them this way and that so you can handle things quite nicely [...] Now, I want to build much the same device – a master-slave system which operates electrically. But I want the slaves to be made especially carefully by modern large-scale machinists so that they are one-fourth the scale of the 'hands' that you ordinarily maneuver. So you have a scheme by which you can do things at one-quarter scale anyway [...] Aha! So I manufacture a quarter-size lathe; I manufacture quarter-size tools; and I make, at one-quarter scale, still another set of hands again relatively one-quarter size! [...] Well, you get the principle from there on. [Feynman 1999]

As Colin Milburn and Ed Regis point out, Feynman probably got this idea from a short story by Robert Heinlein. This is not unusual for the field; indeed, it is one of the oddities of nano that it relies so much on science fiction to supply thought experiments and fodder for 'proofs of concept'. It is perhaps not surprising, though, that nano, with its predilection for simulation and the re-enchantment of the material world, should recognize an affinity with fiction, the art of making the unreal seem experienced and ready-to-hand.

Social constructionists have critiqued Heidegger's formulation as containing its own kind of technological determinism – the tool that is ready-to-hand seems pinned to one and only one use, whereas with most technologies users show a great deal of flexibility in alternately regarding and using artifacts in idiosyncratic ways. Analysts interested in exploring this issue and pushing the Heideggerian interpretation toward a more nuanced position will find exquisite material in nanotechnology. On the one hand, nanoists have really embraced the handedness of Feynman's original vision. For instance, almost incontrovertibly the most famous nano image thus far produced is Don Eigler's (Eigler & Schweizer 1990) 'IBM' written with individual xenon atoms positioned by a scanning tunneling microscope (STM). Eigler has his STM set up such that one can simply move the STM tip around with a mouse, click on an atom, drag it to where it should go, and release it. It is almost impossible when doing so to think of the atom as an object of theory, as the heuristic fiction so beloved of positivists a century ago. Instead, mouse and atom are simply ready-to-hand, ready to be moved around, placed into various two-dimensional structures, and generally experienced as a bright spot on a computer screen with which one has some haptic engagement.

Other nanoists take this several steps further. Among nano experimentalists who specialize in building very high-end instrumentation (particularly in the scanning tunneling and atomic force microscopy community) there has been a rush in the past few years to incorporate more and more sensory engagement into their instruments, to make the nanoscale ever more ready-to-hand. Builders of molecule pullers, such as Paul Hansma (Viani *et al.* 1999) and Hermann Gaub (Clausen-Schaumann *et al.* 2000), for instance, have designed instruments that slowly pry apart the internal domains of complex biomolecules. Some of these pullers have built-in resistance on the controls – the operator can actually 'feel' the domains popping, rather like feeling the jerks of a fish caught on the end of a line. Other pullers have a simple circuit that allows the shaking of the puller cantilever to be translated into a sound; operators can *listen* to the molecular domains popping. One puller designer describes how these instruments provoke a feeling that the nanoscale is ready-to-hand, and how this handedness is epistemically (and commercially) useful:

> It's really good at [trade] shows too, because if you're actually introducing a subject to somebody, thermal noise for example, it's one thing to explain it to them, it's another to hand them a pair of headphones and say 'look, this is what thermal noise is' and you can explain the concepts of damping and things like that and how the spectrum shifts because it's totally obvious when you just hear it, it's like 'yeah of course, that's what's happening'.[20]

Perhaps the most well-known attempt in this direction is the Nanomanipulator at the University of North Carolina (Guthold *et al.* 2000). There, Rich Superfine's group has built an atomic force microscope with special haptic feedbacks and virtual reality controls. Users can 'stand' in the landscape of the nanoscale, they can 'feel' how rough or smooth nanoscopic surfaces are, and they can even nudge nano-objects (such as buckytubes) around.

At the same time, nanoists enjoy playing with the handedness of the nano realm by pushing their audience into an ambiguous state where images and representations oscillate between the ready-to-hand and the present-at-hand. Witness all the nano-plows and nano-shovels and nano-trains and abacuses and whatnot – all these nano-artifacts seem like tailor-made tools in Heidegger's simple, ready-to-hand kit. Again, this plays well to nano's epistemic shyness; just seeing an image of nanoscale abacus or guitar or train and apprehending these objects instantly *as such* makes the audience's first experience of them an engaged, ready-to-hand involvement rather than distanced, theoretical or conceptual observation. Yet, that instant recognition carries with it a simultaneous wonder and shock – the nano-object is all too familiar, yet all too different and exotic. The nanoscale has become a place that tourists can visit, where everything is different, yet exactly the same – all the building blocks are atoms, at which we should wonder, but they are being used to make ordinary, familiar, everyday objects whose use is something we intuit rather than theorize about.

For now, I have to turn my spade in digging at this phenomenon – I am not sure how to read the handedness of nano, though it seems clear many layers of practice and rhetoric are involved. What I would encour-

[20] From an interview with a commercial probe microscope designer, March 23, 2001.

age as this, hopefully, becomes a topic for analysis is that we remember that nanoists' tweaking of intuitive understandings is done, usually, in a spirit of fun and play. From Feynman's first playful call for researchers to make tiny motors and write words on the head of a pin to today's silicon zoo of tiny guitars, flags, signatures, and so forth, nanoists have let themselves be seen to be having fun. The debates between Drexler and his critics have taken an acrid and unpleasant tone in the past few years, but analysts of nano should not take this to be the whole show. For many practitioners, nano is still a bit of a put-on, a bandwagon whose content they do not quite understand but which they are trying to make the best of. This 'making do' has a distinctively light-hearted cast, as practitioners trot out parlor tricks that double as proofs of concept, and as they avoid interdisciplinary frictions by sticking to relatively uncontroversial play. Nanoists have created a technological sublime, but in shrinking the dimensions of the sublime to such an extent, they have made it provoke both awe and a bit of laughter.

More generally, we should keep this playfulness in mind in examining what uses nanoists make of determinist arguments. For many nanoists, nano *is* inevitable and (nano)technology does drive (some of) history. Yet there is little fatalism in the nano community; practitioners seem more eager to ride the tiger of nano than they are apprehensive that they will be crushed by it. Nanoists seem, for instance, willing to *play* with the design logic made possible by the analogy between biological and artificial nanomachines. While they agree that everything will change because of the new technology, nanoists have used this agreement to inspire both serious discussion of *how* to prepare, as well as dramatic, sometimes inspiring, flights of fancy about *what* to prepare for. Nano is still an incoherent mass of often conflicting communities. Determinist arguments advance the particular interests of various kinds of practitioners within this mass, as well as various critics and supporters on the outside. If we are to understand nano, we must see how participants build these arguments into their practices, and how they do so in ways that allow them to live with the field's current incoherence.

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CHAPTER 6

WHEN IS AN IMAGE NOT AN IMAGE?

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It is argued that the pictures generated by scanning tunneling electron microscopes are not images. Rather they should be regarded as 'imaginings'. That they are sometimes proposed as images has two negative consequences: (1) It suggests that we have the kind of epistemological access to the nano scale that we do not, and (2) it has ethical consequences to the extent that we fail to tell the public the truth about what we can and cannot know.

1. Introduction

The challenge is to tell the truth. In the world of nano this is not as easy as it sounds. Take, for example, the question of images claimed to represent what some nano configuration or another looks like. It is alleged Scanning Tunneling Electron Microscopes (STEMs henceforth) produce such images. Let us rehearse what happens: According to Rasmussen and Hawkes (1998, p. 383):

> [...] 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...interaction of the beam with the specimen 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 [...] All electron microscopes depend on the capacity of magnetic and electric fields to alter the path of electron beams according to the laws of optics.

Using an STEM is one of the ways it is said that we can see what is going on at the nano level. However, I am suspicious. Or, to put it in a less antagonistic way, to accept this claim will, I believe, force us to expand or change our understanding of what it is to see something, and in this case in particular, to understand what constitutes an image. There is nothing wrong with this. The meaning of words do change over time – they often expand, as the meaning of 'men' in 'All men are created equal' has expanded to include African Americans, other minorities, and women. However, we often do not pay attention to the fact that while we continue to use a word whose meaning we think we understand, in this instance 'see' and 'image', we also sometimes extend the meaning of that word by applying it to novel situations where they only apply at best metaphorically, as I argue below. Eventually what is at first a metaphorical extension of the meaning of a term may become an accepted part of the meaning of the term, but we should be sensitive to the fact that the meanings of words change over time. This claim is part of a more general thesis I am developing: to explain what we are doing when we employ novel instrumentation, we often employ words whose meanings we already understand in an effort to characterize the sort of thing we think we are now doing with this new instrument, despite the fact that seeing through a microscope is not the same as opening one's eyes and seeing a tree in front of me, if we are to adhere to a strict sense of 'seeing'. I argue elsewhere that in extending the meaning of words metaphorically we also change the meanings of the family of concepts with which they are associated, such as evidence and explanation.[1]

If we take Rasmussen and Hawkes seriously, what the electron microscope does is to produce an image. But, I suggest, this is unintuitive for the reasons given below. Furthermore, to claim that an image is produced, suggesting by that that the image is a genuine and *realistic* representation of what is really there, has serious ethical and social consequences. I want to talk about images first, and then I will turn to some of disturbing consequences of thinking about 'seeing' by way of an STEM.

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[1] This thesis is being developed in a book length manuscript under construction tentatively entitled *Seeing Near and Far, A Heraclitian Philosophy of Science and Technology*.

Imagine if you will, a very accurate tennis ball machine. It is a device that shoots tennis balls at you so you can practice returning them without having a serving partner. Lets assume you take this machine and aim it at a wall built from rough hewed stone. Your job is to construct an accurate representation of the surface of the wall simply by observing the directions of the balls as they bounce off the wall. Well, clearly you need some help to do this. You need to know a lot about the physics of objects colliding and how irregular surfaces change the vectors, *etc.* You also need to know a lot about translating what you see happening to the balls after they collide with the wall onto paper in a way that captures not the picture of the ball shooting off in this direction and then that, but the texture of the surface of the wall. It is not as if you are directly drawing what you see when you look at the wall. You are interpreting the action of the balls as indicating something about the surface and then you are putting that guess down on paper. That, with some minor modifications, is what the alleged image produced by an STEM is supposed to have accomplished. But instead of a person doing the drawing, a computer program does it. And, we are asked to consider the result an image of the surface. Take your hand, if you will, and run it over your shirt. Now draw what you felt. It is not easy is it? That is why I am asking this question: when is an image not an image?

2. What Is an Image?

Let us begin by trying to figure out what an image is. This is not an easy task, for we tend to use a substantial vocabulary of what we often take to be more or less synonymous terms when talking about what STEMs produce. Thus, there has been a lot of loose talk about images, representations, *etc.* Terms like these have been casually interchanged, mangled, and generally semantically violated. I will not claim that I offer much of an improvement – but I at least want to alert us to the problem of image talk. In cases like this, my preferred method is to work our way toward a common sense understanding of what ought to count, in this case, as an image.

My intuitions tell me an image is a representation – where a representation is the result of an attempt to capture the salient features of an object, scene, state of affairs, or idea, *etc*. Fortunately or unfortunately, what constitutes a salient feature is a function of the person or persons constructing the image. As a first pass, consider the following items as images:

- Sculptures
- Photographs
- Portraits
- Still lives
- Landscapes
- Various kinds of drawings
- Motion pictures – both animated and 'realistic'
- Visualizations inspired by poetry
- Visualizations inspired by music
- Plays
- Operas
- Ballet and interpretive dance

If we accept the fact that these are images, then a Picasso such as the Guernica counts as an image, but it would seem that a Jackson Pollack does not only in so far as it is unclear what a Pollock is supposed to represent.[2] This entails declaring that to be an image is to be representational. But it says nothing about what makes something representational. That said, nevertheless, it is not shocking to note that not all paintings are images, where a painting is nothing more conceptually complicated than paint deliberately applied to a surface. But, if it is true that not all paintings are images, especially when they are not representational, have we not found a way into our topical question, when is an image not an image? It looks like we could reasonably say that an image is not an image when it is not representational. On the other hand, doesn't that just beg the question? After all, it isn't at all clear that for an image to be an image it must be an image of something. When you think about it, on the one hand, it seems arbitrary to demand that images be representational, but, on the other hand, to do so seems to beg the question. For example, consider the following as candidates for being added to the list above.

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[2] If turning to art is seen as somehow cheating, it is important to remember that the creation of images began in art.

- Diagrams
- Flow charts
- Data tables

The interesting feature of these sorts of things is that while they are not representational, they do convey information in visual form. For, on the surface at least, it seems as if these forms of images have a different semantics than written language. The important point however, is that they do seem to have a semantics, for they do manage to convey information. The unresolved problem that remains for us is how to determine if the image is an accurate representation. So, if we accept this approach, then one answer to our question is that an image is not an image when we do not know if it is representational but conveys information nonetheless.[3] With your permission, let us accept that for the time being as a first pass.

3. Epistemology of Representations

However, that just moves us back one step, for now we can re-ask the question that our quick look at electron microscopes motivated: when is an alleged representation a representation? The point here is epistemological.

I think it not too radical to suggest that seeing is a complex activity in which after learning to see that as a tree or as a car, we forget that we had to learn that. In our mature state we see the world around us and assume we see it for what it is. That is why philosophical questions like 'but are you seeing what is really there?' seem so silly. But, on reflection, we also understand that seeing is an interpretive process and that we bring to our seeings a load of background information and experience. Elsewhere I have argued that to call it a seeing by way of images generated by an electron microscope is a metaphorical extension of our common sense notion of seeing (Pitt 2004). But, I have now come to realize that there is a lot involved in appealing to metaphor here. If we unpack it, as I would like to start to do here, we can see that to understand through metaphor is

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[3] Yes, 'information' is not defined. But, I suggest, we have to start somewhere. If we succeed in making progress by proceeding in the manner suggested we can always return and fine-tune the argument by going deeper into concepts like 'information'. Call this approach 'conceptual boot-strapping'.

to do a number of things at once. First, we use metaphor to access what is new and different because in a metaphor we take what we know and apply it to the unknown and say that the unknown is like the known in these various ways. It makes the new seem familiar and approachable, usually. Sometimes, as in the example of the tennis gun above, it makes the unknown or the new seems even stranger than we first thought. Second, when using metaphor to make the new and unknown approachable, we are also asked to accept that certain things that we do not really understand are reliable. Metaphors tell you this is like that in certain limited ways, and by the way, just accept that everything else is working just fine, however that happens. In the case of the electron microscope, when asked to accept what it produces as a representative image, we are also asked to accept the fact that the assumptions built into the manner in which that image is constructed are correct and reliable. To use the language of science studies, we black-box the process and merely look at the result. But to call the image created by the electron microscope an image is to ask us to accept in some fundamental way that the science is sound and the technology (programming?) reliable and the people manipulating it reliably are honest.

But, I suggest, this ought to be a lot to ask. What is interesting is that it appears that it is not. It is a measure of the success of the scientific establishment that we, the general public, tend to accept claims based on the use of increasingly complicated instruments working in the realm of the frontiers of science with increasing readiness. That is, the more complicated the science and the more simplified the public explanations, the more readily we tend to accept those fantasies. That is why it is important to know what really happens in an electron microscope before buying into the claims with which it is associated. Before I explore what that ominous sounding remark is supposed to suggest, let me give you just one example of the kind of phenomenon to which I am referring. I think we are all in awe of the images sent to us by the Hubble Space Telescope. The ones of the horse head and crab nebulae are just breathtaking – and the colors are truly inspiring – just one catch – the colors are computer generated. When I tell my students that, the looks on their faces resemble the one when they learned that there is no Santa Claus. What got me going in this direction was a presentation at the Conference 'Discovering the Nanoscale' at Darmstadt in October 2003 that revealed that the picture of the nano-scale IBM was not just constructed through the assistance of computers, but it too was computer enhanced – with the colors added, for example. This, it turns out is a pervasive problem; even the choice to use grey-scale is a decision to create the image in a certain way. So when we say of an image that it must convey information, should we not also be asking (1) whether there is a claim that reality is being representing, and (2) is the image presented of something real or imagined? Perhaps, then, should we not be asking this slightly different question: When is an image *not* an imagining?

The issue here is both epistemological and ethical. The epistemological issue concerns, for lack of a better term, noise. We are familiar with the problem of filtering out noise when searching for an identifiable signal. The problem is multi-faceted: what to filter out and on what criteria, what to amplify, to what degree, *etc.*? The problem with color-enhancement and sharpening up of nano-images is that we don't yet know what is important and what is not. Further, the problem may become intractable since we do not have a god's eye view from which to determine if we have it right. In a certain sense then the problem here is an *in principle* lack of access, or to put it differently, a case of very strong underdetermination. But is this really a problem? We have in-principle-lack-of-access to many astronomical events, like the big bang, and we still claim to know a lot about the early universe. We have images from the Hubble of far distant galaxies that we can never get close to in person, and yet we can still understand a lot of what is going on there – or so we think.

My worry is that, unlike the 'images' from the Hubble, we have relatively little experience in enhancing the images produced by STEMs. We have ways of checking up on the Hubble images. For example, we can experiment with filters and use smaller telescopes here on earth to check out their effect when we look at mountains or trees. However, although we have many experiences with so-called images from STEMs – we do not have such successes in fixing them up. This is, in a curious way, a new version of the what-are-we-going-to-do-when-we stain-a-specimen-that-we-are-going-to-examine-under-a-standard-microscope problem (*cf.* Pitt 2005). Computer enhancement of images is fun, especially with all the nifty colors we can use. But is it producing an honest replication of the object/surface in question? Clearly not, and that raises the ethical issues.[4]

4. Ethical Issues

The ethical issues arise in two forms: strong and relatively minor. The relatively minor issues have to do with the relationships between science and the public. For example, we are misleading the public when we fail to disclose fully what we are doing when we computer enhance our electron microscope constructed images. The strong ethical issues center around the fact that these images raise false expectations. Among them, that we know more than we do. The presentation of these beautiful pictures suggests in a very strong way that this is indeed what it is like out there, in there. But more importantly, they mislead in crucial ways. The beautiful computer simulations we see of nano interactions are not only beautiful simulations, they are also almost heart-stopping in their ability to feed the hubris we sometimes exhibit when employing the newest technological toys, computer and advanced programming techniques, among them. Please do not get the wrong impression – I am not suggesting that we should not employ the latest technologies in science. What I am talking about is the illusion we create not just in the general public but also sometimes in the practicing scientific community. The illusion is that we know more than we really do. Never underestimate the ability of human beings for self-delusion. These computer generated and enhanced pictures suggest that the world is at rock bottom a simple place. It can be pictured as individual atoms resting on stable fields that we can manipulate at will, twirl them, enlarge and narrow them, put them to music, make them dance, when in fact nothing of the kind is the case. The world

[4] The "Clearly not..." might be considered contentious, but with a little expansion, I believe it will be obvious. Consider, for example, that the surface on which nano scale objects exist is at the interface between the quantum domain and the atomic. We have no idea how to visually represent what happens in the quantum domain, so we cannot say we are accurately representing the surface on which the atomic structures we are picturing sit. If we cannot claim to be accurately depicting the surface, then how can be sure of the space in which nano structures function, and if that is uncertain, so must be our representation of the nano structures themselves.

at the nano and quantum mechanical level is buzzing, shifting, and constantly in motion in non-linear and non-classical causal fashion.

This is all heading in one direction. It is not just misleading to suggest that the world is simple at the bottom. It is epistemically suspect. It employs a crucial but faulty assumption. It is the assumption that the world is better understood if we simplify our presentations of it. I humbly suggest that this is wrong-headed. It may in fact be helpful to extract some feature of the world, color it non-natural colors, and play with it. But it is more important to put that heuristically altered item back into the buzz and try to understand it in that environment, its 'natural' environment. Most importantly it is crucial that we explain to the public and our colleagues the purpose of the heuristic move and what it reveals about what is really going on at the bottom.

So what is wrong with simplification? It suggests that we know more than we do and, crucially, that we can do more than we can. The scientific community has done a good job of convincing the public that it has god-like properties – but this situation presents a double-edged sword; the public feeds on gods that fail. Be honest about the mess and you will repeat positive rewards. Further, it is not the simplicity of the universe that makes it the object of our enquiry, it is the complications, the unanswered questions, the mess of it all. The more we look, the more complicated we find it to be. If you cuddle the public and give them simplicity and then in the crunch, when, for instance, in the hospital, you say, well it is more complicated than that, then you will have failed miserably. I love the pictures, but they are not representations. They are heuristic imaginings, extended metaphors, if you will, and they should be recognized as such and treated that way. How will that affect the way in which the work of science is perceived? My guess is that it will enhance it. Doing science is hard work. The public should know that and when they do the successes of science will be all the more appreciated. Telling the truth is also hard.

5. Conclusion

To conclude, let me summarize. The question is, in what sense is a STEM computer generated picture of nano structures an accurate representation of what is there? Following some discussion of how 'seeing' using a STEM involved a metaphorical extension of the concept of 'seeing', it was argued that to be a representation the image must convey information. The problem is in understanding what the information is conveying, since we cannot directly access the domain that we are purporting to represent. The problem is not that we do not know how to interpret what is presented to us as an image, but, rather, that we have loaded the creation of the representation ahead of time without being able to know if our guess that this is what the STEM and its fellow traveler computer programs are producing is an accurate picture of what is really there. The reason why there is so much discussion of when an image is an image is that this really is a question of whether or not the image that is produced is an accurate portrayal of something that is really there or a mere fabrication.

Consider one last attempt to convey a sense of the magnitude of the problem. If we do a random sample of some domain and then plot the results in three dimensions, assuming that is sample is truly random and that there is no natural clumping of the data, which curve is the correct one? We can draw an infinite number of curves through those data. Without an independently certified decision procedure for selecting the correct curve we are simply left with the data. The problem is further complicated by the fact that there are ethical dimensions. (1) To say that this is what is taking place at the nano-level, is to lie, since we don't, in fact, know that to be the case. (2) To present these standard, nicely colored, enhanced, and simplified pictures as genuine representations of what is going on at the nano-level is to claim falsely that nature is in fact simple and clean and neatly colored at that level. But, nature is not neat and tidy at that level. To suggest otherwise is to mislead by way of making it appear that there are simple answers to very complex problems. That approach gets us into trouble at the political level and it should get us into equally big trouble in our epistemology.

Acknowledgments

My thanks to Thomas Staley for his assistance. All mistakes are my own.

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CHAPTER 7

CHANGES IN THE DESIGN OF SCANNING TUNNELING MICROSCOPIC IMAGES FROM 1980 TO 1990

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This chapter investigates nanotechnological images as carriers of variable, dynamic knowledge. In a case study, it analyzes changes in the design of images based on scanning tunneling microscopic investigations between 1982 and 1990. The time period saw a gradual transition to an image design in which the atom itself appeared to have been made visible. The shift involved questions of how to image and how to represent atoms. This chapter argues that image designs were developed to make scanning tunneling microscopic images compatible with nanotechnological visions. Thus, image design contributed to the view that tunneling microscope is a central scientific instrument for visionary nanotechnology.

1. Introduction

The study of images in the history of science has been a subject of continuous interest for the past twenty years, and these studies have come to encompass numerous case studies and have undergone much differentiation.[1] The majority of these studies examine images as representations that are transformable within chains of representation.[2] Only rarely are

[1] For an overview of this topic see Lynch & Woolgar 1988, Pang 1997, Gugerli & Orland 2002, Heintz & Huber 2001, Hentschel 2002, Rasmussen 1997, Latour & Weibel 2002.
[2] The probably most influential contribution on this topic is Latour (1996), *cf.* also various articles in Lynch & Woolgar 1990.

the formal aspects and the design of the images themselves analyzed. Since the declaration of the 'Pictorial Turn' (Mitchell 1992), respectively the 'Iconic Turn' (Böhm 1994), however, it has become clear that there is a desire and a need to address the images themselves and to take them seriously as a medium of knowledge, instead of underestimating them as mere illustrations.[3]

Taking this approach, the following study investigates the formal aspects and design of scanning tunneling microscopic (STM) images. Images created by the scanning tunneling microscope and other scanning probe microscopes are omnipresent in current scientific research routines, popular science articles, and visionary utopias of nanotechnology. The tunneling microscope has been repeatedly described as the prerequisite and trigger for the development of nanotechnology, but there has been justified criticism of this 'standard story'. Some critics have pointed out that the possible applications of the STM are limited and that other technologies like electron microscopy have great potential (Baird & Shew 2004). Others emphasize the discrepancies between the actual possibilities of STMs and Eric Drexler's nanotechnological visions (Hessenbruch 2004). Despite these justified doubts, the STM has been able to occupy a prominent position. Why this is so is a question that remains to be investigated further.

In the following, I argue that image design contributed fundamentally to the prominent status of STMs within nanotechnology. In order to do this, I will show how this image design changed in the time period from 1982 to 1990. This time period saw the gradual development of an image design that portrayed the object of study – in this chapter I will be talking about individual atoms – according to its supposed natural appearance. Thus, around 1990, a type of image design had emerged, in which the creation process was no longer manifest in the images in the same way as before. Removed from the context of their experimental construction, these images consequently acquired their own suggestive power. Individual atoms were portrayed technical building blocks that could be made visual through instruments and that had been given an external

[3] For a review of developments since the declaration of the iconic and pictorial turns see Bredekamp 2004.

form. Thus these images became compatible with nanotechnological visions.

2. The Instrument in the Image

In their first publications on STM, Gerd Binnig, Heinrich Rohrer and their colleagues[4] described its mode of operation with the help of a sketch (Figure 1, Binnig *et al.* 1982a): A tip is placed over the conductive surface that is to be examined. When a voltage with the intensity of several volts is applied, a current flows between the tip and the surface, overcoming the vacuum, that is, the non-conductive gap between the tip and the surface. According to the classical physical approach, electrons are unable to bridge the potential barrier represented by the vacuum. It is only in accordance with quantum mechanical interpretations of probability that they are able to *tunnel* through this potential barrier with a certain degree of probability. For this reason, the current between the tip and the surface is called the *tunneling current*; the instrument is called a *scanning tunneling microscope*.

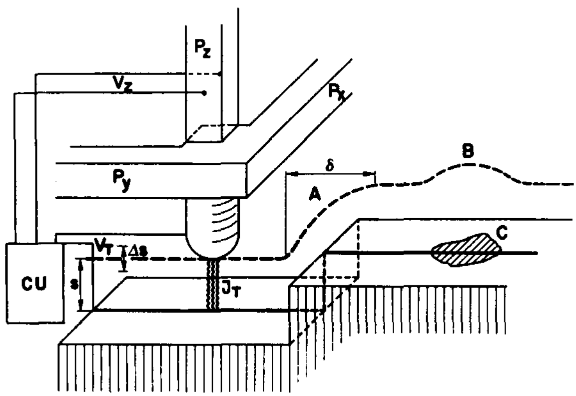

Figure 1. The principle of the scanning tunneling microscope as sketched by Binnig and Rohrer in 1982 (courtesy of IBM research center Zürich).

The current flow is dependent on the gap between the tip and the surface. When the tip is moved over the surface, the current flow changes. The

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[4] Although it is not my intention to perpetuate the tradition of unnamed assistants in this paper, for the sake of readability, I will be naming only the experimentators.

vertical position of the tip is then readjusted by an electronic feedback current, so that the current flow once again reaches the originally chosen value. The signal is generated by the vertical movement of the tip while it laterally traverses a surface. In their sketch, Binnig and Rohrer describe two distinct cases: On the one hand, the current can increase at a step, since the gap between tip and surface decreases. The tip is then routed upwards (Figure 1, A). On the other hand, the electrical properties of the surface can alter the current, so that once again the tip height varies in order to compensate for variation (B). Although Binnig and Rohrer referred to these two causes in their first publication on the scanning tunneling microscope, it became apparent in the first few years of STM research that this separation could not be maintained. Even in case A the electrical properties of the surface and the tunneling current arising from it always provide the signal. The course of the surface is only defined by the selection of the tunneling current that is to be kept constant and by the applied voltage.

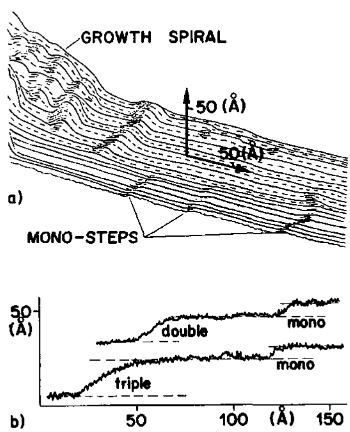

Figure 2. Representations of scanning tunneling microscopic investigations by Binnig and Rohrer in 1982 (courtesy of IBM research center Zürich).

In addition to introducing the instrument in their first publication on "surface microscopy using vacuum tunneling" (Binnig *et al.*, 1982a, p. 57) Binnig and Rohrer also visualized the scanning tunneling microscopic investigation of a calcium-iridium-tin crystal (Figure 2). The lower diagram shows two single scans of the surface, in which the movement of the tip has been traced by a shaky zigzag line.

This shaking must be distinguished from the several clear raisings of the tip to a level two to three times as high, which given as 6.7 Å in the article. This height agrees in general with the value of 6.87 Å, which was already established in crystallography as the step level of this crystal's individual atomic layers. The heights and distances measured with the STM are derived from the voltages in the piezo elements moving the tip. Thus, the magnitudes of the scanning tunneling microscopic images were known from the outset. For this reason, the scale of dimensions, which was calculated from the voltage, could be given on the axes of the graph.

While these two single scans have the character of two curves in a diagram, in the upper image in Figure 2 several scans are related to each other. This image depicts a surface scan. Consequently, the recapitulation states: "Scanning tunneling microscopy yields a true three-dimensional *topography of surfaces* on an atomic scale [...] with the possibility of extending it to work-function profiles (fourth dimension)" (Binnig *et al.* 1982a, p. 60; italics by JH). In conformity with the sketch of the mode of operation of STMs, distinguishing between case A and B (Figure 1), topography and the electronic parameter of the work-function are described here as separately measurable phenomena.

As part of the first wave of publications on scanning tunneling microscopy in 1982/83, Binnig and Rohrer's group also published an investigation of 7 x 7 silicon (111), which forms after heating in ultra-high vacuum (Binnig *et al.* 1983). Binnig constructed a three-dimensional model based on the line picture of this measurement. Binnig and Rohrer have described the photo of this model (Figure 3) as "a shining example of an STM graph" (Binnig *et al.* 1982b, p. 732). It was also used in publications on the award of the Nobel Prize to Binnig and Rohrer in 1986 (*e.g.* Binnig & Rohrer 1993) and was reproduced in innumerable review articles and summaries of the historical development of scanning tunneling microscopy.

The "relief", as Binnig and Rohrer called it (Binnig *et al.* 1983, p. 120), conveys the impression of a body floating in empty space, its wavy upper surface etched with tracks. The shadows correspond to a light source coming from the right and heighten the impression of spatiality.

Obviously, shadows have no reality in atomic dimensions, and the instrument cannot leave scratch marks on individual atoms. Through these tracks, however, the principle of the instrument is visualized in the image. It does not suggest a 'true' appearance of the silicon surface. Instead, it traces the trail of the instrument for the observer.

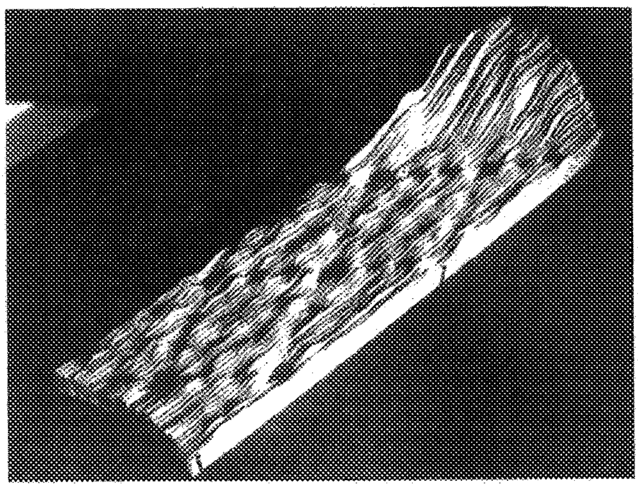

Figure 3. The 'relief' of 7x7 silicon (111), produced by Gerd Binnig in 1982 (courtesy of IBM research center Zürich).

In the text of the article, the authors discuss the position and the distances between the measured maxima and draw comparisons to the maxima pattern in the so-called "milk stools" (Binnig *et al.* 1983a, p. 121) in an already existing model. Only subsequently do they interpret these maxima: "The maxima observed should reflect the dangling-bond positions of the topmost atoms" (Binnig *et al.* 1983a, p. 121). The maxima measured with the STM are thus interpreted as dangling bonds that cause a high tunneling current. According to this careful interpretation, an individual maximum is not an atom as such, but every maximum is assigned to an atom.

In the publication, these results were also derived from a grey-scale image, in which the different heights of the tip are coded with different shades of grey (Figure 4). It has since become conventional to emphasize the respectively higher position of the tip through lighter shades of grey.

In the grey-scale image, the positions of the maxima are definitely more visible than in the relief image. Nevertheless, the grey-scale picture has rarely been reproduced, whereas the 'shining' relief image has been reproduced repeatedly and has become the first *Leitbild* (exemplary image) of scanning tunneling microscopy. Its spatiality and shadows reflect macroscopic visual conventions and aesthetic expectations. It demonstrates the atomic resolution capacity of an instrument that appears to have inscribed itself into the image. The inscription, however, requires interpretation.

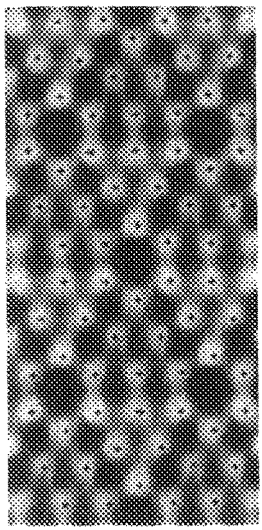

Figure 4. Grey-scale image of the 7 x 7 silicon (111) investigation (courtesy of IBM research center Zürich).

3. The Manifold Possibilities of Turning Data into Images

While in the following years line images analogous to Figure 2 dominated as representations of tunneling microscopic measurements, in the middle of the 1980s different digital STM image designs were tested and publicized. Binnig and Rohrer's group continued to play the role of an avant-garde, in collaboration with the visualization work group at the IBM research laboratory Rüschlikon.

In 1985, researchers working on the scanning tunneling microscope met for a workshop organized by the Zurich IBM laboratory. The papers were published in two editions of the *IBM Journal of Research and Development* Binnig and Rohrer made extensive use of the possibility of color publication in this journal, an opportunity that they did not have in professional journals at the time. Once again they presented an investigation of 7 x 7 silicon (111) with a scanning tunneling microscope (Binnig & Rohrer 1986). In their summary article they discuss the application of STM to create topographical, in contrast to spectroscopic images.

They define topographical images as the result of measurements in which the z-position of the tip is measured dependent on the (x, y) position, whereby the tunneling current is kept constant. Thus, for the investigation of electrical properties, the tunneling current is measured at every position (x, y) dependent on the applied voltage (Binnig & Rohrer 1986, p. 362).[5] Unlike the relief image, the representation from 1985 did not use supposedly three-dimensional imaging to visualize either the topographic or the spectroscopic measurements on 7 x 7 silicon (111). Instead, color-coding was chosen (Figure 5).

In contrast to the grey-scale image with continuous grey-scales in earlier publications on 7 x 7 silicon (111), only four shades of admittedly garish, artificial colors were selected.[6] This type of coding with only a few colors was used several times in scanning tunneling microscopic images in the 1980s, but it did not become standard. The high z-direction resolution obtained with scanning tunneling microscopes could not be adequately represented by a small selection of colors. In these images, the comparison between 'topographic images' and electrical properties stood in the foreground. The earlier suggestion of a 'surface landscape', which conforms to macroscopic visual conventions, was replaced by a design and coloring that creates the impression of artificiality.

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[5] Tunneling spectroscopic measurements already existed before the introduction of scanning tunneling microscopes, but they did not have electrode tips like STMs. These tips made a higher local resolution of spectroscopic measurements possible. For an overview of the current state of research on tunneling spectroscopy at the time of the development of the STM, *cf.* Hansma 1982.

[6] For the original colors of all the pictures, printed here as grey-scales, see: http://scholar.lib.vt.edu/ejournals/SPT/v8n2/hennig.html.

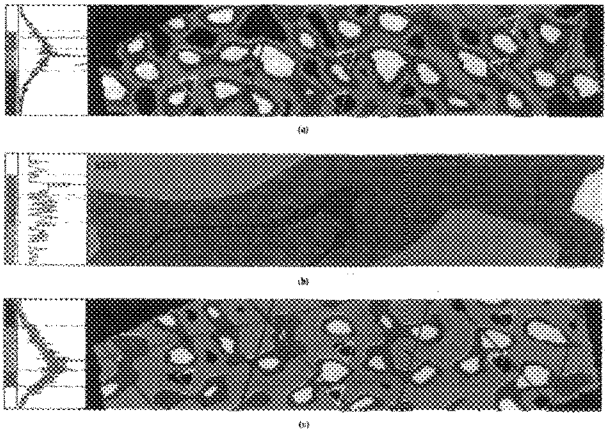

Figure 5. In the original publication four discrete garish colors (yellow, pink, cyan, ocean blue) were used as color-code for this representation of a 7x7 silicon (111) investigation in 1985 (courtesy of IBM research center Zürich, reproduced from Binnig & Rohrer 1986).

In the same article, Binnig and Rohrer describe another study they had made on the surface of graphite (Figure 6). In this study they used a completely different type of image design. The representation includes both implied three-dimensionality and the use of colors. Here, the individual lines do not point to the scanning of the probe tip. Instead, a mesh forms a surface representing points of equal tunneling current between the tip and the investigated surface. The heights were given a geographical color code consisting of only five colors: The lowest points are dark blue, followed by light blue. Then come green 'mountains' that rise into brown and are finally topped by 'snow-covered' peaks.[7] The detail section floats freely in front of a white background, whereby the external form strengthens the impression of perspective. In addition, geometric figures, black and white circles that are connected to each other by lines, are laid over the mesh. Thus, one can discover several characteristics of the visualization of computer simulations in this image: In simulations, calculations are made for defined points on the grid and the results of the next-closest grid points are graphically connected to each other. For that

[7] Erich Stoll, who was responsible for the design of this image, mentioned elsewhere (Stoll 1985) that he consciously chose color-codes used in cartography.

reason a mesh is used. The free floating in space, the use of garish, unambiguous colors and the application of geometric codification can also be found in visualizations done in the context of simulations (Warnke 2002). The image was designed by Erich Stoll, who had been employed at IBM Rüschlikon since 1970 and who had worked on computer simulations until 1982. Since 1982, he had been responsible for the visualization of STM data. He had acquired his know-how in other research areas and transposed their customary design models onto STM images. Nevertheless, such grid representations did not gain long-term acceptance and were only published a few times. The technical effort and the necessary know-how were probably factors hindering their widespread application, but it is also likely that there was no interest in making measurements done with the scanning tunneling microscope look like simulations.

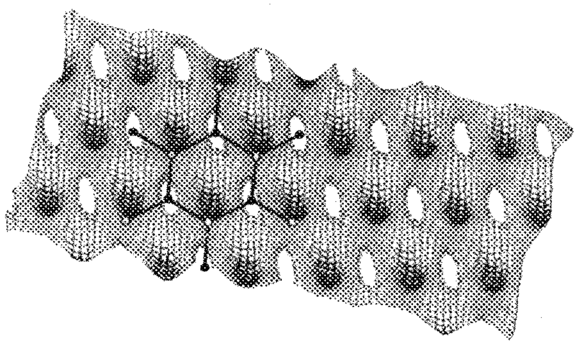

Figure 6. Representation of a graphite measurement using five discrete colors (blue, cyan, green, brown, and bright yellow in the original publication) and three-dimensionality at the same time (courtesy of IBM research center Zürich, reproduced from Binnig & Rohrer 1986).

This investigation of graphite showed that the presence of individual atoms led to a rising *or* lowering of the tunneling current, according to which electronic states the electrons occupied. That is, the tip is drawn downwards or pushed upwards, in order to keep the tunneling current constant. This interpretation of the image relies on crystallographic knowledge about the atomic lattice of graphite. In contrast to the measurement of 7 x 7 silicon, the atomic structure cannot be derived by counting the maxima. Instead, the familiar atomic lattice is represented by black and white points that correspond to the electrical properties leading to the maximum and minimum in the STM image. According to Binnig and Rohrer's definition, these are topographical images, since the z-position of the tip is given dependent on the (x, y)-position. However, Binnig and Rohrer put quotations marks around the word 'topographical' when they describe this image. They write, "It is in effect a typical spectroscopic image" (Binnig *et al.* 1986, p. 362). That is, it is an image depicting the electrical properties of the sample. Here, it is shown in the image that the topography of the scanning tunneling microscope cannot be constructed isolated from, but only as a result of measurements of electrical properties.

Although the color selection is reminiscent of a mountain landscape, the grid representation and the circles laid over the image correspondingly show that this is a measurement that is to be interpreted. In the mid-1980s, as the analysis has shown, the creators of the images discussed here chose a form of design that emphasized that the images did not reproduce the surfaces, but, instead, required interpretation.

4. Apparent Reproduction of Atoms

As tunneling microscopy became more widespread, further samples were investigated. The physical properties of the samples were not always at the center of attention. In contrast, often well-characterized samples were used as a way to further explore the properties of the tunneling microscope.

Randy Feenstra, Joseph Stroscio, and their colleagues examined for example GaAs, a III-V semiconductor, at the IBM research laboratory in Yorktown Heights from the mid-1980s. They ascertained that in a scanning tunneling microscopic measurement of a GaAs (110) surface, the gallium atoms could be identified with a maximum and the arsenic atoms with a minimum in the STM images. A line representation and a grey-scale representation of the same measurement were published adjacent to each other (Figure 7). The image was published in 1988 (Stroscio *et al.* 1988), as grey-scale images were replacing line images as standard representations. As in the graphite representation from Binnig and Rohrer, in this grey-scale image, the previously known atomic lattice is symbolized by black and white circles for the respective atoms.

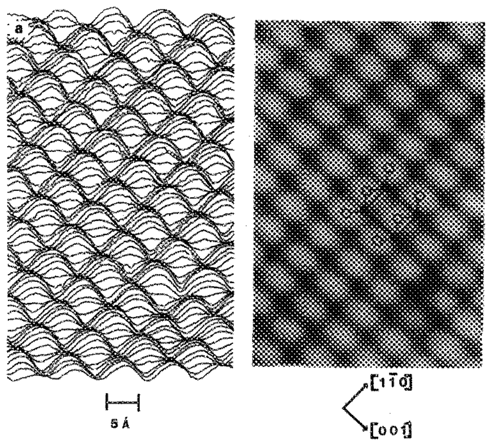

Figure 7. Line representation and grey-scale representation of a GaAs measurement in 1988. (Reproduced with permission from Stroscio *et al.* 1988, © by AVS The Science and Technology Society.)

In conformity with theoretical predictions, they were also able to show that when the voltage between tip and surface was reversed, conversely, gallium atoms were associated with minima and arsenic atoms with maxima, when the tip was again guided over the surface under constant current (Feenstra *et al.* 1987). Figure 8 shows the results of two measurements with opposite voltage in grey-scale images.

In each image, the square indicates the respective location of the measurement and shows that maxima become minima and vice versa. Feenstra, Stroscio, and their colleagues subsequently created a composite image from two measurements with different polarity by using the respective parts that showed the atoms as maxima (Figure 9). They marked the sections of one measurement in red and sections from the measurement with reversed polarity in green. In the publication, they describe the image as follows: "The unoccupied states are colored green, the occupied states are colored red [...] The calculation shows that the occupied state density is concentrated around the surface As atoms, and the unoccupied density around the Ga atoms" (Feenstra *et al.* 1987, p. 1193). They thereby show that they have compared the data from their STM measurements with previously existing theory and have interpreted their measurements on this basis. From these considerations they drew the conclusion that the data from their measurements identified the location of individual atoms.

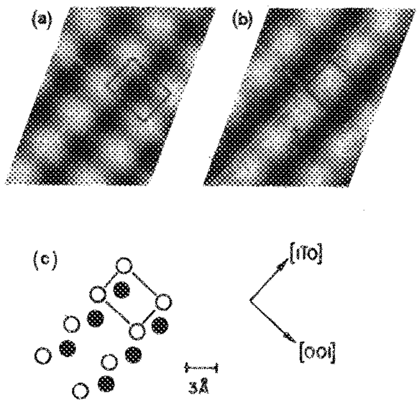

Figure 8. Representations of two measurements of the same GaAs sample with opposite voltage. (Reproduced with permission from Stroscio *et al.* 1988, © by AVS The Science and Technology Society.)

A different tenor underlay the description of images from the individual measurements. It states: "Images show either only Ga atoms, or only As atoms" (Feenstra *et al.* 1987, p. 1193). In this interpretation, only atoms that appear in the image as maxima are visible. Heinrich Rohrer, as well, referred to these measurements in a review article, writing: "As appears in the image of the occupied states, Ga in those of the empty states." (Rohrer 1990, p. 12) Consequently, a minimum, which also arises by keeping the tunneling current between the tip and the individual atom constant, does not *show* an atom, an atom does not *appear*. All participants were, of course, theoretically aware that electronic properties determined the trace of the tip and that the minima could be matched to the position of atoms. Nonetheless, even in professional publications they developed a language that deviated from this knowledge and that reserved the visibility of atoms for the appearance of maxima. Here the expectation seems to have prevailed that an atom must appear as an elevation, that is, as a maximum. Seen thus, the composite image is a realization of expectations and thus easy to comprehend. That high aesthetic standards go hand in hand with the fulfillment of this expectation is shown by the color publication in *Physical Review Letters*, a journal that rarely published color pictures. Compared to the images of earlier STM-measurements, this image marks a decisive change: No longer is the path of the tip transformed into an image. The individual constituent parts of the measurements have been put together in a manner that suggests an apparent reproduction of the investigated object.

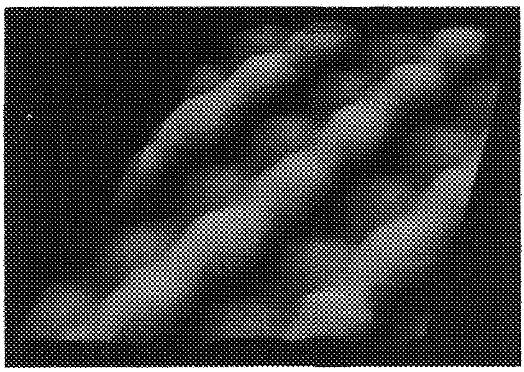

Figure 9. The combination of two measurements was indicated by the use of the two colors green and red (the original red appears in this grey-scale print as a lighter grey than the original green parts, which appear in darker grey tones) (courtesy of IBM research center Thomas J. Watson).

In Feenstra's image individual atoms are visualized according to the expectation that an atom has the shape of a hill or a sphere and not a valley. The image has also been used repeatedly in this sense: Feenstra's IBM colleague, Marc H. Brodsky published the scanning tunneling microscopic composite image, which he had received from Feenstra, in a popular article on GaAs (Brodsky 1990) (Figure 9).[8]

The image's caption reads: "Individual atoms of gallium (green) and arsenic (red) can be recognized in this reproduction done with a scanning tunneling microscope." Although Brodsky was familiar with the history

[8] In an email from June 23, 2003, Brodsky told the author that he was familiar with Feenstra's work and that Feenstra had given him this image. It was the first scanning tunneling microscopic image in *Scientific American* that was not part of an article directly on scanning tunneling microscopy.

of this image's creation, in the new popular context the composite nature of the image and the visualization of states are no longer mentioned. Instead, this representation of atoms as spheres satisfies the expectations of a broad public and thus does not require explanation. According to the text, this image shows not the results of an examination with the scanning tunneling microscope, but reproductions of atoms themselves. Instead of the original idea of using two colors to distinguish two measurements with two different parameters, in this context the representation implies that different kind of atoms have different colors. This view does not reflect the theoretical knowledge of tunneling microscopists, but this reception was made possible by elaborate image design.

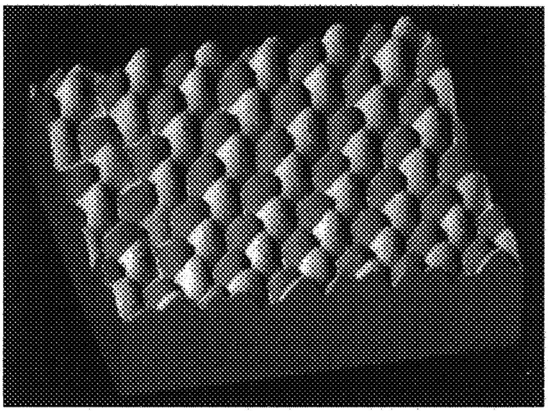

Figure 10. Representation of an indium phosphide investigation; different colors (green and red in the original appear in this grey-scale print as lighter and darker grey tones respectively) indicate the use of two different voltages (reproduced from Forster 1992 with permission from MIT Press).

The visualization of an indium phosphide surface designed by Jun Nogami, a post-doctoral researcher in C.F. Quate's work group at Stanford University, had a similar career at the end of the 1980s. In this image (Figure 10), once again two measurements with opposite polarity between the tip and the surface have been combined into one image in such a way as to allow indium and phosphide atoms to appear as differently colored hills. The measurements and the image design were inspired by one of Feenstra's lectures. Even though there were no plans to publish this image, it belonged to laboratory practice to design and process images in which all atoms took the form of maxima.

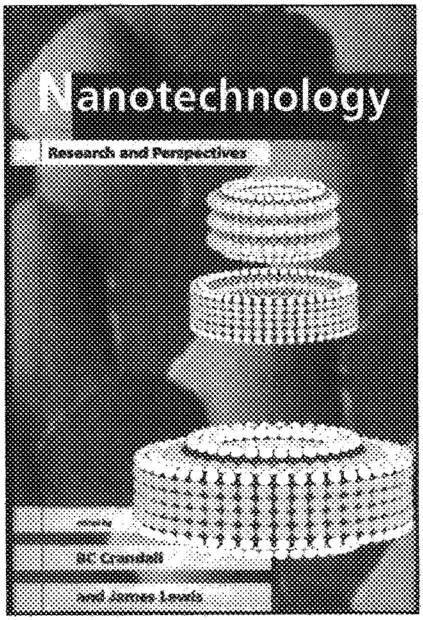

Figure 11. Cover of the first Foresight-conference volume, combining an STM-measurement and a computer-generated model; in the original print the hills in the background are red and green, here appearing as light and dark grey-scales respectively (with permission from MIT Press).

Although the image was not published in a scientific article at first, because the experimenters felt it was too similar to Feenstra's image,[9] it attracted the attention of John Foster. After receiving his degree from Stanford, Foster had moved to the neighboring IBM laboratory Almaden. In 1989, he lectured at the First Foresight Conference on nanotechnology. In a summary article on scanning tunneling microscopy, which was

[9] In an email from August 21, 2003 to the author, Nogami stated that he had seen the GaAs image at one of Feenstra's lectures and that he had subsequently prepared the indium phosphide measurements without discussing the material with the Feenstra group. That the image was circulated despite its lack of publication is due, in his assessment, to the fact that Quate often passed around the latest images or that his colleague, Park, had used it for advertisement purposes after he founded his SPM firm, *Park Instruments.*

published in the conference volume (Crandall & Lewis 1992), Foster referred to this image as an example of how different atoms can be distinguished by the scanning tunneling microscope. He mentioned the modification of the applied voltage and the different electrical properties that are measured by the STM (Foster 1992, p. 18).

On the cover of the conference volume (Figure 11), however, a detail section of the image appears in a different context. Here it composes the background to the representation of a computer-generated model of a bearing, which was constructed by the visionaries K. Eric Drexler and Ralph Merkle. Each one of the 2808 atoms in this model is represented by a sphere. The composite image of the two scanning tunneling microscopic indium phosphide measurements and the representation of atoms as hills harmonizes with this utopia. The representation of a nano-scientific examination of the electrical properties of a semi-conductor forms the background of a nanotechnological utopia, which thus seems to enter into the realm of possibility. The combination of both images creates a bridge between utopia and actual science.

5. Conclusion

For decades, the representation and representability of atoms has undergone constant modification. Discussions between Bohr, Heisenberg, Schrödinger, and Born on the representability of quantum mechanics[10] in the 1920s were followed by representations of probability densities, such as those of H.E. White (White 1931). White photographed a rotating needle with extended exposure time and obtained different degrees of brightness, which were supposed to visualize the probability that an electron was located in different orbitals. This tradition was also followed in representations of electron clouds in textbooks from the early 1980s, where they were used to illustrate the inner structure of an atom (Figure 12).

This tradition of representation emphasizes that atoms have no external form, since the locations of the electrons are stated according to probabilities that decrease with increasing distance. The tunneling micro-

[10] For this discussion, *cf.* Miller 1978.

scope defines a constant parameter through the tunneling current that guides the tip over the surface at a determined distance. If the image design then no longer suggests that it represents the path of the tip and thus requires interpretation, but instead that the atom itself is being portrayed, the atom can be assigned a form, from which this statement of probability can no longer be derived.

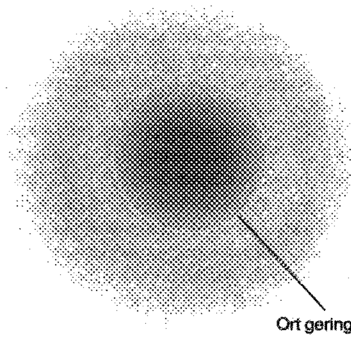

Figure 12. 'Classical' representation of electron clouds in textbooks in the 1980s (from C. Mortimer: *Chemie*, 4th ed., Thieme Verlag, 1983).

In a different pictorial tradition, it goes without saying that atoms are portrayed as spheres, for example in three-dimensional models of crystalline structures (Figure 13).

Interpreted through the theory of signs, these spherical representations are symbols, whose form is determined by convention along. In contrast to this symbolic form of representation, in tunneling microscopic measurements the shape given to the atoms is sanctioned by the instrument. The relationship between representation and object is no longer justified by a convention, but by a measurement. This describes the transition from symbol to icon. This study has aimed to show that this icon is oriented on existing conventions of symbolic representation. In their daily experiments, tunneling microscopists deal with numerous images that have not yet undergone the phases of image design described here, and they must be able to interpret these images. Nonetheless, it is also part of their daily practice to design these images in such a way that they conform to conventional expectations and nanotechnological utopias. Complex image processing and the creation of composite images establish relationships between experimentally sanctioned STM images, for example, and the symbolic representations done by Drexler and Merkle. The status of the tunneling microscope as one of the central instruments in nanotechnology rests on its areas of application and technical possibilities, but also in the power and effect of its images and an image design that emerged out of a dynamic process during the 1980s.

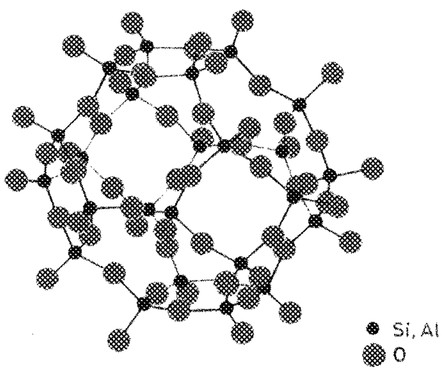

Figure 13. Typical Representation of a Crystal Structure (from: E. Riedel: *Anorganische Chemie*, de Gruyter, 1988).

Acknowledgments

I thank Elizabeth Neswald for the translation of the text and the anonymous referees for their valuable hints.

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CHAPTER 8

ANALYZING THE COMPLEXITY OF NANOTECHNOLOGY

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Nanotechnology is a highly complex technological development due to many uncertainties in our knowledge about it. The Dutch philosopher Herman Dooyeweerd has developed a conceptual framework that can be used (1) to analyze the complexity of technological developments and (2) to see how priorities can be set in the many requirements that result from this complexity. This chapter discusses similarities and differences compared to other approaches.

1. Introduction: The Complexity of Technology

In the past decades engineers have increasingly been confronted with the complexity of technological developments. In the 1950s and 1960s engineers could afford to focus very much on the scientific and technical aspects when developing new products, because they knew that it would not be difficult to be successful on the market. Customers could afford to explore all sorts of new gadgets, as there were no real economic barriers for them. In addition, there was not yet an organized resistance against technology in society. Issues such as environmental damage and ethical questions were not really urgent at that time. This changed in the late 1960s and early 1970s, and from then on engineers have learnt that it is nowadays not enough to come up with a nice technical idea. A great variation of conditions needs to be met. Not only should the new product fit with the current scientific and technological insights, but also economic, social, legal, aesthetical, environmental, psychological and numerous other conditions need to be taken into account when developing new products. This makes the work of engineers both complex and challenging. It also brings about the need to reflect on the nature of this complexity. The question emerges if it is possible to analyze this complexity in a more or less systematic way.

This question most certainly applies to the field of nanotechnology. Although still in its infancy, it clearly is a field in which quite a variety of aspects have to be taken into account. Not only are there gaps in our scientific knowledge, for which reason some people rather talk about nanosciences and wonder if one can use the term nanotechnology at all, but also there are great uncertainties about what will be feasible in the future, and what will appear to be mere 'guru talk' in the end. Already now institutes in a number of countries have started ethical debates about nanotechnology. Also the question has been raised how to set up new legislation for this emerging field, even though it is still uncertain what that legislation should exactly cover. Others worry about economic aspects of nanotechnology and in particular industrial companies are confronted with the difficult question if, and if so, how to invest in this still uncertain new type of technology. In other words: already now it is clear that the development of nanoscience and nanotechnology is a matter of great complexity, in which many different factors and issues are involved. For that reason, here too there is a need to analyze this complexity, in order to gain insights that can support decision making with respect to developments in nanoscience and nanotechnology.[1]

2. Analyzing Technological Complexity

Several options for analyzing the complexity of technological developments have been suggested. Perhaps the most basic one is the 'Dual Nature of Technical Artifacts' approach, which is investigated at the Delft University of Technology.[2] In this approach, a technical artifact is analyzed according to the two natures it has: a physical nature and a

[1] In this paper the concept of complexity will be analyzed differently from the way it is done in complexity research in the context of the theory of non-linear systems and computational theories of complexity. A qualitative approach will be used here.

[2] More information on this project can be found at www.dualnature.tudelft.nl.

functional nature. The physical nature comprises the non-relational (or non-intentional) aspects of the artifact, such as its size, shape, weight, structure, and so on. The knowledge about this nature of the artifact is, generally speaking, of a descriptive nature. On the other hand there is the functional nature of the artifact, which refers to what the artifact should enable us to accomplish. This nature involves relational (intentional) aspects, and the knowledge about this nature has a normative dimension. When an engineer says: 'I know that this is a screwdriver', (s)he means to say: 'I know that this is a device that *ought to* enable me to drive screws'. The 'ought to' nature of this knowledge shows its normative nature. What the engineer has to do is to find a physical nature for the artifact-in-design that fits the desired functional nature. One could say: the dual nature approach analyses in terms of a two-fold complexity. One could wonder if two natures only are sufficient to justify the term 'complexity' here. On the other hand, in practice finding the fit between these two natures can already be quite a challenge for engineers.

In a response to the Dual Nature approach, Carl Mitcham (2002) pointed out that analyzing the artifact in terms of just two natures might be too much of a reduction. Therefore other, more detailed analyses may be necessary. Such an alternative analysis was developed by Andries Sarlemijn at the Eindhoven University of Technology. The acronym he came up with for his approach was STeMPJE, which stands for a range of factors that need to be taken into account in technological developments, if ever they are to be successful: scientific, technological, market, political, juridical and (a)esthetical factors. By applying this analysis to different examples of technological developments, Sarlemijn (1993) was able to show the need for distinguishing between different types of technologies. His distinction was based on differences in the dynamics of these factors in the course of a technological development. Comparing his approach with the Dual Nature approach, one could say that his M, P, J and E factors are a further explications of the functional nature of an artifact, while the S factors and partially the Te factors relate to the physical nature of the artifact (Te factors partially, because those factors also can deal with functional aspects of the artifact, and thus relate to the functional nature of the artifact). One might say that Sarlemijn's approach splits up the two-fold nature of a technical artifact into a six-fold nature. His taxonomy of types of technologies indicates that it makes sense to apply this more detailed analysis.

In this chapter a third, even further detailed approach will be described. This approach was developed as early as in the 1930s by a Dutch Calvinist philosopher, named Herman Dooyeweerd (1969). Because his approach[3] was only applied to technology by Hendrik van Riessen, who hardly ever published in English, it has remained fairly unknown internationally throughout the years. Yet, it has some features that make it interesting as an analytical tool to investigate the complexity of technological developments. By applying this approach to nanotechnology, I will argue that it offers an analytical instrument for reflecting on the complexity of technological developments, while at the same time it offers analytical tools for creating order in the possible chaos that emerges when one explores this complexity. Dooyweerd himself saw his approach as a direct consequence of his Christian perspective on reality. It is interesting to note, however, that recently philosophers coming from different backgrounds have discovered the possibility to use some of his concepts separate from this Christian perspective. In particular in the field of systems methodology, the Dooyeweerd approach is now used to gain insights into the complexity of systems and the design of systems. Bergvall-Kåreborn (2000), for instance, has combined some of Dooyeweerd's concepts with the Soft Systems Methodology, which had been developed by Checkland (1981) and others. In the Proceedings of the annual conferences organized by the Centre for Philosophy of Technology and Systems (CPTS), other examples can be found. These examples show how the analytical instruments that Dooyeweerd developed can have a wider implication than only for a specific denomination of philosophers.

Before applying Dooyeweerd's concepts to the field of nanotechnology, it is useful first to give a more general description of those concepts. What Dooyeweerd claims is that reality can be analyzed in terms of fifteen aspects or modes of existence (see his New Critique, Vol. II). Those aspects can be seen in Table 1. Any entity exists in all of these modes: it has a numerical existence, a spatial, a kinematical, *etc.* Furthermore,

[3] Because of his Calvinist background, we speak of 'reformational philosophy'. More information can be found on www.isi.salford.ac.uk/dooy/and home01.wxs.nl/~srw/

Dooyeweerd's claim is that these aspects or modes of existence show a certain order: each 'higher' aspect presupposes the existence of the 'lower' aspects. For example: the spatial aspect cannot exist without the numerical (because we have one, two, three, *etc.* dimensions). Similarly, the biotic aspect cannot exist with all previous ones (life presupposes the possibility of energy conversion and movement, and movement can not exist without space). Up until the psychic aspect, Dooyeweerd explicitly argued for this particular hierarchy in the aspects, but for the later aspects he wrote more loosely about their order, and it is obvious that here it is much more problematic to set up a proper argumentation for this particular order of aspects. For that reason, his followers have had many debates about the proper order of the aspects, and nowadays several of them take a pragmatic approach and leave the exact order of the higher aspects in the middle. This approach will be used in this chapter. The number of aspects also has often been debated. Dirk Vollenhove,[4] one of Dooyeweerd's colleagues, for instance, challenged the idea that the historical (or development) aspect should be regarded as a separate aspect. In his opinion the concept of time, which overarches all aspects, should be seen as the proper conceptualization of development. In this chapter I will keep the historical aspect but take it as an expression of the fact that every entity exists in a developmental way: it is able to bring forth or has been brought forth itself. One could use the term 'cultural' or 'developmental' aspect for this.

Another important feature of Dooyeweerd's approach is that entities can have subject and object functions in the various aspects (*i.e.* can exist as subject or as object in the various modes or aspects). For instance, a stone can exist as a subject in the kinematical aspect: it can move. It can also exist as an object in the same aspect: it can be moved. In the economic aspect, it can exist as an object (it can be bought), but not as a subject (it can not buy). Likewise, all entities have a 'highest' aspect in which they can still exist as a subject. Here his idea of a hierarchy in the aspects is used by Dooyeweerd and at first sight it may seem that the uncertainties about the order of the aspects may weaken this subject and

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[4] Some information on his person and work can be found at: home.planet.nl/~srw/nwe/vollenhove/kok.html.

object function concept; but it does not really, because there is a discontinuity in the transition from the psychic to the analytic aspect. Humans are the only entities that can function as subjects in the aspects from the analytic aspect and higher on. For that reason the exact order of the higher aspects does not matter for the analysis of subject and object functions. A third concept related to functions is the qualifying function. This function indicates what defines the entity's purpose or reason for existence. The qualifying function of a coin, for instance, is in the economic aspect, where it functions as an object. The functioning of entities in the various aspects is further analyzed by Dooyeweerd in terms of the 'laws' that hold for the various aspects. To continue the example of the coin: for its proper functioning we need to take into account a 'law' that holds in the economic aspect, which says that each coin can only be spent one at a time. That is why we have to calculate how much money we need to buy something before we commit ourselves to the transaction. One could see this as a sort of 'law of conservation' and similar conservation laws are found in other aspects (for example in the physical aspect where we find the law of conservation of energy). Dooyeweerd distinguished descriptive laws (such as natural laws) and prescriptive laws (of which examples can be found in the technological domain: technical norms and standards, good practice, *etc.*). The different aspects have different laws, although the example of the conservation laws show that there may be analogies between the laws in the various aspects.

How does all that apply to technology? Technical artifacts can be analyzed in terms of their functioning in the various aspects. We can get to know their character by investigating which aspect they can serve as a subject or as an object, and which aspect we must seek their qualifying function. By reflecting on the possible laws in each of the aspects that should be taken into account when developing the artifact, engineers can develop a list of requirements for the artifact design. By taking into account the full list of aspects, one can get a detailed impression of the complexity of the design problem. The Dooyeweerd approach can be seen as an extension of the Dual Nature approach. There is a split between the biotic and the psychic aspect. Functioning as a subject in the lower aspects does not require intentionality (a stone can move without having an intentional state of mind), while functioning as a subject in the higher aspects does require intentionality (one can not buy or sell without having an intentional state of mind). For this reason one can say that the lower aspects relate to the physical nature of a technical artifact, while the higher aspects relate to the functional nature of the artifact. In a similar way one can see Dooyeweerd's approach as a further explication of Sarlemijn's STeMPJE approach (in fact, some of Sarlemijn's factors have the same name as some of Dooyeweerd's aspects).

Table 1. Aspects of reality according to Dooyeweerd

	Aspect	Application to objects
1.	Numerical	Object have a certain number of parts
2.	Spatial	Objects occupy a certain space
3.	Kinematical	Objects can move or be moved
4.	Physical	Objects can interact by mechanical cause-effect relations
5.	Biotic	Some objects live or are a part of other living beings' environment
6.	Psychic/sensitive	People can observe objects
7.	Logical/analytical	People can reason about objects
8.	Cultural/developmental	People develop objects
9.	Symbolic/linguistic	People represent objects by names or other symbolic representations
10.	Social	People can share objects
11.	Economic	People can sell objects
12.	Aesthetic	People can appreciate objects for their beauty
13.	Juridical	People can make laws in which objects feature
14.	Ethical	People can assess objects from an ethical point of view
15.	Pistic	People can believe in the positive effects of objects

3. The Complexity of Nanotechnology

3.1 Non-intentional Aspects

Having seen the basic elements in Dooyeweerd's analysis we are now ready to explore how this approach can be instrumental in analyzing the complexity of nanoscience and nanotechnology developments. I will confine myself here to indicate what issues are raised by the application of Dooyeweerd's approach to nanoscience and nanotechnology without discussing those issues in further detail. Let us now examine what each of the aspects means for the case of nanoscience and nanotechnology.[5] I will take nanotechnology to be the manipulation of individual atoms and molecules at the nanoscale, and nanoscience to be the development of scientific knowledge of the natural phenomena on nanoscale, in so far as they are relevant to nanotechnology.

(1) Dooyeweerd's first aspect (see Table 1) is the numerical. It belongs to their existence that nanoartifacts can be numbered. Already in this first and seemingly unproblematic aspect we start seeing the complexity of nanotechnological developments. As we are within the realm of quantum theory, numbering particles is not as we are used to in the macroscopic world. Furthermore, the most far-reaching claim of nanotechnology, as stated by some nanotechnology visionaries, such as Eric Drexler (1986), is the totally bottom-up construction of macroscale artifacts. For manipulating individual atoms extremely large numbers of assemblers will be necessary in order to get macroscopic results within a reasonable time scale. Drexler has suggested a scheme that would solve this problem by claiming that this can be done in the same way as nature does it: replicators continuously produce the assemblers that make the desired artifacts, and their self-reproduction will speed up this process. However, there is a problem here when copying this procedure from nature. Drexler's replicators and assemblers need to be universal in order to be able to produce any desired artifacts, while their biological analogs, enzymes and ribosomes, are always specific (Burkhead 1999). So it may well be that the problem in the numerical aspect of the nanoartifacts can-

[5] I will assume that elsewhere in this special issue a global description of nanoscience and nanotechnology has been presented already.

not easily be solved (if at all this would be an easy solution, for it is yet unclear what the technological analog of the natural solution would look like).

(2) Next we have the aspect of space. This aspect seems to be what defines nanotechnology, given the fact that nanotechnology by definition has to do with manipulating matter at the level of nanometers. Indeed, most of the struggles that nanoscience and nanotechnology go through are related to the fact that it is difficult to observe and manipulate things at this level.

(3)-(4) The next two aspects in Dooyeweerd's approach are the kinematical and the physical aspects. I will take them together here, as some of Dooyeweerd's followers have suggested. Motion and energy aspects of nanoartifacts both need to be described in terms of quantum phenomena. This description is still in development, and this is why nanoscience and nanotechnology are so closely related and often mentioned together. The fact that the phenomena at nanolevel are not yet fully known, while at the same time scientists try to build nanoartifacts, has as an interesting consequence that the functional and the physical nature of nanoartifacts (the two natures in the 'Dual Nature of Technical Artifacts' approach; see above) are not entirely known, while usually at least one of them is fairly well known in the beginning of the design process. Here the creation of a physical nature and the ascription of functions to the resulting artifact almost happen at the same time. Philosophically, this is perhaps one of the most significant issues in nanotechnology. In particular the process of defining a qualifying function (in Dooyeweerd's terms, *i.e.* not only telling what the emerging artifact can be used for, but also what it's most important function will be) to the artifact is a process that may well be different in the case of the creation of nanoartifacts compared to more traditional design processes.

(5) The fifth aspect is the biotic aspect. Here too, problems have already been identified. Nanoartifacts will interact with living creatures, and this may create problems that are similar to the asbestos problems that have caused quite some concern in the past. So far for the non-intentional aspects.

3.2 Intentional Aspects

(6) Now for the intentional aspects, starting from the psychic. This aspect has to do with consciousness. Here a concern for nanotechnological developments is the fact that our awareness of nanoartifacts is very indirect. We can only conceptualize them through pictures that have been produced by using complicated processes that are far removed from direct observation. A commonly used way of picturing nanoartifacts is by using spheres to indicate individual atoms. This image, of course, is more symbolic than realistic, because of the quantum characteristics of atoms. A different way of picturing nanoartifacts is used when the outcomes of scanning tunneling microscopy are displayed. In such cases we see a surface with blobs emerging from it. The story that we are told is, that the raised blobs represent atoms. However, this again is no more than a pictorial tool to help us conceptualize for ourselves what a nanoartifact looks like.

(7) A problem that is more interesting from a philosophical perspective, but may also have practical impact on the development of nanoartifacts can be identified when we consider the next of Dooyeweerd's aspects, which is the analytic or logic aspect. Analysis to Dooyeweerd is related to distinguishing. One of the perhaps most intriguing problems of nanotechnology is the question of how it could blur the boundaries between living and non-living matter. In terms of Dooyeweerd's concepts, the issue can be formulated as follows: is it still possible to identify a transition between the nanoartifact having its 'highest' subject function (*i.e.* the highest aspect in which it can function as a subject) in the physical or in the biotic sphere, and if yes, how? If indeed nanoartifacts can be built atom by atom, and this could also result in living tissue, then how do phenomena that indicate life emerge in this process? Self-reproduction, for instance, can be seen as a phenomenon that is typical for life. When such a phenomena would emerge in a process of building nanoartifacts, this may mean that we have to take that into account when taking safety precautions. From biology we know that self-reproduction can have as a consequence that the life system becomes autonomous in its growth, which may result in a threat for other life systems. A similar aspect can be asked with respect to the transition from the biotic to the psy-

chic aspect. Is it possible that characteristics of consciousness would 'suddenly' start to appear in the process of building a (very complex) nanoartifact, and if yes, would consequences could that have for our attitude towards that nanoartifact?

(8) Now we come to the historic or development aspect. This is the aspect that we study when we consider the way in which the field of nanotechnology develops. As we noted before an interesting issue in this respect is the development taking place based on only partial knowledge of the underlying natural phenomena.

(9) The study of these phenomena is what the next aspect, the linguistic or symbolic aspect, refers to. It seems that here we have an example in which the 'technology as applied science' paradigm fails to account for the relationship between science and technology. The relationship between nanoscience and nanotechnology is much more complicated.

(10) The issues that can be identified by considering the next five aspects are all related to the fact that nanoscience and nanotechnology are, as yet, in a state of infancy and much is unknown about the possible social effects of nanoartifacts and their use. In terms of the social aspect of nanoartifacts, it is yet unclear how the emergence of nanotechnology will affect social relationships (see *e.g.* Roco & Bainbridge 2002). Already now there are concerns about the possibility that nanotechnology will enhance the gap between those that have and those that do not have access to new technologies.

(11) As for the economical aspect, business corporations are faced with great uncertainties when making decisions about whether or not to invest in nanotechnological developments (at least, as far as the long-term future is concerned; at the short term there are fairly detailed expectations about possible industrial applications).

(12) Next in Dooyeweerd's ladder of aspects is the aesthetical aspect, which is the aspect in which the issue of harmony or disharmony is the key issue. Here too there are great uncertainties. Will nanoartifacts function in harmony with the artifacts that have been produced in more traditional ways? This point was raised by Langdon Winner in his testimony to the committee on Science of the US House of Representatives.[6] Per-

[6] See www.rpi.edu/~winner/testimony.htm.

haps that question presses even more when we consider the option that these nanoartifacts show characteristics of life, and yet are known to be the result of an artificial process.

(13) The juridical aspect raises questions with respect to developing legislation in a situation where the technology is not yet well known. What kind of laws should be defined in such a situation? Can laws be used to prevent undesired practices in an early phase of a technological development? Usually legislation lags behind, and undesired practices have already had the chance of developing. It would be better to prevent such practices than trying to get rid of them once they have already emerged. Could nanotechnology be one of the first examples in which legislation is not just an effort to clean up the mess? But how can we determine what legislation would be appropriate?

(14) Also in the ethical aspect discussions are difficult because of the uncertainties about what nanotechnology will look like in the future. Several possible ethical issues have already been identified: the possibility of nanotechnology running out of hand and causing life-threatening situations (this in fact is the basis of Michael Crichton's (2002) novel *Prey*), and possible privacy problems when miniature equipment can be made and installed without being visible for the naked eye. However, at this stage it is difficult to develop concrete ethical guidelines for nanotechnological developments.

(15) Finally we have the pistic aspect, which refers to beliefs and convictions that people may have with respect to technological developments. Nanotechnology offers a nice example of the important role such beliefs can have. Nanotechnological developments are often strongly pushed by strong beliefs in the far-reaching promises that are made by some nanotechnology visionaries. They suggest that nanotechnology in the end will offer us the means for the ultimate control over our world, because we can manipulate things at the most fundamental level. The pistic aspect raises the question that drives people to be involved in nanotechnology. Is it a matter of having control for the sake of exerting power over others or over nature? Or is it a matter of serving other people? Or is it a matter of responding to God's call to humans to serve Him by bringing into further deployment what He created? The answers to

such questions can also be very determining for one's attitude towards the issues that have been raised by considering the previous aspects.

3.3 Integration of Aspects

An issue that is raised by the considerations above is the integration that is needed to make informed decisions about nanotechnological developments. According to Dooyeweerd integration of knowledge of the various aspects takes place when an engineer is involved in practical design and problem solving work. He/she takes notice of scientific knowledge referring to the various aspects and then tries to take all of that into account in one comprehensive decision. In order to gain that scientific knowledge people in the various scientific disciplines have each abstracted one aspect from the full complex reality and focus on a description of the regularities and particularities of that aspect. The engineer when using that knowledge then moves back to the 'level' of the full complex reality when making his/her design decisions. However, there is also a second way of knowledge integration, which is still at the level of scientific, abstract considerations. It is what we usually call interdisciplinarity. At that level we seek abstract and general knowledge not with respect to one aspect (as in a specialized discipline) but with respect to more than one aspect. Interdisciplinarity is often mentioned as a characteristic feature of nanoscience and nanotechnology. A proper philosophical conceptualization of interdisciplinarity is not yet available (Margareth Boden's [1997] well-known taxonomy of levels of interdisciplinarity is more sociologically oriented than philosophically). Dooyeweerd has not systematically reflected on how knowledge about the various aspects can be brought together in true interdisciplinarity. He does have some notions that may be useful to explore for the purpose of conceptualizing interdisciplinarity. For example, he claims the possibility of analogies between the 'laws' in the various aspects. These emerge as a result of anticipations and retrocipations between the aspects. Anticipation means that a concept in a certain aspect contains a reference to a concept in a later aspect (for example, the concept of emotional value in the psychic aspect refers to the concept of value in the economic aspect). Retrocipation, likewise, means that a concept in a certain aspect contains a reference to a previous aspect (for example, the concept of profit margin in the economic aspect refers back to the concept of margin in the spatial aspect). Because of such relationships between concepts in different aspects, analogies between laws can emerge. For instance, we find conservation laws in several of the aspects. Such analogies could be the basis for finding regularities that would hold for more than one aspect and thus could contribute to interdisciplinary knowledge. However, this needs much further explication in order to be fruitful for conceptualization of interdisciplinarity. One of the fields that can be drawn from here is that of systems sciences. In that field analogies between systems in various aspects (*e.g.* ecosystems in the biotic sphere and mechanical systems in the physical aspect, but also social systems in the social aspect) are studied and conceptualized.

4. Conclusion

A survey of what the aspects may mean in the case of nanotechnology has shown how complex a non-reductionist description of nanotechnological developments will be. The survey raises more questions than it answers. One could also read the previous considerations as an agenda for further philosophical reflections on nanoscience and nanotechnology.[7] A challenge for further reflections is certainly to seek out the consequences of the different 'laws' that we can find in the different aspects, and – as stated above – the integration of knowledge of those 'laws'. Perhaps at this stage the identification of relevant philosophical questions is more important than providing the answers to such questions. Probably the content of this volume will reflect that at the moment we do not have that many answers yet. But in that situation setting up a proper research agenda is important and the Dooyeweerd approach that was described

[7] Probably several of the issues that have been mentioned here will also feature in other articles in this volume. Several of the issues also feature in the University of South Carolina research agenda on the philosophy of nanotechnology (see www.cla.sc.edu/cpes/nirt/nirt200112/nirt.html). It is also possible that some issues have not yet become the focus of philosophical reflections, and in such a case the reward for applying Dooyeweerd's approach is that we may start appreciating the relevance of such issues now.

here can be a contribution to that, as well as to the later effort of seeking answers to the research questions.

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CHAPTER 9

NANOTECHNOLOGY: GENERALIZATIONS IN AN INTER-DISCIPLINARY FIELD OF SCIENCE AND TECHNOLOGY

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This chapter reports on work-in-progress in the area of technology generalization. More specifically, it presents a model that allows integrating various expectations regarding emerging technologies. Nanotechnology is used as an example of a novel field of science and technology. The notion of leitbild ('guiding image') is used as a mediating concept pointing to potentially emerging technologies. Then we discuss to what extent patent and publication data can facilitate identifying scientific and technological trends and how to evaluate the epistemic utility of a leitbild.

1. Introduction

The Kuhnian notion of 'paradigm' is commonplace nowadays. Dosi first introduced that notion in technology studies. He assumed that 'normal' technological change consists of incremental, relatively small improvements that follow bigger, revolutionary (and therefore 'scarce') technological breakthroughs which ultimately result in new technological paradigms. According to Dosi (1982, p. 152) a technological paradigm "embodies strong prescription on the directions of technical change to pursue and those to neglect". Dosi (1988) defined a technological paradigm as a:

> model and pattern of solution of selected technological problems, based on highly selected principles from natural sciences, jointly with specific rules aimed at acquiring new knowledge [...] A technological paradigm is both an exemplar – an artifact that is to be developed and improved – and a set of heuristics.

Since Dosi, the notion of 'technological paradigm' has been used by so many researchers that even this concept has become a commonplace. Substantial qualitative and theoretical work is available on the emergence of a new technological paradigm. Debackere and Rappa (1994) have suggested that technological paradigms typically emerge in two phases: bootlegging and bandwagon.

During the bootlegging period, which may last for a long time, a small number of researchers dedicate themselves to furthering the field. Their peers may not share their enthusiasm. Frequently, researchers from such an emerging community have to face severe criticism. Typically, they have difficulties in securing adequate funding, hence, the term 'bootlegging'. Typically, a few isolated individuals start working on similar problems with roughly similar ideas (Debackere & Rappa 1994, pp. 27-28).

Researchers who are dedicated to a new and unorthodox field of inquiry often face a difficult dilemma. On the one hand, before receiving resources, they need more proof that their work will yield results. On the other hand, without resources, they are unable to precisely do that.

'Bootlegging' enables fledging research to proceed without the full knowledge and scrutiny of managers and other researchers, up to a point at which the promise of the idea is clear. During this phase then, the community will be highly concentrated among a small number of organizations, and the yearly increase in number of researchers is fairly moderate (*ibid.*).

As the number of individuals working on the same problem area increases, a communication network emerges with ties that are much stronger than the ties binding the individuals to the organizations they formally belong to. During this 2nd, so-called bandwagon phase of the community life cycle, a very rapid increase occurs in the number of researchers working in the community, with this taking place over a relative short period of time.

As the community grows, a new paradigm comes into being, indicated by the higher-level network of the (sub-)discipline as competing with the older paradigm. The community tries to organize congresses and found journals, so as to be able to steer the selection process. The R&D community is typically distributed across organizations, sectors, and countries. If the work of a new community seems interesting from a commercial point of view, some scientists may be recruited by enterprises, while some who already work within industry are allowed to devote their efforts openly to the new field. Finally, some scientists may decide to become entrepreneurs themselves.

In terms familiar to the field of futures studies, one can compare the new paradigm in the bootlegging stage with a weak signal that only few take seriously. In the bandwagon stage it develops towards a strong signal that has to be taken into account.

This chapter presents an overview of our theoretical work regarding leitbilds. After introducing the basic concepts we apply our heuristics to nanotechnology. Drawing on a number of technical reports on developments in nanoscience and technology we try to characterize the leitbild system of nanotechnology. We discuss the potential use of patent and publication based data to generate topics within the aforementioned leitbild systems. The chapter concludes with a suggested model as to how one can evaluate the epistemic utility of a leitbild.

2. Technology Generalizations and Leitbilds

Technology generalizations are different types of perceived similarities between the already existing technological innovation and a potentially new technology. Similarities concern both the techniques applied in the innovation and the targets that are achieved based on the innovation (Kuusi & Meyer 2002). Two techniques are similar in the sense that they could replace each other in the achievement of (defined) targets. Another form of generalization is based on the realized techniques of the innovation that are used for new 'similar' applications.

In terms familiar to futures studies, one can compare a new paradigm in the bootlegging stage with a weak signal that only few people take seriously. In the bandwagon stage, it develops towards a strong signal that must be taken into account. A concept that illustrates the guiding function of an emerging technological paradigm is the 'leitbild'. '*Leitbild*' is a German word. Its most general meaning is *ein Bild, das leitet*, a guiding image. According to Marz and Dierkes (1994), a leitbild has two functions, guidance and image. The guidance function consists of three subfunctions: (1) creating a shared overall goal, or 'collective projection'; (2) orientation toward one long-term overall goal, or 'synchronous preadaptation'; (3) working in the same direction, or 'functional equivalency'. The image function consists of three subfunctions: (1) cognitive activator; (2) providing a focal point, or 'individual activator'; and (3) 'interpersonal stabilizer'.

Like a common vision, a leitbild creates a shared overall goal, offers orientation toward one long-term overall goal, and provides a basis for different professions and disciplines to work in the same direction. Leitbild refers not only to a common vision of actors; it also relates to the concept of autopoesis (from Greek, self-organization) and functions as an interpersonal stabilizer. With an efficient leitbild, no center is needed that urges or controls individuals to perform certain functions.

Inspired by Marz and Dierkes (1994), we characterize the general rules of an emerging paradigm as a system of leitbilds. An emerging technological paradigm is typically a system of many competing leitbilds. In the bandwagon (or paradigmatic) stage, one leitbild often begins to dominate. Leitbilds are used in visions, but it is important to distinguish between a 'leitbild' and a 'vision'.[1]

Followers of a leitbild form a kind of 'intellectual community', but as long as their visions differ, they usually do not establish a real R&D community. The intellectual community of a leitbild typically integrates several R&D communities and their members.

We use the notion of technological leitbild systems (Kuusi & Meyer 2002) to explore inter-relations and connections between seemingly separate areas, because a leitbild system can establish links through simi-

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[1] The main difference is that the 'vision' in the framework of visionary management is an actor-related concept. Persons or organizations might have visions that give them the ability to plan or make policy in a farsighted way. A leitbild is not related to any specific actor. It is a principle that can be selected as a part of a vision; *e.g.*, a firm might select 'the sample principle of digital technology' (a leitbild) as a part of its vision.

larities or analogies. A leitbild system is a system of guiding images that create a shared overall goal, offer orientation toward one long-term overall goal, and provide a basis for different professions and disciplines to work into the same direction. Thus, a leitbild system defines the development path of a technological paradigm.

Bijker (1993) has introduced the notion of a 'technological frame' that combines the cognitive and the social sphere, including exemplary artifacts, cultural values, goals, scientific theories, and tacit knowledge. A frame is not fixed, but built up and sustained by the process of stabilizing artifacts, and is internal to the set of interactions within a relevant social group. However, actors can be members of more than one frame/ social group with different degrees of inclusion in any frame. Above all, a technological frame provides "the goals, the thoughts and the tools for action", whilst at the same time limiting the freedom to act. In this way interactions create a structure that, in turn, constrains further interactions (Bijker 1993, Martin 1998).

Bijker's concept of a 'technological frame' is quite close to our understanding of leitbilds. It is an important step toward notions of technological trajectories, which are more closely related to concepts of technological determinism. However, the notion of 'technological frames' does not give technology the prominent role it deserves. Here, our leitbild concept steps in. Our concept appreciates both the importance of social factors that influence the exploration of technological options and the technological determinants that confine the relevant cognitive processes to certain research, development, and design spaces.

3. Types of Technological Generalizations in a Technological Paradigm

In this section we discuss how for an emerging technological paradigm, future applications can be anticipated. Kuusi suggests that a technological paradigm is a "shared generalization language" capable of producing important generalizations (Kuusi 1999). These generalizations are based on a cluster of linked technologies. The language of a promising technological paradigm can be viewed as a cluster consisting of realized and promising targets and realized and promising techniques. Realized targets are existing artifacts – or, more precisely, their properties or functions – while realized techniques are production processes and design methods. The similarity between techniques is based on the perceptions and interpretations of experts in the corresponding field, whereas the similarities between targets are based on perceptions and interpretations of the users of the artifacts.

The underlying idea of the generalization concept is that existing techniques and targets serve as a platform for a process generating technological options in a multitude of ways. Generalizations are always based on perceived similarities. Emerging paradigms provide similarities based on both realized targets and realized techniques. On the other hand, a technological paradigm is the result of this type of generalization process, its successes and failures. Realized targets, which have been achieved with realized techniques ('successful exemplars'), and unsuccessful exemplars are 'concepts' of the generalization language.

Figure 1 illustrates six different types of generalization. Realized techniques can be generalized so as to predict promising techniques (arrow 1), if both techniques are considered scientifically similar. From the point of view of the paradigm, there are no fundamental technical problems in Type 1 generalizations. It simply requires some effort. For example, once you have realized that a certain virus can be used to transfer a gene to a bacterium, it is reasonable to believe that you might also use another (similar) virus for that purpose. Another form of generalization is based on already realized techniques that bear a potential beyond their current range of application. Techniques can be used to create new artifacts that are (from the point of view of the paradigm) similar (arrow 2). Like Type 1, this generalization is based on scientific similarity, but only partly. For example, once you have realized that you can transfer a gene to a certain bacterium with a virus, it is reasonable to believe that you might transfer the gene in a similar way to another bacterium. But is the gene transfer to the second bacterium as acceptable to your customer as the first transfer? The targets (or the transfers) in both cases might be very similar from a technical point of view but very different from the point of view of your customer. Your customer might consider that the second transfer is irrelevant or even unethical. It is important to realize that technological paradigms as 'generalization languages' are also based on customer values. Actually, we assume in our model that similarities between targets are based only on the interpretations of customers.

Once you have realized a target or made a new artifact using a certain technique, you might start thinking about new ways to produce the artifact or new techniques to improve it (arrow 3). This is a new line for technological generalizations, or for enriching the 'paradigmatic language'. You might eventually include in your paradigm new techniques that have technically very little to do with your original techniques. Consider fusion energy. The original technical idea of the fusion bomb has very little in common with the recent techniques based on the use of huge magnets.

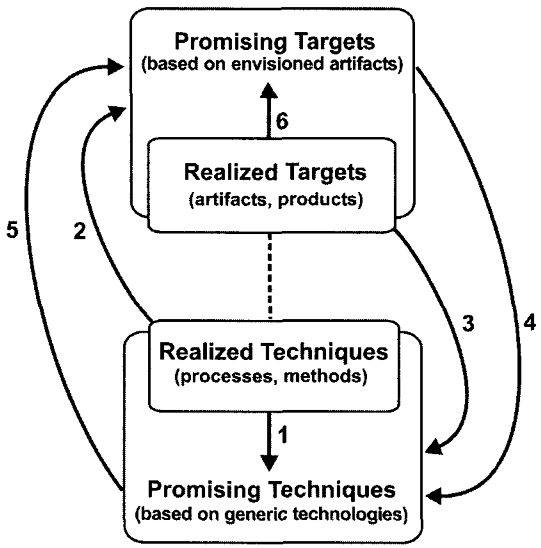

Figure 1. Different types of technological generalizations.

Generalizations of Types 1, 2, and 3 are relatively well grounded. It is possible, however, in the language of a paradigm to make generalizations that are far less grounded. Instead of strong scientific similarities, they are based on possible social developments or on weak scientific similarities (weak scientific or technical signals). One can anticipate techniques that would become promising if somebody first realizes certain targets (arrow 4). For example, if you are able to set up a permanent colony of people on the moon, new efficient ways to produce solar energy on the moon might become possible. Or you might anticipate new targets to be achieved if you could realize a technique that is supported only by weak technical signals (arrow 5). For example, if you can produce energy cheaply, you might provide an abundant supply of fresh water from salt water.

There is still one arrow in our picture left, arrow 6. It means that a person or an organization whose target B has been achieved considers that it is also possible to achieve similar target B'. How successful is this type of generalizations? Frequently such generalizations are irrational and have often resulted in questionable processes. Why are Type 6 generalizations frequently unsuccessful? The important point is that in our model – as well as in reality – the similarity between B and B' is based only on the interpretation of users of the realized artifact. In all other generalizations, similarity interpretations are either made only by technical experts or by users and technical experts together.

We illustrate our point with an example. Energy users realized in the early 1950s that it is possible to make commercial energy from atomic fission by using similar techniques of the fission bomb. Based on this generalization, many users made a Type 6 technology generalization. They considered that in similar way one could proceed from atomic fusion bombs to commercial fusion energy and provided a considerable amount of funding for the development of the commercial fusion power. Though opportunistic technical experts have used the funding for the development of commercial fusion energy, they were surely aware already in the early 1950s of huge technical difficulties of that project. In order to produce commercial fusion energy, you have to keep the fuel for a relatively long period at extremely high temperature and under equally high pressure. That is not needed in the production of energy from atomic fission. If all the money that has been used for the development of commercial fusion energy would be have been used, *e.g.*, on solar power, the energy situation of humankind might be much better.

4. Application of the Model to Nanotechnology

Now, we apply our approach introduced in the previous sections to the field of nanotechnology. The term 'nanotechnology' was first coined by Norio Taniguchi in the 1970s in Japan where it is associated with top-down miniaturization "which can be regarded as the latest stage in mechanical engineering, which has pursued ever-tighter precision of manufacture and tolerances throughout its history" (Budworth 1996, p. 13). In the 1980s, Drexler began to use the term nanotechnology to denote his vision of molecular manufacturing (Drexler *et al.* 1991, p. 294). The main difference between leitbild and vision is that 'vision' is an actor related concept in the framework of visionary management. Persons or organizations might have visions that give them the ability to plan or set policy in a far-sighted way. Leitbild is not related to any specific actor. It is a principle that can be selected as a part of a vision.

According to Grupp (1993, p. 65), "nanotechnology will have a key position in the technological development of the 1990s and in the first decades of the 21st century". He described the field as an enabling technology that "makes possible engineering at the level of atoms and molecules" and continues:

> This new basic technology can stimulate future innovation processes and new generations of technologies. It is based on the interaction of information technology, polymer research, optics, biochemistry and medicine and micromechanics.

Grupp's characterization of nanotechnology indicates the early-stage character of the field, but also shows the potential it holds. His description further underlines the interdisciplinary and cross-boundary nature of the area, which provides a substantial challenge to what is perceived as necessary collaboration between sectors and disciplines. Considerable efforts from various sides have been undertaken to forecast the development of this novel field of science and technology. For instance, the German Mini-Delphi study chose nanotechnology as an explicit category.

Table 1 contains a number of Delphi topics that can be used as examples and which represent the nanotechnology section. We have rearranged the topics according to various leitbild types and analyze them according to our five types of generalization.

Table 1. Nanotechnology topics in the German mini-Delphi study (adapted from BMBF 1996)

Leitbild	Topic	Realized
I	20. An analytical method that sorts out a particular type of atoms using high-definition surface-analysis techniques will be in practical use.	2001–05
I	22. Reaction and synthesis methods at individual atoms or molecules of, respectively, atomic or molecular level of magnitude will be in use applying techniques from scanning tunneling microscopy.	2006–10
II	16. Methods to synthesize substances with new functions (*e.g.*, polymer crystals with weak bonds) will be developed by way of combining various types of bonds at the atomic level.	2006–10
II	17. Nanostructured materials with predetermined properties will be manufactured.	2001–05
III	14. Functional materials and/or semiconductor components whose compositions and dotting densities vary from atomic layer to layer are widely used.	2006–10
III	18. Organic hybrid composite materials that are based on the control of monomolecular layers will be developed.	2006–10
IV	19. Organic–inorganic composite materials will be developed (*e.g.*, biomimetically) whose elements are at the level between several and a few dozen nanometers.	2001–10
IV	B. Organic, molecular composed materials will be developed using the natural method of self-organization	2006–10
V	15. Electronic solid-state components that consist of 'super atoms' of artificially composed atoms will be developed.	2006–10
V	21. 'Atomic function elements' (atomic switches, atom relay transistor, *etc.*, in which movements of a small number of atoms cause logical and/or storage functions) will be in practical use and have a higher reliability and processing velocity than solid-state components.	2011–15

Leitbild I ('Nano-resolution tools'): Generalizing from realized to promising techniques (Type 1)

Nano-resolution analytical methods as depicted in topics 20 and 22 can be viewed as generalizations of Type 1 – from already realized techniques to other promising techniques. The aim here is to further improve existing tools, typically in an incremental fashion, by adding new functions to analysis tools. In our example, realized techniques, such as atomic force microscopes (AFM's) or scanning-tunneling microscopes (STM's), are further generalized into promising tools that are not yet developed but conceivable from the already existing technological platforms. Further, very incremental developments of scanning force microscopes can be expected to improve the reaction and synthesis methods or chemical analysis.

Along with further technical development of scanning-probe methods, researchers are discovering new phenomena in the fields of physics, chemistry, and biology. At the same time these microscopy techniques are increasingly used as a 'tool' rather than a 'probe'. The idea is to modify surfaces and tailor their structures on the nano-scale, down to the manipulation of individual atoms (Frenken, 1998, pp. 289-299). Ultimately they might facilitate large-scale manipulation at the nanometer level. However, this transcends the possibility of Type 1 generalizations (see leitbild V below).

Leitbild II ('Nanomaterials'): Generalizing from realized techniques to promising targets (Type 2)

Nanomaterials are an area that is characterized by Type 2 generalization, the transition from realized techniques to promising targets. Together with a better scientific understanding of the subject matter, a variety of already realized techniques allow developing rather specific ideas of improved materials. By taking advantage of nanoscale characteristics of structures and substances, one may create new materials with enhanced properties, such as polymers, composites, or other materials (topics 16 & 17). Rather than direct control of individual atoms, bulk operations suffice to exploit these nanoscale properties.

Another example of bulk-processing nanomaterials are colloidal dispersions (Philipse 1998, pp. 171-8). Colloid science deals with the physics and chemistry of finely dispersed particles with at least one dimension in the submicron range, including nanoparticles that are frequently considered smaller than 100 nm. Colloid science has a long tradition involving nanoparticles such that not all that is nano is necessarily new. In this sense, colloids encompass gold colloids, colloidal silica, and aluminum oxide powders. Due to their small dimensions, colloids exhibit Brownian motion. Owing to their large surface area, the interaction between colloidal particles in the liquid phase is determined by surface forces, such as van der Waals attractions, and repulsions due to the particle charge. The balance between these forces critically depends on the details of the particle surface and the liquid composition. Colloids easily aggregate to form large aggregates, networks, or gels. While there are already techniques to control these aggregation processes to some extent, our understanding remains limited. Yet we know enough of the existing techniques and about potential ways to improve them to envisage also improved properties of materials and, ultimately, products, such as milk, cosmetics like toothpaste or sunscreen, or ink, which are nothing but suspensions of colloids or dispersions. Computer simulation and statistical mechanics are tools that are used to further understand colloidal systems.

Leitbild III ('Ultra-thin Films'): Generalizing from promising targets to promising techniques (Type 4)

Thin-film techniques are an example of Type 4 generalization from promising targets to promising techniques. Realized techniques already permit sufficiently exact operations at the nanometer level to suggest the idea of future products that would require even more exact and precise tools. This generalization requires a preceding Type 2 generalization. Thin-film technologies are a considerably well-developed field. The ultra-fine production of thin films is necessary for the subsequent characterization. Designing ultra-thin layers is associated with a number of aims, such as atomically exact delineations of layers, quantized potential distribution, defined pore distribution in layers, ultra-thin separation and protection layers, and improved layer function by way of multilayer structuring. These targets are in turn motivated by and related to many technical applications, including information storage layers, films with quantum effects, optical layers, multilayer piles for semiconductor laser and X-ray optical compounds, displays, sensor layers, tribologic films, biocompatible films, photovoltaic films, membrane films, and chemically active surfaces (Bachmann 1998), which are the starting point for Type 4 generalizations toward new, improved techniques.

Two topics in our Delphi example correspond to this type of generalization (topics 14 & 18). Here efforts appear to be directed at characterizing these structures. Topic 14, for instance, suggests that the control of monomolecular layers will allow developing organic hybrid composite materials. The aim of controlling monomolecular layers, while not yet possible, is based on the progress made with existing tools and techniques that allow speculating about the properties of new products or processes, which in turn leads to the next step towards improved instruments.

Leitbild IV ('Biomimetics'): Generalizing from realized targets to promising techniques (Type 3)

The topics in the area of biomimetics (19, B) are examples of Type 3 generalization from realized targets to promising techniques. The idea is to simulate nature in order to develop materials with novel properties by way of self-organization. The biomimetic approach can be used as a path to obtaining novel materials, using self-assembly techniques to make organic templates on which inorganic structures are then deposited (Budworth 1996, p. 7).

While basic principles of self-organization are known, we still need to integrate various techniques to achieve the target of controlled self-assembly. Although one can create structures by way of self-organization in a biomimetic process, our technological means are still incomplete to fully utilize the potential this leitbild offers. Being aware of the general feasibility – thanks to already realized artifacts – we can make reasonable assumptions about the requirements of the techniques necessary to pursue this path of development further.

Leitbild V ('Direct control of atoms'): Generalizing from promising techniques to promising targets (Type 5)

Topics 15, 21, and 23 in the Delphi study describe a leitbild that focuses on the direct control of atoms in order to rearrange them to form new structures that could result in novel materials. This leitbild follows a Type 5 generalization, from promising techniques to promising targets. Building on Type 1 generalization, it is first based on the availability of promising techniques from which promising targets are then projected. As pointed out in leitbild I, we can reasonably expect current STM and AFM technologies to be further developed into more complex tools that, beyond measurement and observation, can efficiently manipulate structures at the nanometer scale. From such promising technique one can make the Type 5 generalization step to improved and novel artifacts.

The difference between the materials approach, leitbild II, and leitbild V is the different control of processes, bulk reactions versus atomic control. Atomic control is also strongly related to the idea of atoms being effectively used as carrier of certain functions, such as data storage, *etc.*

5. The Leitbild System of Nanotechnology

All the different approaches we call leitbilds belong to one greater whole that eventually will develop into a technological system. As long as the exact shape of that technological system is unclear, we speak of a leitbild system instead. One element of this leitbild system might even substitute and outdate another leitbild. For instance, what we identified as leitbild V could replace II one day. Even though both approaches refer to nanostructures, they are essentially different. While II uses bulk methods, V aims at direct atomic control.

A leitbild and, even more so, a leitbild system is coined by the integration of a number of communities. Even though leibild II is a field that is relatively close to realization, it still critically relies on the integration of knowledge from a variety of disciplines and of expertise from a number of industrial sectors. For instance, even for monitoring and controlling activities at the bulk level, it is necessary to use nano-resolution instruments. The borderlines between science and engineering disciplines become blurred, and disciplinary fields tend to fuse as in the field of materials science and engineering. This is even more apparent in the area of biomimetics, which tries to simulate natural principles to build up structures. At the nanometer level, the boundaries between disciplines tend to disappear.

This is why we can refer to nanotechnology as a leitbild *system* that integrates different approaches, each of which being autonomous enough to bear its own identity, but also depending to a greater or lesser extent on results from the other fields.

6. How to Promote Technological Generalizations Related to Emerging Leitbilds?

People committed to different leitbilds considerably differ in their evaluations of the future prospects of generic technologies. How can we make different evaluations/interpretations more explicit? Kuusi (1999) has suggested that that we can handle the difference by measuring the *epistemic utility*. The idea is that for an actor it is more reasonable to start a realization process of a certain option, if the epistemic utility of that option increases.

In the bootlegging stage of a leitbild, there are only few actors who believe in the reasonability of the underlying generalizations. Most experts think that the generalizations will not be realized at all or that it takes too long before it is reasonable to start the realization process. If the leitbild has proceeded to the bandwagon stage, a majority of actors believe in rather quick realization of the generalizations. The epistemic utility of the topic has increased dramatically for average actors. Any new successful generalization of the emerging technology presented during the process between the bootlegging stage and the bandwagon stage has some impact on this growth of the epistemic utility.

In this chapter, we will not discuss how to measure epistemic utility (see Kuusi 1999). It is sufficient to mention four aspects of the epistemic utility of a technological generalization. The epistemic utility is related, first, to the anticipated impacts of the generalization; second, to the value (positive or negative relevance) given by relevant stakeholders to different impacts; and, third, to the techniques available for the realization of the generalization. Typically a champion of a technological generalization has in the bootlegging stage much more positive evaluation concerning these aspects than mainstream actors. The important fourth aspect is the evaluated validity of the three anticipated aspects.

National technology foresight Delphi studies have had 'proxy' measures for the variables of the four aspects of the epistemic utility. The degree of the importance of each topic has been measured by the Delphi panelists' evaluations (Cuhls & Kuwahara 1994, NISTEP 2001), which refer to our first two aspects: the impacts and their relevance. The evaluation scales exclude topics being evaluated feasible but undesirable, which implies the questionable assumption that the realization of topics is always desirable, though more or less important.

In the latest Japanese Technology Foresight study, the impacts are also discussed with expected effects and potential problems of technology generalizations (NISTEP 2001). Evaluated effects are socio-economic development, resolution of global problems, people's needs, and expansion of intellectual resources; potential problems are adverse effect on the natural environment, on safety, and on morals, culture, and society.

Proxy measures for feasibility are the anticipated cost constraint as well as technical, funding, human resources, and R&D system constraints on technological generalizations (Cuhls & Kuwahara 1994). Two proxy measures for the validity of an evaluation are the degree of certainty of an expert concerning the realization time of a topic and the self-evaluation of the expertise (Loveridge *et al.* 1995, NISTEP 2001).

Evaluations of the epistemic utility of technological generalizations also provide a heuristics for the decision making of a company. Let us suppose that a company includes only one champion of a technology generalization based on an emerging paradigm who considers starting the realization project a reasonable choice, which means that only for him or her the epistemic utility sufficiently high. The managers of that corporation could base their decision in favor of the project on two reasonable necessary conditions: (1) the champion is a reasonable person; and (2) the champion is ready to take an economic risk with this project. If these two conditions are met, a reasonable choice for the firm would be to start a new venture with the champion. This strategy has been empirically found *e.g.* by Lovio (1993) in the Finnish electronic industry in the 1980s. Another reasonable policy is to allow the champion to continue the bootlegging as long as the epistemic utility is growing both for the champion and other key persons in the company. This means that the champion has to produce new arguments (*e.g.* realized minor generalizations) which step by step convince new protagonists.

7. Outlook

With respect to forthcoming research activities, we approached the question as to how to generate candidates for leitbilds from data on the current research and technology. In the early 1990s, patent data was used in mid-term oriented Foresight activities (Grupp 1993). With respect to nanotechnology, more recent work was carried out by Meyer *et al.* (2002).

Using bibliometric techniques with patent and publication data allows filtering and identifying core concepts that emerge in a specific area.[2] Mapping an area over time can illustrate when new concepts have emerged and may allow speculation on what new technological steps can be expected. Using elements of our leitbilds, experts may be able to identify clusters of techniques that would allow addressing some promising targets or conversely could speculate on how nanoscale techniques currently under development could be extended in their area of application.

However, keyword maps are typically limited to a set of the top 60 or so concepts that occur most frequently and are therefore by default fairly general in nature. Instead of focusing on the top 60 concepts, we plan to investigate a subset of nanotechnology areas (nanobiotechnology, nanostructured materials and surface characterization) to generate a set of more specific concepts from which experts could generate topics suitable for a Delphi study. We assume to find candidates for different leitbilds by applying cluster analysis to second order concepts in the patent applications (*e.g.* ranks 100-200).

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[2] For an illustration, see the maps of the most frequently co-occurring keywords in Meyer *et al.* 2002.

Another application of bibliometric techniques would be the identification of potential experts, based on mostly cited or linked documents in the leitbild system candidates. Interviews with these experts may allow further analysis of their key technology generalizations and leitbilds.

Acknowledgments

This paper was first presented at the 'Workshop on Expectations in Science and Technology', Risoe, Denmark, April 29-30, 2004. We thank participants and referees for their helpful comments.

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CHAPTER 10

WHAT COUNTS AS A 'SOCIAL AND ETHICAL ISSUE' IN NANOTECHNOLOGY?

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As 'social and ethical issues' becomes a recurring phrase in the community paying attention to nanotechnology research, a crucial question becomes: what counts as a social and ethical issue? A typical list includes privacy, environmental health and safety, media hype, and other apparently unrelated issues. This chapter surveys those issues and suggests that concerns about fundamental concepts of ethics, such as fairness, justice, equity, and especially power, unite the various issues identified as 'social and ethical issues' in nanotechnology.

1. Introduction

As 'social and ethical issues' becomes a recurring phrase in the community paying attention to nanotechnology research, a crucial question becomes: what counts as a social and ethical issue?[1] Even the field in which the question occurs is in dispute: is it 'nanotechnology', 'nanoscience and nanotechnology', 'nanoscale science and technology', or 'nanoscale science, engineering, and technology'? Each of these labels implies something different about the relationship between inquiry, research, development, and application. If we set aside these differences, which are likely to be examined in other chapters in this volume, and constitute a

[1] See, for example, 21st Century Nanotechnology Research and Development Act, 2003.

single 'nano' field, we are still faced with boundary issues. For example, questions about the ethical implications of creating and deploying nano-sized particles, which might or might not have deleterious health effects on humans or animals who inhale them, have been taken up by the technical research community as 'safety' questions.[2] Is a safety question an ethical question? Who decides? This chapter is an attempt to begin to ask these questions in a deeper way, to identify what underlying principle(s) might define 'social and ethical issues' in nanotechnology.

2. Overview

Much of the excitement about nanotechnology exists because it offers the possibility of many societal benefits, such as reduced energy use, better medical treatment, and lower costs for computing and other common technologies (Amato 1999). Many observers have also expressed concerns about risks associated with nanotechnology – environmental risks, privacy risks, social and political risks (Arnall 2003, ETC Group 2003, Joy 2000). In that context, they have called for studies on 'social and ethical issues' in nanotechnology. But there is a danger in using the label for studies associated with risk, for it might imply that social and ethical issues are associated only with potential dangers of nanotechnology, or that the risks of nanotechnology will outweigh the benefits.

To say that there are 'social and ethical issues' (SEI) in nanotechnology assumes no position on the question of risks and benefits. Indeed, it is not even clear that talking in terms of 'risks versus benefits' is a useful way to approach nanotechnology. Rather, to say that there are social and ethical issues is to say that science and technology exist only in a social context, and that we cannot understand how science and technology develop without understanding both the social conditions that produce them and the simultaneous scientific and technological conditions that produce society. Better understanding of the interaction of science, technology, and society at many levels of the polity leads, I assert, to more informed

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[2] For example, a workshop on 'safety and environmental issues' was held in December 2004 in Atlanta, Georgia, organized by the National Nanotechnology Infrastructure Network (NNIN); the organizers represented a separate branch of the NNIN management than the 'social and ethical issues' branch.

decisions about how to invest in science and technology, when and how to regulate – or not regulate – technological development, how to address inevitable ethical challenges, and so on. Note that this perspective, of mutual interdependence of science, technology, and society, is why I prefer the term 'social and ethical issues' to the phrase used by some nanotechnology funders, most notably the U.S. National Science Foundation, which is 'societal and ethical implications' of nanotechnology. The latter phrase implies that science and technology come first, followed by 'implications'. The history of science and technology does not support such a perspective.

Much of the promise of nanotechnology, and the early identification of social issues associated with nanotechnology, appears in documents associated with the U.S. National Nanotechnology Initiative (Roco *et al.* 2001, Roco & Bainbridge 2005). In the remainder of this chapter, I will adopt this necessarily American perspective, while acknowledging that similar discussions are being held in other countries.[3] Some of the major categories of social and ethical issues identified in the American documents include the following.

Economic and political implications of potential technology

These issues include the economic value of new materials and new industries created through nanotechnology, as well as economic dislocations caused by shifts in investment and the decline of industries and companies tied to displaced technologies. Other implications might include increased lifespans made possible through nano-based medicines or diagnostic techniques, leading to greater numbers of active senior citizens seeking employment and active participation in the political process.

[3] See, for example, a recent British report jointly produced by the Royal Academy of Engineering and the Royal Society (2004) and a report from the Büro für Technikfolgen-Abschätzung of the German Bundestag (TAB 2004).

Science and education implications

Nanotechnology is perceived by many as an interdisciplinary field, requiring knowledge of chemistry, physics, engineering, and, for many applications, biology.[4] But although American science education reforms of the 1990s led to recommendations for more interdisciplinary science studies in primary and secondary schools (National Research Council 1996), countervailing political pressures for instruction in basic topics and for accountability have stymied many reformers in their attempts to change curricula. Nanotechnology proponents therefore perceive a need for changes in educational systems in order to prepare students for careers in nanotechnology, whether as technicians with only minimal post-secondary training or as cutting-edge doctoral-level researchers.

Medical, environmental, space exploration, and national security implications

That nanotechnology will have impact in a great many areas of application is assumed by most participants in the field. A listing of 'medicine, environment, space, and national security' is in some ways only a listing of areas where the political imperatives for funding mean that applications are likely to appear sooner rather than later. Put another way, acknowledging that public funding is available precisely because these are areas important to society means that society expects developments in science and technology to contribute to improved medical care, environmental quality, space exploration, and national security – and supporters of nanotechnology expect to produce those developments. Thus, any advance in nanotechnology necessarily has societal implications.

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[4] The question of whether nanotechnology is 'inter-', 'multi-', or 'trans-' disciplinary is in fact one of the first questions posed in the Call for Papers for the joint special issue of *Hyle* and *Techne* on 'Nanotech Challenges'. I leave that debate to others, but note merely that the question of how to describe cutting-edge research is a recurring one in American science. See, for example, Kohlstedt *et al.* (1999, pp. 104ff, 163-165).

Social, ethical, legal, and cultural implications

The list of social, ethical, legal, and cultural implications includes such issues as privacy, avoiding a 'nano-divide', unintended consequences, university/industry relationships and potential conflicts of interest, research ethics, and so on. It is widely acknowledged that, precisely because the applications of nanotechnology are not yet clear, neither are the ethical issues clear. And yet, many argue, the nano community must begin to address these issues now, before they overwhelm nanotechnology and derail potential benefits.

The NSF and other funding agencies are to be congratulated for recognizing and actively promoting discussion of SEI, which required the active work of a small group of socially-concerned scientists working in research centers, federal agencies, and legislative offices (Radin 2003). Yet the categories they have produced and that appear in other reports (including, for example, the June 2004 British report cited in note 3, which contains separate chapters on regulatory, environmental, and 'social and ethical' issues) require exploration. An odd element of the categorization is that it separates 'social, ethical, legal, and cultural implications' from economic, national security, workplace, and other issues that are also fundamentally social, legal, and cultural in their construction and implications. This, then, is the problem to be addressed: What are the implications of setting boundaries that separate 'social and ethical' issues from other inherently social and ethical issues? To address the problem, we need to determine if there is any principle that can distinguish among these topics, or if there is some underlying principle that can better be used to characterize what counts as a social and ethical issue.

3. Building from the Bottom

A recurring metaphor in nanotechnology research is between 'top-down', *i.e.* defining a nanostructure and then etching away material until only the nanostructure is left, and 'bottom-up', *i.e.* building nanostructures atom-by-atom or molecule-by-molecule. In the spirit of that metaphor, and without taking sides in the technical debate about whether 'top-down' or 'bottom-up' is a superior approach to 'real' nano, I suggest that the confusion of categories and labels described above comes from an attempt to pre-define what counts as a social or ethical issue. Whether deliberate or not, the attempt to set boundaries is necessarily an exercise of power that precludes our ability to understand the properties inherent in issues that make them social or ethical. Instead, I will try in what follows to avoid boundaries, to survey many of the issues identified by others in ways that allow them to be seen in the same space – and so show what the connecting principle is. From the bottom up, I will try to build a principle for identifying social and ethical issues in nanotechnology.

The following list of issues and questions comes from perusing many of the reports and discussions about SEI of the last few years.[5] The list is not intended to be comprehensive, but I believe it covers the main issues identified by others.

Environmental issues

Environmental issues associated with nanotechnology are currently, in winter 2005, the most prominent in the news, and 'environmental and safety issues' is becoming a standard discussion among the nanotechnology community. The public notice of these issues was most noticeably drawn by a *Washington Post* article in February 2004 (Weiss 2004) but other news has continued to keep the topic current. To some people, these are 'technical' issues, separate from social and ethical issues. To others, the inherently social process of identifying what constitutes a risk and what constitutes safety make these issues 'social and ethical' ones. Generally, nanotechnology proponents argue that making things much smaller will make them more energy efficient, thus reducing energy demands. Others argue that the presence of very tiny manufactured nanoparticles in the environment may cause health problems associated with inhalation. Some people associated with nanotechnology have also ex-

[5] Except where I have drawn a particular issue from a particular source, or where some canonical reference seems useful, I have not attempted to identify the sources for the ideas listed here. I believe they are sufficiently widespread or easy to imagine (think of a mathematical text's injunction that 'it is left to the reader to show…') that no references are needed.

pressed concern about the environmental impacts of nano-manufacturing processes, particularly those involving large amounts of water. Will nano-manufacturing face some of the same environmental challenges regarding toxic waste streams as semi-conductor manufacturing currently does? Still others, including prominent nanotechnology researchers, have called attention to the difficulties in stating with any confidence what the environmental issues might be, because too little data is available (Colvin 2003). In this state of uncertainty about *implications*, the *issues* remain: Who is likely to bear the risks of any environmental challenges – investors, workers, or communities near the manufacturing plants? Who will reap the benefits of environmentally-friendly materials – producers, consumers, or anyone who breathes the air and drinks the water? How will decisions about risks and benefits be made, and by whom? What influences will shape those decisions?

Workforce issues

As noted above, the need for people ready to work in a nanotechnology-enabled world leads to a variety of needs. Some are specific: training programs for technicians, undergraduate and master's level programs for engineers and managers of nanotechnology companies, and advanced research training for doctoral and post-doctoral students. Others are more general, such as the suggestion from the Royal Academy of Engineering and the Royal Society that all research students be required to study social and ethical issues (Royal Academy of Engineering and Royal Society 2004). Most far-reachingly, people concerned about the workforce argue that, at least, American education must change to make students capable of working in interdisciplinary advanced technology arenas. But a key element of American education is the commitment to local control. Unlike most countries, the United States has no mandatory national curriculum; in addition, funding for education varies dramatically by state and locale. Some locales will invest in new curricula or new approaches to education that foster technological innovation, while others – even if community leaders wish to try new methods – may be stymied by lack of access to money or technological expertise. Given competing priorities for educational resources, including time, how will decisions about preparing students be made? How will the best techniques for training students be identified? Will some students find easier access to new ideas, techniques, and information than others? To what extent will issues of financing, ideology, local politics, and local industrial base shape these decisions?

Privacy issues

Nanotechnology is likely to lead to smaller, faster, cheaper computers. The notion of 'ubiquitous computing' with all the benefits it promises becomes much easier to develop with nano-based processors and memory. The proliferation of powerful computers, however, will make it even easier to compile and process databases of personal information. Current privacy regulations may serve to regulate the large databases maintained by credit companies and consumer manufacturing companies, although even this claim is questioned. What happens when, for example, any individual can use a tiny video camera to record people passing into a particular store, face-recognition software to identify those people, publicly-available databases to find those people's addresses and personal data, and then create marketing pitches based on the stores they have entered? Who will control access to information? In the field of genetics, many laws have been introduced, but not always implemented, to protect the privacy of medical records so that, for example, insurance companies will not be privy to individual health profiles. But is that fair to the investors in insurance companies, whose business model is based on the assumption that risks can be fairly identified and apportioned across groups? How can the claims and needs of individuals, corporations, other groups, and the state be adjudicated?

National and international political issues

Much of the U.S. government's investment in nanotechnology is driven in part by global economic concerns, a perceived need to maintain technological leadership. What obligations does a nation have to share technological developments with other countries, especially economic allies? In what ways is the development of technological leadership a force in global politics? The relationship between the developed world and developing countries is a particular concern, as a recent Canadian study suggests (Court *et al.* 2004). Even within a country such as the United States, what obligations are there for sharing technological development across the country? Several states, for example, are creating 'nano centers' in the hope that nano-based businesses will locate there, with attendant economic benefits. Questions of benefit and obligation, of resource allocation, are fundamentally political questions, in the 'good' sense of politics as a tool for balancing competing interests, values, needs, and responsibilities in ways that yield the best outcome for both individuals and the community at large.

Intellectual property issues

Like other 'emerging technologies' that are tightly linked to basic scientific research, nanotechnology generates intellectual property that is perceived as valuable and thus protected by patents. Various laws, regulations, and treaties govern the relationship between 'the public good' and the protections offered by patents. These rules vary across nations, and even within any one country there is not necessarily agreement on what should be patentable and how the benefits of protected intellectual property should be shared. In the United States, where much nanotechnology research is funded by government grants, the 1980 Bayh-Dole Act encourages universities to seek patents, on the grounds that such protection will ultimately encourage universities to transfer technology into the commercial sector, yielding economic, *i.e.* social, return as well as intellectual return on the government investment. Research studies on the effects of Bayh-Dole, however, have illustrated the potential unintended consequences, such as restricted dissemination of faculty research, delays in publication, deleted information, and – most ominous to those who believe academic research should be 'pure' in its motivations – a change in direction of faculty research toward projects with commercial potential (Thursby & Thursby 2003, Jensen *et al.* 2003). New questions arise: Do existing rules and regulations function in the nano-oriented economy? Are there differences between nanotechnology and, say, genomics research that should be explored? Does the close association of entrepreneurial companies with particular university-based researchers compromise the 'public' mission of research universities, or does it enhance the ability of students to explore technological developments that can contribute to the public good? Is a different language needed for discussing the interaction of funding, ownership, development, and returns? How can the interests of public and private be balanced?

Human enhancement

Among the applications of nanotechnology that some researchers consider 'science fiction', while others are actively attempting to implement, are enhancements to human memory, physical strength, and other characteristics. Though usually framed as attempts to monitor or repair ailments or disabilities such as Parkinson's disease or genetic abnormalities, some of these technologies can simultaneously be used to control or enhance particular human characteristics in 'normal' humans as well. These possibilities raise many of the same issues as stem cell research and other aspects of biotechnology: defining the boundary between treatment and change, establishing common understandings of what counts as 'human' and 'natural', the rights and needs of the ailing and their families versus broad social interests in establishing clear guidelines that a broad mainstream of society can support, the role of religion and morality in public life and in the governance of science, and so on. As with so many of the issues listed above, the 'right' answer is not clear, and neither is the way forward. How might social consensus be achieved on such issues? Who should determine what research and what applications can or should be developed? On the issue of implants that might relieve symptoms of Parkinson's disease, for example, I have heard researchers arguing that they should continue their research because 'ultimately, it is a decision between the patient and his or her surgeon'. Others have argued, as the atomic scientists of World War II did, that research scientists have a moral obligation to guard against misuse of their research. How can such issues be resolved?

4. The Common Frame

What holds each of the issues above together, the principle that links the individual items into a common frame, is that all involve questions of fairness, equity, justice, and especially power in social relationships. That is what makes them 'ethical' issues. In each case, not only are legitimate questions possible about how nanotechnology research and application should develop, but even more fundamental questions exist about how to make decisions and who should control those decisions. These fundamental questions are asking about the source of power in societies with unequal social distributions of power.

Yet, precisely because the 'top-down' approach to defining social and ethical issues has separated 'social and ethical issues' from economic, political, national security, and other issues, the exercise of power has been hidden even in the definition of what is legitimate to study. Consider the interaction of economics, workforce, and safety issues, for example. Addressing the need to create safe working environments for manufacturing nanomaterials will require social negotiations for setting standards and levels of acceptable risk, a political process in which manufacturers and their workers will bring different levels of power. If economic, workforce, and safety issues have been excluded from the definition of 'social and ethical issues', then the place of power in the negotiations can be hidden, with rhetoric focusing more on technical safety or national competitiveness – both important issues, but ones clearly different than allocations of power.

Though scientists often complain about what they perceive as a lack of social power, they are in fact one of the most respected social groups in society and their judgments are highly regarded (National Science Board 2004). In the United States, in particular, 'expertise' is a valuable social resource, and in times of political conflict, such as in debates about stem cells, nuclear power, or global warming, competing groups fight to claim the mantle of 'science'. When individual scientists or scientific groups argue that because *they* interpret available evidence to say that a particular technology is possible or not possible, and that therefore development should proceed or be abandoned, they are claiming the social power granted to them by society. The difficulty comes when, as necessarily happens in areas of emerging technology, the scientific community itself is unsure of what is possible or not possible. Then power becomes a liability, an invocation or imperative to take action without consultation when the group in fact needs other perspectives. Defining such technical issues as *not* part of 'social and ethical issues' prevents us from seeing the interdependence of science, technology, and society with which I began my argument.

I do not want in any way to be read as saying that scientists have power illegitimately or inappropriately; I want only to emphasize the importance of recognizing the linkage among social groups and social power. For other groups also have social power, such as large corporations, organized ethnic enclaves, labor, and the elderly. The ethical challenge is to find ways for these groups to manage their competing interests, making clear what obligations and opportunities they perceive, exercising their power in responsible ways – including acknowledging the power held by others and the flexible boundaries between their interests.

At this point, other issues that are frequently listed as 'social and ethical issues' in nanotechnology enter the discussion. These include studies of public opinion about, media coverage of, rhetoric in, and history of nanotechnology. Do the principles of equity, fairness, justice, and power allow us to include these issues in a carefully defined 'social and ethical issues' category? Or must we start listing them in some new grouping?

Consider first the *media and public opinion issues*. Many people in the nanotechnology community worry that media coverage of nanotechnology focuses too much on risks and not enough on benefits. They believe that the risks have been overstated, and they worry that media coverage may affect public opinion, making it difficult to achieve the promise that they see for nanotechnology.[6] They point frequently to the example of genetically modified organisms, which many, but by no

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[6] There is little substantive data to support these claims. Both general data on media coverage of science and public opinion and specific data on other controversial subjects such as biotechnology and stem cells show that media coverage and public opinion are overwhelmingly positive (National Science Board 2004, Nisbet & Lewenstein 2002, Nisbet *et al.* 2003). Preliminary studies support the belief that the situation will be the same in nanotechnology (Lewenstein *et al.* 2005; Cobb *et al.* 2004).

means all, scientists believe was unfairly tarnished with safety concerns. The nano community does not want nanotechnology to be what they perceive to be prematurely prevented from development. This seems clearly to be a question of power: the nanotechnology research community wants to be able to define what constitutes appropriate development of the field, without fear that some other social group – for example, a politically-savvy coalition of nanotechnology opponents or advocates of a particular direction in nanotechnology research – might exercise its power to direct nanotechnology.

Tied to questions about media coverage are *rhetorical issues*, including analysis of the images, both textual and visual, associated with nanotechnology. Again, many proponents of nanotechnology worry that images of 'grey goo' or of self-replicating nanobots that could take over the world, as in Michael Crichton's *Prey*, misrepresent the risks of nanotechnology and could affect public opinion. Clearly, such concerns raise the same issues of power as the concerns about media coverage. But, like issues such as intellectual property or workforce preparation, rhetorical issues can also be addressed in ways that do not directly deal with ethical concerns. Rhetorical analysis can show, for example, how the use of particular phrases, such as 'more changes in the next 30 years than we saw in all of the last century', can set expectations for inventors and investors.[7] It can also show how images of 'revolution' can be used both to promote a technology by highlighting the new and exciting opportunities and to criticize it by emphasizing its disruptive elements. If, through some exercise of power, we were to use some arbitrary definition of 'ethical issues' that included some rhetorical issues, but excluded others, we would miss the inherent interweaving of social and technical.

The final set of issues often labeled as 'social and ethical' are *historical and philosophical issues*, of the sort addressed in this journal. Such issues clearly raise questions of fairness, equity, and power – indeed, it is often through historical and philosophical research that such questions are most clearly identified and presented. History and philosophy also make clear the complexity of scientific development, in ways that show

[7] The quote is from Mihail Roco, director of the National Nanotechnology Initiative, and appeared in the *Houston Business Journal* on 16 January 2004.

the interweaving of social, ethical, and technical issues. Historians and philosophers have demonstrated clearly that science and technology do not develop entirely through a pure internal logic, but exist only in a social matrix of funding, institutions, personnel, politics, and culture. Studying the history and philosophy of nanotechnology as it emerges is likely both to confirm previous understandings of how science, technology, and society interact, and simultaneously to pose new questions about the interactions, as the social matrix shapes the development of nanotechnology and is as well shaped by the new technology. Though such studies may challenge the power of science to maintain its boundaries separate from society, they represent our deepest understanding of the integration of 'social and ethical issues' throughout the nano – and indeed all of the technical – world.

5. Conclusion

The ability to see principles of fairness, equity, justice, and especially power – in short, the key social interactions that shape the co-existence of science and society – in so many aspects of nanotechnology suggests they can provide the frame on which to build a broader definition of 'social and ethical issues'. Indeed, the attempts to define 'social and ethical issues' narrowly is itself an exercise of power that can prevent us from understanding how central social issues are to the development of scientific knowledge and its implementation through technology in the modern world.

Thus at the same time that we congratulate the nano community for embracing studies of 'social and ethical issues', we should be wary of the attempt to draw boundaries between those issues and 'technical' ones. As I have tried to show in this chapter, the 'top-down' attempt to separate some social issues from others hides from us the degree to which power operates as a unifying principle across many issues. Even more so, the attempt to separate social and ethical issues from other areas of nanotechnology research shields us from understanding the ways that equity, justice, and power are inherent elements of science and technology. We must allow 'social and ethical issues' to emerge from the bottom up, through the nano community, wherever they appear.

I will conclude by noting that nanotechnology may not be any different than any other area of emerging science and technology. Virtually every argument of this chapter would hold if the words 'biotechnology' or 'information science' or 'cognitive science' were substituted for 'nanotechnology'. Social and ethical issues permeate science and technology. Only the exercise of power prevents us from seeing that.

Acknowledgments

An earlier draft of this chapter was prepared for the National Nanotechnology Infrastructure Network, and I thank the social and ethical issues coordinators from NNIN institutions for their comments. Many of my ideas on nanotechnology have been developed in conversation with Stephen Hilgartner, but my expression of them here is entirely my own and he should not be blamed for my lapses. I also thank two anonymous reviewers for pressing me to make my argument stronger.

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CHAPTER 11

THE PROMISE AND THREAT OF NANOTECHNOLOGY: CAN ENVIRONMENTAL ETHICS GUIDE US?

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The growing presence of the products of nanotechnology in the public domain raises a number of ethical questions. This chapter considers whether existing environmental ethics can provide some guidance on these questions. After a brief discussion of the appropriateness of an environmental ethics framework for the task at hand, the chapter identifies a representative environmental ethic and uses it to evaluate four salient issues that emerge from nanotechnology. The discussion is intended both to give an initial theoretical take on nanotechnology from the perspective of environmental ethics and to provide a clear indication of the direction from which environmental resistance might come.

1. Introduction

In the light of the immense hype and publicity that currently surrounds nanotechnology, it is somewhat surprising that a search of the Center for Environmental Philosophy's bibliography in early 2004 reveals not a single article on nanotechnology by an academic environmental philosopher.[1] One can loosely speculate why. Perhaps it is that environmental philosophers can be a touch technophobic and little inclined to track the latest scientific developments. They tend to look romantically at what is being lost rather than prospectively at what may be around the next cor-

[1] The bibliography is available through the Center for Environmental Philosophy [www.cep.unt.edu]. Lee 1999, which will be discussed below, is a rare example of a monograph in environmental philosophy that specifically discusses nanotechnology.

ner. When environmental philosophers do look forward, their bias towards the living world means that they often look towards technologies with the prefix bio- (such as biotechnology) rather those with prefixes such as chemo- or nano-. Whatever its cause, while professional environmental philosophers have stood on the sidelines, nanotechnology has surged into popular and scientific consciousness. According to the Science Citation Index database, the number of research publications on nanotechnology rose by an average of 27% per year in the 1990s. The United States government appropriated $792 million in 2004 for the National Nanotechnology Initiative, indicating that the technology has become a major federal research priority. State and private dollars add considerably to that investment (Greenpeace 2003, pp. 18-20). In popular culture, nanotechnology looms increasingly large, with the screen version of Michael Crichton's novel *Prey* expected to be released shortly. From Bill McKibben's cautionary tale *Enough* (McKibben 2003) to front pages stories in the *Washington Post* (01/31/04), from the visionary ideas of the Foresight Institute to a $1.3 million National Science Foundation funded study of nanotechnology's societal and ethical implications,[2] from NGO reports on emerging technologies to activist protests in Berkeley, California over the construction of a carbon nanotube factory, there is already a vigorous and contested discourse on what nanotechnology means and what its implications might be for society and for the environment. Professional environmental ethicists need to join this fray and join it fast.

2. Environmental Ethics as a Suitable Lens

There can be no doubt that the philosophical issues surrounding the development of nanotechnologies and their products are both interesting and complex. In addition to the numerous technological and scientific issues, nanotechnology raises profound questions in the philosophy of science, the sociology of science, the philosophy of technology, and the philosophy of chemistry. It also poses serious political and ethical ques-

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[2] See ^{nano}Science and Technology Studies at the University of South Carolina [nsts.nano.sc.edu].

tions. Nanotechnology is fairly unique amongst recent technologies in that there do exist efforts to formally address some of these issues. In the United States, early government commitments by the Clinton administration, a reasonably long period of anticipation for the promises of this new technology to actually arrive, and a National Science Foundation sensitized by contentious experiences with genetically modified organisms have combined to create a unique rhetorical space within which the philosophical questions can be investigated.

Included within this emerging discourse are suggestions that nanotechnology is so radical and its disciplinary foundations so unusual that it requires an entirely new ethical framework, one tailor-made for the issues (Khushf 2004). So electric is the buzz around nanotechnology that some of those cognizant of its implications want a completely clean ethical slate for their discussions. Here I argue a different case. The first part of this chapter makes the case that the discipline of environmental philosophy already provides a particularly suitable framework to bring to bear on many of the pertinent questions.

The ethical issues that are most often brought up in relation to nanotechnologies are almost all issues that have arisen in relation to other environmental promises and threats. Specters such as the threat of biological harm, the danger of runaway replicators, the creation of radically new kinds of materials, the hubris of 'playing God' with natural processes, and the threat to the meaning of being human are all familiar worries raised by previous technological developments such as nuclear power, genetically modified organisms, ecosystem restoration, and human genetic therapies. Environmental philosophy, one might argue, developed specifically in response to these sorts of threats. Optimistic promises by the boosters of nanotechnology such as future material abundance, the end of pollution, and the cessation of extinction are equally familiar to environmental advocates, as is the speculative idea of bringing extinct species back from the dead.

Like nanotechnology, environmental philosophy is inherently interdisciplinary, building bridges between philosophy and ethics on the one hand and ecology, biology, and evolution on the other. This means that environmental philosophy might be readily adapted to perform the cross-disciplinary investigations between chemistry, biology, engineering, and philosophy that nanotechnology demands. Complex ontological questions raised by nanotechnology about the relationship between the natural and the artificial are also firmly within the purview of environmental philosophy and have been discussed by environmental philosophers in relation to biotechnology and genetics. Questions weighted with social rather than environmental dimensions – the fear of creating a socio-economic nano-divide, puzzles about who can patent nanotechnologies, worries about corporate and government abuse, concerns about liability for possible harms caused by nanomaterials – are also issues with which environmental ethicists have experience. So while it is clear that nanotechnology promises tremendous technological advancement, it is not so clear that it takes us into completely new ethical terrain. Turning to an existing ethical framework provides an important economy of labor for those addressing the difficult challenges of nanotechnology. It also provides a helpful orienting point in what might otherwise be only lightly charted territory. So while environmental philosophy certainly should not pretend to be the only lens through which to consider the ethical issues that nanotechnology generates, it certainly seems that the discipline might be a proficient guide for many of them.

There is a further consideration at work that makes environmental philosophy a particularly suitable framework to use. This consideration relates to a potent guiding metaphor that frequently slips into the discussion of how to frame nanotechnological endeavor. Nanotechnology is often cast as a way for humans to fabricate biological and evolutionary processes. It does this essentially by building from the atom or molecule up. James Van Ehr, CEO of Zyvex, a company dedicated to producing the world's first molecular assemblers, begins his talks on nanotechnology by offering wood and abalone shells as prototypical nanomaterials.[3] Biology is the proof by example for many nanotechnological dreams. The report on nanotechnology by the U.K.'s Economic and Social Research Council contains the claim that "cell biology offers a proof that at least one kind of nanotechnology is possible" (ESRC 2003, p. 7).

[3] Van Ehr made this claim at his keynote address at the University of South Carolina's 'Imaging and Imagining the Nanoscale' conference in Columbia, SC, March 4-7, 2004.

Kevin Yager of the Barrett Research Group at McGill University in Canada similarly opines that "the best proof comes from nature, which has (over the course of billions of years of evolution) created highly sophisticated nanometre-sized devices, including catalysts, motors, data encoding mechanisms, optical sensors, *etc.*"[4] The most audacious proponents of nanotechnology suggest that the implicit aim of the endeavor is for humans to "do better than nature and improve on evolution" (Dinkerlaker 2003). George M. Whitesides laid down this gauntlet in *Scientific American* remarking that "it would be a marvelous challenge to see if we can outdesign evolution" (Whitesides 2001). Nanotechnology, seen in this light, is a human effort to fabricate biology and to do a better job at it than nature has done. Given this provocative guiding metaphor, it seems probable that a great number of the ethical issues that surround the technology will reside either within environmental philosophy or at its intersection with bioethics.

A final practical reason for considering nanotechnology through an environmental ethics lens has more to do with the way that public perceptions of nanotechnology have been developing than with any proposed theoretical link between the two. It turns out that much of the emerging and anticipated resistance to the development of nanotechnology is coming from the environmental community. Canada's Action Group on Erosion, Technology, and Control (ETC), now calling for a moratorium on the commercial production of nanoparticles until more is known about their toxicity, is the same group that in the past led the fight against genetically modified organisms (ETC 2003). Berkeley's Community Environmental Advisory Committee has spearheaded protests against the construction of a 'molecular foundry' for the production of carbon nanotubes at the Lawrence Berkeley National Laboratory (Artz 2004). Greenpeace U.K. was one of the first to publish a comprehensive discussion paper of the societal implications of nanotechnology (Greenpeace 2003). Whether or not it is in fact the case, nanotechnology is clearly being perceived as a potential environmental threat. Environmentalists are concerned both about the effects of nanomaterials on the biol-

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[4] See Yager's opinion piece at www.barrettresearch.ca/teaching/nanotechnology/nano01.htm.

ogy of individual organisms and about the consequences on local and global ecologies of the widespread dispersion of nanomaterials into the environment. Looking at these technologies through an environmental ethics lens will provide a better idea of exactly how these threats are perceived by the communities that are concerned about their development. The first claim of this chapter, then, is that while a full discussion of the societal implications of nanotechnology calls upon a diverse range of specialists from across the humanities and the social sciences, the discussion makes particular and targeted demands on the skills of the environmental philosopher.

3. Selecting an Environmental Ethic

One immediate problem with the intention to look at nanotechnology through the lens of environmental ethics is that environmental ethics, like nanotechnology, is not a single thing but a diverse and complex cluster of issues, theories, and practices. Different environmental ethicists would approach the promises and threats of nanotechnology in different ways. Some environmental ethicists might adhere to a reverence for life ethic, others to a form of weak anthropocentrism, a third group might orient themselves around an ecosystemic holism, a fourth a deep ecology approach, still others would choose an ethic of care.[5] It is impossible in one chapter to consider how each of these frameworks might apply to nanotechnology. But having pointed out the diversity of positions that environmental ethics offers, it might yet be possible to identify a central environmental intuition that hovers somewhere in the background of many of them. The intention is not to argue for the validity of the chosen intuition here. Such arguments fill many pages of the environmental ethics literature. Rather, the idea is to identify an important ethical principle held by many in the environmental ethics community and then judge how nanotechnology measures up against it.

The one intuition that appears to be common to many environmental positions is the intuition that there is some value associated with histori-

[5] For notable contemporary proponents of each of these approaches see Taylor 1986, Norton 1987, Rolston 1988, Drengson & Inoue 1995, and Warren 2000.

cal evolutionary and ecological processes. The process of evolution and the ecologies that have resulted from those processes are believed by many environmental ethicists to possess moral considerability. Since evolution is an open, random, and stochastic process it is necessary to immediately add a scalar modifier to this suggestion. J.B. Callicott, borrowing much from Aldo Leopold, has suggested in this vein that the primary loci of value in an environmental ethic are evolutionary and ecological processes that occur "at normal spatial and temporal scales" (Callicott 1999, p. 139). If we set aside the difficulty of establishing what 'normal' would mean in this context, the identifiable ethical intuition that remains is that nature deserves moral consideration for its own sake on the basis of the fact that the biotic community is the product of millions of years of natural forces that have generated a system that is life supporting, complex, and often diverse.

This central ethical intuition is one that can be found in numerous places in the environmental literature. Aldo Leopold, Holmes Rolston, III, and Robert Elliot provide archetypical articulations. Leopold, for example, states "a thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community, it is wrong when it tends otherwise" (Leopold 1987, pp. 224-5). Rolston claims that "systemic nature is valuable intrinsically, as a projective system [...] for its capacity to throw forward (pro-ject) all the storied natural history" (Rolston 1988, p. 198). Elliot, while trying to explain why environmental restorations are morally suspect, remarks that "we value the forest and river in part because they are representative of the world outside of dominion, because their existence is independent of us" (Elliot 1982, p. 86). Many other examples could be cited. Even distinct environmental orientations such as the ecofeminist ethic of care appear to share some portion of this intuition about the evolutionary process (Preston 2001). In each of these cases, the products of non-human, evolutionary processes are considered to be worthy of some degree of moral consideration. People feel that there is value in the parts of nature that have been created independently of human activity. Other values often championed by environmentalists such as 'wildness', 'beauty', 'spontaneity', 'complexity', and 'ecological integrity' each have direct or indirect connections to this central intuition about the evolutionary process. Exactly how to cash out this value, whether as value that is entirely independent of any valuer, or value that requires a human or non-human valuer to be ascribed, or value that only gains its merit when it functions in human lives in some fashion, has been the subject of vigorous debate in environmental ethics for nearly thirty years.[6] It is not necessary to go into the nuances of these debates here because, for current purposes, it is relevant only that each of the positions share a common commitment to the significance of the historical evolutionary process. In each case, the historical evolutionary process has a moral significance that is distinct from any of the products of human intentional activity. Choosing the evolutionary process as grounds for environmental value therefore supplies a firm grip on a persistent ethical intuition. It also allows us to work with an intuition that crosses over well from academic theory into policy and public discourse. Even those unfamiliar with environmental ethics often speak about nature as having some ineffable quality possessed by virtue of how it evolved independent of human activity.[7]

It is important to emphasize that according to this ethical framework the objects in nature that warrant moral concern gain that warrant from being products of a particular creative *process* deemed to be more important than any features of the products themselves. The capacities possessed by biotic nature – capacities such as rationality, sentience, or the ability to photosynthesize – do not themselves earn a natural object moral consideration; it is its relationship to a historical process that creates the bulk of a natural object's value. As the products of natural evolutionary processes, both river valleys and orangutans have natural value, regardless of whether one or the other is sentient (Rolston 1994, Katz 1996).

A second point to note is that temporal realities dictate that this ethic largely excludes any human contributory factor to the value. This is not to deny that humans can on selected occasions contribute to natural values by, for example, carefully managing a prairie through burning and grazing or by restoring a species through captive breeding. Nor is it to

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[6] For just a sample of these debates see the special issue of the *Monist* on intrinsic value (*Monist*, 75, 1992).

[7] The congressional testimony in support of the 1973 U.S. Endangered Species Act is replete with examples of lawmakers trying to find ways to express this intuition.

deny that humans can create their own kinds of intrinsic values through arts and culture. Rather, these emblematic types of evolutionary ethics simply indicate that environmentalists often have a strong intuition that nature has value in-itself, independent of humans. Nature was operating according to its laws long before humans appeared on the scene. To further emphasize this point, some environmental ethicists assert that it is nature's status as some kind of "radical other" that creates its moral significance (Birch 1990). This observation about the value residing in nature's otherness makes these ethics mostly 'non-anthropocentric'.

Before moving on, it may be necessary to quickly speak to one concern this orientation raises. Some may find the whole starting point objectionable. A large number of people who care about the environment feel that environmental values are always relative to human goods. For these people, it simply does not make any sense to talk about intrinsic natural values in some feature of nature apart from humans. This analysis, for them, seems to start in the wrong place. Furthermore, even those that claim a non-anthropocentric ethic might be concerned about the way the environmental intuition described above seems to look down on any kind of human manipulation of nature. It would be reasonable to object that by choosing the historical evolutionary process as the key value in this environmental ethic, the framework of this chapter already begs the question against nanotechnology by looking negatively upon any human manipulation of nature.

While it is true that nature-aside-from-human-manipulation has a major role to play in this ethic, the orientation is not as unhelpful as it may at first seem. It will become clear below that the value of the evolutionary process gives us only a *prima facie* and defeasible moral obligation towards nature's own creative processes. The value of unmanipulated nature is not an absolute one. After all, every organism must manipulate nature in order to stay alive. And all organisms, including humans, obey the laws of nature at every moment in these manipulations. It cannot be the case then that every human manipulation of non-human nature is wrong.[8] What this orientation can do for us is to set the burden of proof

[8] There is a large and complex question lurking beneath this paragraph about whether humans are natural beings and consequently whether human manipulations of nature are

for those that intend to manipulate nature in the place that environmentalists tend to assume it belongs, namely leaning towards the moral value of the historical evolutionary process. While there are a host of problems in determining just how high that burden of proof will be, the intuition about the value of non-humanized and naturally evolved nature is a useful reference point. And in fact, many proponents of nanotechnology may be sympathetic to portions of this ethic. Nanotechnology is often advocated for its potential environmental benefits, benefits such as pollution detection, hazardous waste clean-up, and energy efficiency. Those benefits are often measured in terms of their ability to help us protect the evolutionary and ecological values discussed. Both nano-advocates and those that protest the development of nanotechnology seem often to have the same environmental intuition in mind.

4. Sampling the Ethical Issues

The enormous range of nanoproducts envisioned makes any simple ethical judgment about nanotechnology impossible. These products range from tennis balls coated with nano-materials to help them retain their bounce to body armor made from nano-materials to protect soldiers in combat, from nano-particle coated bandages already used in many hospitals to nanobots that roam the blood stream eliminating undesirables such as cholesterol and cancerous blood cells, from nano-sensors in agricultural fields to detect moisture and the presence of salts to nano-machines that can be spread over toxic waste dumps to neutralize pollution, from nano particles able to deliver targeted drugs in the body to nano-sized interfaces with brain neurons to deliver information directly from computers to the brain.[9] Making an already murky ethical arena more complex in this case is the difficult task of telling the science fiction apart

natural or unnatural events. I will studiously avoid any attempt to answer this question here. It is one of the hardest questions in environmental ethics. But it is worth noting in this regard that very few people believe that every human action that impacts nature – including detonating nuclear bombs, making tigers extinct, converting forest into parking lots – is as natural as every other.

9 The examples come from a number of sources including *The New York Times* (11/21/03), *The Ecologist* (May 2003), *Scientific American* (September 2001), and *No Small Matter II* (2003).

from the science fact. Also coloring any potential ethical consideration of these products is a tortured history of public policy battles over technologies such as nuclear power, agricultural biotechnology, and human genetic therapies. Despite these complexities it is easy to see that some projected scenarios, for example those of escaped nanobots roaming uncontrolled through native ecosystems, are the environmentalist's worst nightmare. Others, for example the development of highly efficient solar cells and cheap pollution sensors, are the environmentalist's dream.

One strategy adopted in this chapter to help simplify the complex ethical terrain is to set aside for the moment a host of issues that are importantly associated with the development of nanotechnologies but are in no way specific to it. These could be loosely categorized as social issues (some of which were mentioned above) such as the proprietary rights of those that develop nano-materials, the dangers of creating a socio-economic nano-divide, the legal issue associated with nano tort claims, the separation between scientific nano-elites and the publics that bear the potential costs of the technologies, the privacy issues that nanotechnologies will raise, and associated concerns about personal liberties and freedom of information and opinion. While each of these is an important issue that in some cases is given particular urgency by the development of nanotechnology, there is nothing about these issues that is new or distinctively nano. The frameworks provided by existing and familiar ethical theories that deal with social questions, such as Rawlsian notions of distributive justice or Lockean ideas of natural rights, are as applicable here as elsewhere.

With this attempt to narrow the ethical territory in hand, a useful way to proceed is to select a representative sample of the ethical issues that emerge out of nanotechnology. The following four are chosen primarily for two reasons. The first is that these issues appear to be the ones that have attracted most of the attention of those concerned with the ethics of nanotechnology. The second is that they seem to speak most directly to what is worrying about nanotechnology from the environmentalist's perspective. The four issues are as follows:

(1) The creation of radically new types of materials,
(2) The uncontrollable replicator problem,
(3) The use of nanotechnologies to enhance the human condition, and

(4) The projected ability of nanotechnologies to satisfy all human material needs.

These categories are by no means intended to be exhaustive, nor are they mutually exclusive. They do, however, capture a range of the ethical issues that nanotechnology presents. They also lend themselves to the kind of modest initial environmental ethics analysis that is the goal of this chapter.

4.1 The Creation of New Kinds of Materials

Top-down and bottom-up types of nano-technologies can create materials, structures, and devices of kinds that have never before appeared in nature. There are two types of concern this raises for environmentalists. The first is a somewhat abstract ontological worry about the ethics of creating new, artificial kinds that have never been seen before. The second is the question of whether biological and ecological systems can continue to function in the presence of these new kinds of materials.

The first worry has been raised in an articulate way by Keekok Lee in *The Natural and the Artifactual: The Implications of Deep Science and Deep Technology for Environmental Philosophy*. Through a careful discussion of the nature of artifacts, of Marx's understanding of ourselves as *homo faber*, and the role of the machine metaphor in human discourse, Lee suggests that the threats to the environment that have hitherto been considered urgent pale into insignificance when placed alongside the threat of artificial kinds produced by nanotechnology. With nanotechnologies, environmentalists have to worry not just about the loss of 'secondary values' such as nature's complexity or its alleged stability, they have to also worry about the loss of 'primary values' such as the very nature of nature as an ontological kind. Nanotechnology, Lee claims, is capable of "turn[ing] biotic and abiotic entities into artifacts" constituting "a radical threat to the ontological category of the natural" (Lee 1999, p. 114). This new threat means that environmental philosophy should orient itself around combating dramatic ontological challenges rather than axiological ones.

There appear to be two reasons why this creation of artificial kinds is a problem for Lee and these reasons can both be traced to the ethical intuition described above. Lee appears to be worried that the replacement of nature with a world of artifacts ("material embodiments of human intentionality") represents a significant ontological loss in itself. Something of considerable intrinsic value has disappeared to be replaced by something of less value. Nanotechnology threatens a diminution of metaphysical kinds by replacing the products of the evolutionary process with something artificial. The second reason, clearly not entirely separable from the first, is that this leaves humanity in an ethically and psychologically impoverished position. Lee contends that systematic elimination of the natural leads to a "narcissistic civilization". The narcissistic civilization created by nanotechnology would no longer have available the "radical otherness" of nature to keep itself in perspective. Lee believes that there is something about the radical alterity of unmodified nature that is important. The independence of nature is an "ontological value" that needs to be preserved in order to maintain an appropriate sense of where humans fit on earth (Lee 1999). A proper sense of ourselves, Lee supposes, is strongly connected to otherness.

The ontological worry that Lee articulates does indeed appear to be a loss. The environmental intuition detailed above values processes and products that are separate from humans. 'Separate' here can mean a couple of different things. Sometimes it will mean valuing organisms that are self-sustaining without human intervention and sometimes it will mean valuing ecosystems that have causal histories independent of any human interference. Environmental ethics will tend to grant a Hereford cow, for example, more moral standing than a car since, unlike the car, the cow is an 'autopoietic' entity or a 'teleological-center-of-a-life' able to sustain itself independently of humans. Similarly, these same ethics will tend to grant the North American bison even more value than the Hereford cow since the bison's causal history does not contain human manipulation of the genome in the way that the Hereford cow's does.

Lee finds an analogy to the kind of replacement of nature she is concerned about in Bill McKibben's *The End of Nature*. In this influential 1989 book, McKibben pointed out how human activity has quickly led to lives lived in a wholly artificial world. According to McKibben, human-caused effects on the atmosphere and global climate have lead to the replacing of nature with an artifact, an artifact that McKibben sometimes calls "Earth 2" (McKibben 1998). Lee presses her argument by claiming that the end of nature to which McKibben drew our attention is less serious than the kind she is worried about with nanotechnology. Human-caused global climate change is not deliberate in the same way as is the creation of new materials through nanotechnology. It is an accidental by-product of human actions. Moreover, Lee points out, climate change threatens something metaphysically different from the threat posed by nanotechnology. What climate change eliminates is nature-unimpacted-by-human-caused-effects ($\text{Nature}_{\text{Non-humanized}}$) rather than the nature-constructed-by-natural-processes ($\text{Nature}_{\text{Natural Kind}}$) that nanotechnology threatens. Lee insists that the latter is a more significant loss.

While granting that the environmental ethic we are using as a guide will recognize a loss here, it is doubtful that this loss is quite as significant as Lee suggests. One reason to suspect Lee is exaggerating her concern is that while she is certainly right that environmentalists tend to see more value in cows and bison than they do in cars and washing machines, few of them really want to ban cars and washing machines. Neither the creation of artifacts, nor the creation of artificial kinds, seems in itself to ever be enough for environmentalists to talk about prohibitions. If the creation of artificial kinds were itself morally objectionable then synthetic chemists creating over 900,000 new chemical substances a year would receive much more scrutiny from environmentalists than they currently do (Schummer 2001). For the most part, we seem to live alongside artifacts and artificial kinds reasonably well. In some cases, we find artifacts such as paintings and antique wooden furniture especially valuable and appealing. Occasionally we are glad to use artifacts – for example, recycled plastic – to prevent us from destroying more of pristine nature. While many do lament how our lives are increasingly surrounded by artifacts rather than by nature and while others do express some alarm at the activities of synthetic chemists, such resistance hardly amounts to an ethical basis for a prohibition of nanotechnology.

To sustain her case, Lee would have to show two additional things. First, she would have to show that there is something particularly significant about the creation of artifacts at the nanoscale as opposed to the creation of artifacts at the scale of plastic cups, tables and chairs, and climate-changed landscapes. There would have to be something about human intentionality embodied at the atomic or molecular level that is more morally culpable than human intentionality embodied at the level of tables and chairs. Unfortunately, making this case would seem to involve indicting chemistry and particle physics at the same time, a radical position that would be difficult to maintain if those sciences are to have any merit at all. The second thing she would have to show is that there is a real danger of the products of nanotechnology entirely replacing all natural kinds. Except in the 'grey goo' scenario – discussed in Section 4.2 – this does not seem likely. As long as one's ethic still insisted upon the inherent value of the natural kinds produced by evolutionary processes and as long as it ensured that those natural kinds received adequate protection even as more and more artificial kinds were created, Lee's worry about an ontological loss appears to be overstated. An ethic based on the value of the evolutionary process simply does not do enough for a blanket prohibition on all nanotechnologies since there is nothing about nanotechnology that logically entails the total elimination of evolved nature.

The argument from the creation of novel materials, however, has another side to it, one that seems to have considerably more normative force. This is the argument articulated by Canada's ETC Group. The ETC group has called for a moratorium on the production of nanomaterials in the absence of prior testing for health, safety, and environmental impacts (ETC 2003). The ETC group argues that since both human and other parts of biotic nature evolved in environments largely absent of any notable presence of nano-sized particles, extreme caution should be exercised before exposing biotic organisms to these particles.[10] The unnatural character of nanoparticles, according to ETC, makes them potentially dangerous.

Recent studies have indicated that nano-particles do indeed provide problems for organisms that did not adapt in their presence (Gorman 2002, ETC 2003). Buckminster Fullerenes in water at 500ppb have been

[10] Exactly how much nanosized material we were exposed to over evolutionary time is unclear. Some natural salts that evaporate from the ocean are nanosized. Some carbon products of combustion are also nanosized. Scientists have recently discovered part of biotic nature they call 'nanomes'. The possible existence of naturally occurring nanobacteria is still under debate (*New Scientist*, 19 May, 2004).

discovered to cause brain tissue damage in fish (Oberdörster 2004). Carbon nanotubes washed into the lungs of mice have proved resistant to any natural process of ejection, causing unusual and long-lasting lesions (Lam *et al.* 2003). Nanotubes also have the ability to make their way into the nucleus of a cell and pharmaceutical companies have known for some time that nanoparticles can cross the blood-brain barrier (Howard & Maynard 1999, Oberdörster 2003). While many companies are hoping to use these features of nanoparticles to deliver helpful substances into the human body, it seems clear that the potential exists for these processes to cause biological harm. Even if the nanoparticles themselves prove to be mostly benign – something beginning to look increasingly less likely at this point – Vicky Colvin at Rice University has recently shown that known toxins such as PCB's and pesticides can bind to carbon nanotubes and use them as vehicles to hitch a ride into different parts of the body (Colvin 2003).

Two observations add to the growing sense of alarm. The first is the worrying lack of research on the human and environmental health and safety effects of these new materials. The technologies are so new, and the driving forces behind their development have been so firmly located in the military and the commercial sectors, that health and safety studies have generally been neglected.[11] The National Nanotechnology Initiative devotes only a very small portion of its funds to environmental and biological health studies (ETC 2003, p. 3). The second observation is the fact that there is no regulatory mechanism in place at all at the moment directed specifically towards the unusual mix of quantum and classical properties present at the meso-realm. Regulations are still geared towards familiar macro forms of the material. In the U.S., carbon nanotubes and buckminster fullerenes are currently regulated in the same way as graphite. Given that it is precisely the *differences* between the properties of the classical and the nanoscale materials that make the latter so interesting, it seems imprudent for the protocols for the different types of materials to be the same. As Eric Drexler of the Foresight Institute, a nano-booster in

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[11] The Center for Biological and Environmental Nanotechnology (CBEN) at Rice University is one of the few research establishments devoted to investigating these health and safety issues.

most areas, points out "You can't simultaneously proclaim a product is new and has all these novel properties and at the same time claim that it can be regulated as if it were nothing different" (*Washington Post* 2/1/2004).

One quick pause for perspective is appropriate at this point. It is certainly possible to overstate worries about the biological and ecological harm attending non-naturally occurring substances. Our chosen ethic would be unlikely to prohibit all artificial kinds. If fear of the unnatural was an absolute norm then the first time that pieces of wood were fashioned into a table we might have worried about the health effects of tables. It is clear that not all artifacts are harmful simply because humans did not evolve alongside of them and some (such as multi-vitamin pills) are even believed to be beneficial for health under the right circumstances. There is, however, a principled reason for being more cautious about the fabrication of novel nano-materials than about the fabrication of tables and chairs. Past experience with human and environmental health suggests that scale is a relevant factor in determining whether a material will cause harm to a biological system. Inhalation, absorption, diffusion, and transmission across natural barriers have all proven to be vectors for disease and biological harm that depend upon scale. The introduction into the human and natural environment of large numbers of nano-particles before their biological and dispersion effects are well known does seem to be a cause for concern.

A quick historical comparison is illuminating. The conditions that created the public uproar in Europe over genetically modified organisms (GMOs) seem to be strikingly similar to what is currently going on with nanotechnologies. In the case of GMOs, scientific unknowns over environmental and health effects, the lack of an effective regulatory structure, and an unknowing public exposed without their consent by commercial interests combined to generate considerable anger and activism amongst environmentalists. Given the well-established ethical presumption of informed consent before exposing an individual to a possible danger, this resentment appears to have been justified even if it should turn out that the genetically modified crops in question were largely benign.[12] All of the unsettling factors that motivated resistance to GMOs seem to be in place in the case of the products of nanotechnology. The European Union's Environmental Bureau is seeking to apply to nano-materials the same 'No data, No market' precautionary principle originally developed for their chemical industries.[13] Given that it is certainly possible there are real risks to human and environmental health created by the newness and scale of nanomaterials, some form of precautionary approach seems appropriate. The ethical value of the evolutionary process at the very least suggests that the burden of proof lies with those seeking to introduce new nanomaterials into the environment rather than with those resisting them.

4.2. A Brief Dip into the Goo

Most people who have heard or read anything about nanotechnology have come across the uncontrolled replicator or 'grey goo' problem. It was nano-booster Eric Drexler who first raised the possibility of nanomachines going out of control (Drexler 1986). Drexler pointed out that since molecular manufacturing takes place at such a small scale, large numbers of manufacturing units would have to be working simultaneously on the same project in order to ever create anything useful on the macro-scale. Practical necessity would therefore probably require that such a fabricator be able to reproduce itself. In addition to its ability to reproduce itself and perform its manufacturing tasks, each fabricator would have to be able to solve the problem of directed locomotion in order to be able to procure energy for itself from its environment to complete its tasks. The worry Drexler raised was that a population of such machines left to its own devices could increase in numbers exponentially and consume itself out of an environment. The result would be an environment transformed into a grey goo of nanobots and their waste products. 'Green goo' is an artificially created self-replicating *biotic* entity

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[12] See 'UK Scientists Back GM Maize Crops' at newsvote.bbc.co.uk/mpapps/pagetools/print/news.bbc.co.uk/1/hi/sci/ tech/3532927.stm.
[13] See 'EU Chemicals Policy' at www.eeb.org/activities/chemicals/main.htm.

that carries the same risk. These possibilities are more technically termed global ecophagy by omnivorous replicators.

Bill Joy, co-founder and chief scientist of Sun Microsystems, suggested in an article in *Wired Magazine* in 2000 that nanotechnology masks too many dangers for us to allow ourselves to be seduced by it (Joy 2000). He points out that a grey goo scenario could happen by accident or, more worryingly, it could happen deliberately. The combination of technologies known as GNR (Genetics, Nanotechnology, and Robotics) is so powerful, Joy warns, that it will "spawn whole new classes of accidents and abuses". Self-replicating nanobots will make possible knowledge enabled mass destruction (KMD), a threat that greatly exceeds any we face today. Joy worries that "we are on the cusp of the further perfection of extreme evil, an evil whose possibility spreads well beyond that which weapons of mass destruction bequeathed to nation states" (Joy 2000).

There are plenty of empirical questions about whether the goo threat is real. Some commentators doubt that we could ever be foolish enough to let loose machines that are able to replicate and nourish themselves. Others suggest that the relatively high energy requirements for such machines preclude their possibility. Drexler himself has recently co-written an article that attempts to dispel the worries that his earlier remarks created (Phoenix & Drexler 2004). Since one of Phoenix and Drexler's main points about exponential manufacturing is that nobody but a terrorist would purposefully let loose a material that would end up consuming the whole planet – a possibility that they refuse to dismiss – an ethical evaluation of the grey goo problem initially seems likely to follow the same path as any discussion about a powerful technology that has the potential to be used for murderous means. The argument would essentially be that such a technology should not be allowed to fall into the wrong hands. Nevertheless, consideration of what exactly is wrong with self-replicating nanotechnologies in the light of our selected ethic is illuminating.

An uncontrollable, environment-consuming goo is obviously undesirable for reasons of self-interest. This is to say nothing of its lack of aesthetic appeal! But the more interesting moral issue that it raises from an environmental ethics perspective is adroitly anticipated by Joy. Joy states that GNR technologies cross a fundamental line when they allow the "replicating and evolving processes that have been confined to the natural world [...] to become realms of human endeavor" (Joy 2000). If self-locomoting nanobots are able to solve problems and to replicate themselves, then the process of natural selection has been altered. If the fabricators sometimes produce copies of themselves that are not perfect, then they will also be able to evolve. It is this attempt to reproduce the evolutionary process with artificially created replicators and then let this process loose on an unprepared natural environment that is most worrying to the environmental ethicist. The fabricated biology of a nanomachine will now be able to interfere directly with the historical evolutionary process, the very thing that is the basis of the environmental ethic.

The dangers of amending the evolutionary process to serve human ends are many. Some of these problems have already appeared with varying degrees of severity in the case of hybridization of plants and other agricultural genetic technologies. The ecological problems of the homogenization of the biotic community, the extinction of wild species, the evolution of more persistent insect pests, and the spread of non-native flora and fauna into native ecosystems have all accompanied previous human interference with the evolutionary process. But each of these existing problems are just pale shadows of the troubles that self-replicating nanomachines could cause.

Self-replicating nano-sized fabricators differ from these other human interferences with the evolutionary process in at least three important ways. The first is biological dissimilarity. The products of agricultural biotechnology are subject to several layers of natural limitation due to their biological similarities to natural products of evolution. Because of its biological similarity, a Hereford cow, for example, is subject to many of the same natural checks and balances as a bison. Left to its own devices, in fact, the Hereford cow will fare considerably poorer in the face of natural forces than the bison. But while a cow bred for milk production and docility is biologically similar to a bison, a nanomachine is absolutely not. The abiotic self-replicating products of nanotechnology will be so dissimilar to anything that has naturally evolved that the chances of there being any natural checks and balances on their populations are slim. The second factor that differentiates previous anthropogenic disruptions to the global ecology from those of nanotechnologies is the issue of ecological niche. When humans introduce species like kudzu, cheatgrass, and zebra mussels into non-native environments these organisms wreak such havoc precisely because there is nothing to check their spread outside of their native ecological niche. Since self-replicating nanotechnologies lack any native ecological niche at all the likelihood of there being any ecological checks on their spread is small. Other than limitations on its energy supply, it is completely unclear what – if any – natural factors will limit the reproductive success of an abiotic nanobot. The third reason that the prospect of self-replicating nanobots differs from the hybridization of flora and fauna has to do with volume. The sheer number of entities that could be produced in a short time by self-replicating nanobots makes this prospect dramatically different from any previously known artificially produced organism. A nanosized particle is one one-hundred-thousandth of the diameter of a human hair. This means that the number of nanomachines required to perform any task at the macro level would have to be simply vast. The power of an exponential increase in the number of self-replicating nano-machines (if they were ever allowed to exist in these kinds of numbers) would be simply staggering. Plagues of rats or locusts would look like trivial biological phenomena by comparison.

Joy's concern about human interference with the process of evolution seems to rest on fairly solid precautionary ground. In Section 4.1 the initial reluctance to fiddle with the products of the evolutionary process turned out to be defeasible in the light of the fact that we create many artifacts, even biological ones, that are often not dangerous to us. But problem-solving self-replicating nanobots co-opt not just biology but also the evolutionary process itself for human ends. This seems to add a whole different level of ethical concern. So regardless of the empirical likelihood of the grey goo scenario ever actually occurring, environmental ethicists seem to be on solid ground to reject any attempt to create them. The central value of the environmental ethic upon which they rely is directly contravened and this provides a good reason to object.

4.3. Human Enhancement Technologies

A third area of the application of nanotechnologies that raises concerns for an adherent of our environmental ethic is the area of human enhancement. Ethical questions about enhancements of human health are not uniquely associated with nanotechnology and discussion of this issue is already well developed in the medical ethics literature (Parens 1998, Resnik 2000). But nanotechnologies are likely in the near future to make possible more subtle and effective enhancements including some that will involve dramatic modifications of the human genome. The ability to operate at the scale of telomeres makes possible extending or shortening the life of a cell (Leutwyler 1998, McKibben 2003). The projected creation of microscopic nanobots that can repair cells from the inside or wander through the bloodstream destroying cholesterol and other undesirables promises mark improvements in longevity and quality of life. The technologies being developed for molecular assembly will make direct genetic manipulation easier and cheaper than before. Nano-visionaries believe that these kinds of technologies will dramatically improve health and delay aging. Some even suggest that nanotechnology brings human immortality within reach (Drexler 1986).

In addition to these versions of human enhancement that work with the patient's existing biology, there are other areas of nanotechnology that see the real promise as lying in a new synthesis of the biotic and abiotic. The ability to construct machines with parts that are no bigger than neurons offers the possibility of tying the electrochemical activity of the brain directly into electronic circuits. Significant progress is being made on interfacing biological materials directly with nanomaterials (Webster *et al.* 2004). The proposed area of research known as Nano-Bio-Info-Cogno (NBIC) combines nano and biological technologies with information technologies and cognitive science. NBIC pursues the goal of human-machine hybrids (or cyborgs) that can outperform existing humans in numerous ways.

The prospect of enhanced cyborgian humans with microelectronic implants that increase their memories or genetic enhancements that increase their intelligence has provoked a predictably strong reaction from political and environmental commentators. Francis Fukuyama, addressing mainly the application of traditional biotechnologies to human enhancement has lamented that our 'posthuman' future would be a troubling one in which many of the social and political frameworks that have been successfully developed to accompany our existing concept of human nature would no longer be effective (Fukuyama 2002). Liberal democracies work, Fukuyama believes, because they fit the way we naturally are, a condition that promises to be irrevocably changed by biotechnology. For similar reasons, Bill McKibben – more alert than Fukuyama to how nanotechnologies bear on this debate – has asked us to yell a technology-halting "Enough!" to post-humanism through nanotechnology. McKibben makes the case that it is our very mortality and imperfection that makes life meaningful (McKibben 2003). Without death, or with significantly longer lives, or even with some of the more modest enhancements promised by nanotechnicians, McKibben questions how meaning-generating pastimes such as staying physically fit or mentally alert could continue to provide us with the same rewards.

The arguments for and against human enhancement are complex. The fact that many of the enhancements discussed are still squarely in the realm of science fiction makes them harder to think about in a principled way. It is difficult, for example, to reflect on a human future that does not include death. The ethical frameworks that we might use – utilitarianism, rights, autonomy – all seem seriously compromised in certain ways. Nevertheless, there is a range of arguments that can be leveled against human enhancement. Some are social justice arguments that deal with the issue of who will have access to these technologies and who will profit from them. Others are arguments specific to human biology and include concerns about the unknown health effects of human enhancement, worries about the homogenization of the human genome, and arguments like McKibben's about potential loss of meaning given a changing human potential. There is also suspicion of 'playing God' in addition to a simple aesthetic revulsion towards cyborgs.

The first point to note about human enhancement from the perspective of one that values historical evolution is that our existing genetic and biological inheritance is indeed held to be something worth protecting. Our biological inheritance takes the particular form it does as the result of epochs of crafting at the hands of the very natural selective pressures that are valued. It is precisely this history that environmental ethics has identified as being valuable. Aldo Leopold displayed his commitment to the value of this historical lineage when he embraced the sound of a sandhill crane as "a trumpet in the orchestra of evolution" and the crane itself as wearing "a paleontological patent of nobility" (Leopold 1987, pp. 96-7). Others argue that the genetic material inside an organism, perhaps more than the organism itself, is the carrier of the evolutionary value because the genome symbolically embodies the evolutionary process. With DNA, Holmes Rolston, III has suggested, "earth gained memory" (Rolston 1988, p. 98). It is the memory of the eons embodied in DNA that makes a token organism valuable. So any alteration to the human genome will be problematic for a person committed to the value of the historical evolutionary process.

However, beyond this initial acknowledgement of the value that organisms and their genomes inherit from their evolutionary past, environmental ethicists will soon find themselves deferring to medical ethicists once they recognize that there are a large number of medical procedures performed on humans today that already tamper with this evolutionary inheritance. *In vitro* fertilization and other reproductive technologies make it clear that humans do not think it necessary to stick with the evolutionary hand we have been dealt. Commonplace medical technologies such as artificial hips, heart pacemakers, and retinal implants already tinker with our inherited biology and raise the issue of human cyborgs (Haraway 1991). Innoculations and even multivitamin pills demonstrate that we are seldom happy with the functioning of the biological machinery with which we were born. Attempts by medical ethicists to find principled reasons for restricting manipulations of the human body and its genome have met with mixed success. Distinctions such as the one between therapy and enhancement have proven notoriously slippery. Other distinctions based, for example, on the degree of invasiveness of a particular method of treatment or on how much of an original biological process is left intact after treatment have varying degrees of traction. Even in the cases in which useful distinctions are still made, it is clear that there exists no absolute prohibition on anthropogenic manipulations of either the human body as a naturally evolved biological organism or its genome as a representative of a biological kind. Given what is already agreed to be ethically acceptable, the environmental intuition selected above does not appear to contain grounds for a blanket prohibition on human enhancement through nanotechnology.

But this being said, the environmental intuition identified can still provide a helpful orientation to the question of what may or may not be acceptable degrees of manipulation of human biology or the human genome. There is one class of enhancements envisioned by nano-enthusiasts that are distinctive because their advocates seem to have in mind not only the goal of improving human health but also the goal of fundamentally changing what we mean by a human being. The Extropy Institute, for example, interested in the possibility of 'transhumanism', unabashedly claims, "We aim to gradually but firmly change the rules of the game called 'being human'." Their startling mission statement goes on saying that "many of us passively accept or stridently defend the inevitability of human stupidity, malice, conflict, aging, and death [...]. The primitive parts of our brain spur us to envy, to hate, to despair, and to kill. Our philosophies and our religions attempt to express our highest values, yet we use them to oppress and control. We use them to crush the world's complexity into a simplicity that we can clutch like a security blanket for the human condition [...]." Their mission statement encourages us not to remain "slaves to our evolutionary history" and invites us to participate in their quest to "connect and cultivate the ingenious and intrepid shapers of the future".[14]

Such a statement illuminates possible grounds for the environmentalist to object to some forms of human enhancement through nanotechnology. If the intention is to use the technology to deliberately divorce humans from our evolutionary and ecological past, then the holder of an environmental ethic that values the evolutionary process can loudly object. The statements of the Extropy Institute are examples of such an intention. It would not be consistent for the environmental ethicist to champion the evolutionary process and then to embrace a post-human future that depended upon departing from this heritage. The chosen environmental intuition therefore provides a reason to be suspicious of manipulations that dramatically change the meaning of what it is to be hu-

[14] See www.extropy.org.

man. While the line that the environmentalist wishes to draw will likely prove to be fairly fuzzy and tricky to administer, this fuzziness would certainly not be unique amongst the tough questions that reside within medical ethics. Environmental ethics for its own part still wrestles with the question of the degree to which humans are (or should remain) natural beings and so will certainly have a difficult time establishing what is to count as an undesirable departure from our ecological and evolutionary heritage. But at the very least, the commitment to the value of the evolutionary process sets the burden of proof in such a way that it provides a good starting point for the discussion.

4.4. Projections about Satisfying all Human Needs

This category is a broad catch-all for many of the promises of the nano-boosters that have escaped mention already. These promises include unarguable benefits such as overcoming material scarcity, eliminating pollution, creating unlimited low cost solar power, ending poverty, curing cancer or the common cold, restoring extinct species, and making available to everyone cheap and powerful computers. Mark Modzelewski, Executive Director of the Nanobusiness Alliance, states confidently "the importance of nanotechnology to the future of mankind cannot be overstated. Nanotech's promise is clean industries, cures for disease, nearly unlimited energy supplies, a continuance of Moore's Law, and perhaps the end of hunger" (Ecologist 2003, p. 36). Others suggest advances in the quality of life comparable to those achieved after the industrial revolution (ESRC 2003). One of the reasons for including this broad additional category is to bring attention to the politics of promoting nanotechnology. It is a veritable utopia that the nano-boosters describe.

The first thing that the environmentalist will notice about all these promissory notes is that they have a ring of familiarity to them. Most technological optimists have promised futures in which we would apparently be free to sit on the beach soaking up the sun while the little drudgery left in the workplace was performed by machines. Humans are continually assured by cornucopians that they will soon be freed up to do nothing but pursue art, recreation, and rewarding personal relationships. As has proven to be the case with these previous utopian promises, there is reason to be skeptical about the likelihood of these conditions ever coming about. The promises are made expressly to sell a project or a product. The benefits are touted particularly loudly when the public is getting a hunch that there also might be some risk associated with the product. Electricity too cheap to meter was never a result of nuclear power, nor did its boosters ever think to offer any warnings about the health and safety issues associated with the disposal of nuclear waste. The Pollyanna attitude towards technological futures is often vastly misleading.

Environmentalists that value the historical evolutionary process have particular reasons to see through this kind of talk. Such rhetoric may encourage people to drop their guard with prudential actions that are important today. The promise of electricity too cheap to meter does not encourage energy conservation in the present. The promise of the end of resource scarcity can do nothing but foster the profligate use of currently available resources. Promises to end all pollution and clean up all toxic waste dissuade people from worrying about the messes they are creating today. In each case, existing environmental values such as clean water, intact habitat, and species diversity end up being imperiled by the extreme optimism of the boosters of a technology. Since ecological harms like extinction are not likely to be reversible, it seems prudent to be initially skeptical of the kinds of promissory images that many of the boosters of nanotechnology promulgate.

On the other hand, since the promises and threats of nanotechnology are so multiple and varied, it also seems wise to evaluate them on a case-by-case basis. Better pollution sensors made possible by nanotechnology are hard for environmentalists to reject. Materials made out of carbon nanotubes that are 6 times stronger than steel and 100 times lighter make possible vehicles for transportation that would be vastly more energy efficient than current models. Nanobots that can descend into the depths of contaminated sites and neutralize the pollutants found there are an attractive prospect if safeguards are in place to prevent them from causing additional environmental harm of their own. All of these new technologies would make possible the preservation and restoration of habitat, which in turn might enable natural evolutionary processes to continue. In each case, the costs and benefits of a technology should be weighed in much the same fashion as any cost and benefit is weighed; using tried and tested ethical structures to make the calculations. Such calculations demand a sober analysis of the relevant risk in order to be meaningful. Unfortunately, there is normally a bias against doing adequate risk analyses when a product promises great commercial gain. The case of genetically modified crops in the United States is an example of commercial interests rushing a product to market without adequate consideration or even public admission of possible costs. The same thing appears to be happening today with carbon nanotubes. Concerns about the possible toxicity of nanoparticles discussed in Section 4.1 have to remain clearly in view. Serious consideration of where the burden of proof lies will remain important. Doug Parr, chief scientific advisor to Greenpeace UK, reminds us of how easy it is to confuse "no evidence of risk" with "evidence of no risk" (Ecologist 2003, p. 38). The European Union's "no data, no market" policy again seems appropriate.

Nanotechnology comes with both utopian and dystopian visions. In *The Arrogance of Humanism* David Ehrenfeld pointed out the danger of quasi-solutions, solutions that solve one problem while creating several others (Ehrenfeld 1978). Nanotechnology, with such lofty goals and so little known about its effects on biology and ecology, is a fertile arena for generating quasi-solutions. Sometimes it is good to be spurred on by optimistic visions about what a developing technology might do for the human condition. However, environmental ethics can indicate when that vision is becoming distorted. If the vision explicitly includes the goal of fabricating biology and outdesigning evolution, almost all existing environmental ethics will object on both prudential and theoretical grounds. The grey goo scenario is just the most extreme example of a number of dystopian possibilities which, while they need not be used as reasons for abandoning some of the real promises of nanotechnology, should at least be kept in mind alongside the rosy futures outlined by its more enthusiastic advocates.

Those who value the evolutionary process will also always insist that whatever benefits to humankind are promised by nanotechnology, an ethical obligation will remain to continue to protect existing natural diversity. Bald eagles and high deserts, temperate rainforests and two-toed salamanders will all continue to be of inherent value even in the face of whatever technological developments are in the pipeline. Those that value the evolutionary process will continue to advocate their protection. With this in mind, these advocates will likely be moderately skeptical of the most optimistic promissory notes of nanotechnology and be prepared to proceed cautiously with the developments that appear capable of delivering the greatest environmental benefits for the least amount of risk.

5. Conclusion

There were two goals in this chapter. The first was to suggest that environmental ethics supplies an appropriate framework to begin to consider many of the most salient ethical issues surrounding emerging nanotechnologies. The second was to take a representative environmental ethic, one with wide appeal and broad applicability, and to evaluate a number of the most frequently discussed promises of nanotechnology through the lens of this ethic. An environmental ethic that values the evolutionary process proves to offer a number of prima facie reasons to be cautious about many of the promises and threats of nanotechnology. However, because it proves harder than expected to make conceptually clear distinctions between the products of nanotechnologies and those of existing chemical and biological technologies such as plastics and *in vitro* fertilization, the reasons for caution are often advisory rather than absolutely prohibitive. Only in a few cases do the promises and threats of nanotechnology send up particularly strong red flags. One of these is the case of the introduction of radically new materials into human and natural environments, materials that may prove to be biologically and ecologically harmful. Another is the case of technologies that consciously seek to replicate the process of evolution by natural selection. A third is the prospect of using nanotechnologies to enhance humans away from their inherited evolutionary identity. The latter of these two are occasions in which the developer of the technology seems to be too carried away with the idea of a fabricated biology. The red flags that this behavior raises are likely to provide strong rallying points for activist communities.

The quick evaluation performed here in the light of the selected ethic is in no way intended to exhaust the range of ethical considerations relevant to nanotechnology. There are plenty of additional tests – both environmental and social – that nanotechnologies will have to pass before any of them can be embraced with the kind of enthusiasm of their boosters. But the analysis does provide warnings worth heeding at a time when the environmental community is just beginning its mobilization against the threats of nanotechnology it perceives.

Acknowledgments

The author is grateful to Joachim Schummer, Jason Wiener, Lisa Miller, and two anonymous referees for helpful comments and editorial suggestions on earlier drafts of this chapter.

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CHAPTER 12

NANOSCIENCES AND THEIR CONVERGENCE WITH OTHER TECHNOLOGIES: NEW GOLDEN AGE OR APOCALYPSE?

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Nanosciences and nanotechnologies are developing at an incredibly rapid pace, promising a true revolution in a wide variety of fields where the capability to manipulate matter at the atomic or (supra)molecular scale is essential. This includes information processing systems, medical diagnoses and treatments, energy production and sustainable development, as well as a number of more futurist ideas that, as yet, remain pure fiction. These developments have begun to generate controversies and fears in the scientific community itself and the larger public. This chapter critically reviews the potential problems of an uncontrolled 'nanoworld' (grey goo, toxicity of nanoparticles, RFIDs, privacy, *etc.*) and the associated fears, as they appear in the literature. Suggestions to effectively manage controversies in this field, based on a sociological approach, are proposed.

1. Introduction

The end of the twentieth century witnessed a major scientific and technological development, the consequences of which are only now beginning to become apparent. Three factors – a better understanding of the properties of matter at the atomic level, progress based on the molecular approach to the way living organisms operate, and the rise of information processing – have led to the increasing unification of condensed state sciences (physics, chemistry, biology) on the nanometer scale, forming what we now know as the nanosciences. The origins of this movement are often traced to the end of 1959, the date of the founding speech by Richard Feynman 'There's plenty of room at the bottom',[1] made at the annual meeting of the American Physical Society at Caltech. Rather than the emergence of a fundamentally new discipline, the nanosciences can be considered the result of the convergence of various disciplines on the (supra)molecular level, or even as a new way of looking at old questions. We can imagine a future meeting of these disciplines with the science of complexity, currently the missing link between the well-controlled nano-scale objects and much 'richer' systems, such as Nature develops for cells and the brain. At the same time, propelled by new and ever increasing numbers of applications, the world of technology is undergoing a similar evolution. During the 1990s there was increasing awareness of the potential of hybrid applications bringing together microelectronics, biology, and information technology, particularly in the form of communicating objects, biochips, and miniature mechanical systems.

The coming-together of this group of disciplines is sometimes referred to as NBIC convergence, (for nanoscience, biology, information technology and cognitive sciences). This evolution – sometimes considered a revolution – can be seen to herald major innovations, the implications of which could in certain cases profoundly affect our way of life. All fields are concerned, and huge investments (billions of euros) have been approved in the US, Europe, and Japan. In the short term, these have been directed to sectors such as information technologies, medicine, sustainable development, and the energy sector, for all of which there are significant research programs and already products on the market.

Similar themes, exploring the long-term developments of the nanosciences, have also been taken up in literature, in books by Ray Kurzweil, Hans Moravec, and Eric Drexler, among others. These works should be regarded as seeking to stimulate long-term reflection, rather than as predictions to be taken literally. They are based on certain scientific facts (their authors having worked in the fields they explore) but for the moment are fictional accounts. They paint a picture of a society

[1] The text of Feynman's speech is on the Caltech website [www.its.caltech.edu/~feynman/plenty.html].

where control of manufacturing on the atomic scale enables the most extravagant ideas to be realized.

- One of these is increasing computational capacity to the point where it is possible to create systems with a higher level of performance than the human brain, the goal being to produce autonomous machines, which may demonstrate 'consciousness' (the meaning of which remains to be defined), and interfaces with the human brain (to extend its capacities, or to plug our senses into a virtual reality) (Moravec 1999, Kurzweil 1999).
- In the same way, convergence of nanotechnology with other disciplines would enable deficiencies in the human body to be repaired, influence our senses and the way our brains work in a profound way, and even improve human being. This topic is addressed in the NSF report *Converging Technologies for Improving Human Performance* (NSF 2002).
- Another idea is the possibility of manipulating matter at the molecular level to produce optimized devices from which all the elements could be re-assembled, atom-by-atom, after use. The founding document for this line of reflection is the often-quoted book by Eric Drexler *Engines of Creation* (Drexler 1986). In this seminal work, the author spends a long time describing 'assemblers', nanomachines capable of manufacturing optimized products, and also of creating themselves: machines imitating living entities.

Scarcely have the promises of nanoscience been formulated in the fields for which significant progress is expected (see above), that terrifying perils are held to await us in a future that is both apocalyptic and imminent. Furthermore, it has often been the pioneers themselves, such as Eric Drexler and Bill Joy in his famous 2000 article[2] 'Why future doesn't need us', who have provoked these fears at a stage where no-one – and certainly not the general public in its ignorance of nanoscience – had started to pay attention to it. It is a strange case of the Sorcerer's Apprentice taking on the role of Cassandra.

This means that nanoscience and nanotechnology are subject to controversy before they can be said to really exist. They are expected to

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2 Joy's article can be downloaded from [wired.com/wired/archive/8.04/joy.html].

demonstrate real advantages while supposed negative effects are already being criticized and held to be the harbingers of veritable catastrophes. Over the past few decades, developments in science and technology have inspired ever-greater fear: nuclear technology, cloning, information technology, GMOs (see, for example, Farouki 2001) in a broader context of increasing, and apparently irreversible challenges to the traditional notion of progress. However, the question posed by nanoscience and nanotechnology is in the end perhaps not simply one more question that specialists and decision-makers have to deal with, through a new governance process, in order to continue to move forward despite the reservations (supposed, real, or emerging) of society.

Jean-Pierre Dupuy underlines another viewpoint (Dupuy 2004). The NBIC convergence implies an evolution of our representation of Nature, in particular life and cognition: while considering all the processes at the molecular level and trying to identify the 'algorithms' that rule theses processes, humans are tempted to simulate and then create what up to now only Nature can achieve. The evolution is accompanied by a focus on complex systems of increasing analogy with natural systems and also by a modification of the methodology. The investigation consists in a development phase followed by observation, as in the study of some complex systems like the one with distributed intelligent agents or genetic algorithms. The empirical method for which the discovery is precisely the unexpected, requires careful attention according to Dupuy. Indeed, the use of complex systems ('mock up' of living or thinking objects) could result in unexpected effects which cannot be reduced to a probability distribution.

The contrast between the flood of technological marvels promised in the relatively short term (happiness tomorrow, just invest a few billion euros!) and the irreversible catastrophes forecast (this time, it really is the end of the world!) ought to lead us to consider: what is at stake in nanoscience and nanotechnology, what risks have already been identified, and what measures do we need to take to be prepared.

In a field which is characterized by exceptional diversity, in terms of both scientific and technical results, and of positions adopted in the debate by actors from very different backgrounds, we wish to examine the various ingredients of the controversy, to stimulate reflection on the part of the scientific and technical community and, by extension, of all those who are starting to be concerned by this question. In Section 2, we briefly review the history of the controversy and discuss four examples that illustrate the variety of themes.

We may consider that these questions belong to a considerably vaster debate, bound up with the notion of progress. Under the sign of progress, scientists, engineers, and industrial corporations are quick to place themselves when coming up with technological innovations, while the benefits of progress are strongly contested by other groups who, with the same degree of sincerity as the scientists, try to warn us of the possible negative effects of nanoscience and nanotechnology. In Section 3, we will propose a typology of these fears according to three fundamental themes around which they seem to revolve. We will show that these themes, which are generally associated with fear of science and technology, are profoundly rooted in the Judeo-Christian tradition.

This suggests that, on the one hand, a range of responses must be proposed to tackle these questions of different types, and that, on the other, it would be unproductive to address these issues from a purely scientific viewpoint. In Section 4, we will try to identify some practical solutions that could lead to a better manner of responding to these questions.

2. Nanosciences and their Convergence with Other Technologies: Doubts Set in

2.1 First Opposition

Several writers were quick to signal the potential risks associated with nanoscience and nanotechnology. In his book *Engines of Creation*, at the beginning of the chapter 'Engines of Destruction', Eric Drexler mentions the potential danger of his assemblers: "unless we learn to live with them in safety, our future will likely to be both exciting and short" (Drexler 1986, p. 171). The most vivid image of fear related to nanotechnology is undoubtedly 'grey goo'. The original premise is that one day we may be able to manufacture nanometer-sized machines capable of working on the atomic scale. 'Grey goo' is a mass of such machines that, having become independent, could cause damage to the human race or even devour everything in their quest to reproduce, including the earth's crust. This last scenario is sometimes called ecophagy.

For some years now, the rising status of nanotechnology has been accompanied by some publications and debates about possible consequences, like ecophagy or the development of weapons of mass destruction.[3] The year 2003 does in fact stand as a turning point where this debate, which until recently had taken place mainly in private, came to involve a growing number of people. Publicity and the excessive or even utopian promises accompanying research contributed to bringing the question to a head for many. Three events occurring in a short space of time then seem to have provided the trigger.

First there was Michael Crichton's novel *Prey*, published in November 2002 (Crichton 2002). The plot of this novel concerns a company specialized in nanotechnology, which makes nanorobots intended to fly in a swarm to form a virtual camera. Interestingly, the systems used by this company for its production are hybrids of bacteria and nanomachines. The inventors then lose control of their invention. This book was a big success and, even if this was not the aim of the author, it is often cited as revealing the concerns that nanoscience can provoke.

Soon after, in January 2003, came the publication by the ETC group of long and virulent manifestos warning of the dangers of nanotechnology, which they call 'atomtechnology'. The principal message of this group is the need for a moratorium in the manufacturing of nanotechnology based products to first understand their effects on the environment and living organisms. In *The Bigdown* (ETC 2003a), the group relates the dangers associated with nanotechnology, the development of which is described in four stages (of which the first two correspond to the current situation or immediate future): nanomaterials; manipulation of nano-objects to carry out assemblies with precise positioning; the creation of factories or nanorobots working on the molecular level; and finally, convergence with living organisms. With regard to the nanoparticles generated by this industry, the ETC group mentions their possible accumula-

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[3] Rocco 2001, Mnyusiwalla 2003; see for instance the debate on April 9, 2003 at [www.house.gov/science/hearings/full03/index.htm].

tion in the organism, their potential toxic effects (with reference to asbestos), and their ability to find their way anywhere, including the food chain. They also mention long-term risks such as 'grey goo', and the possibility of creating unknown materials that may in some way be 'anti-Nature'. In the report entitled *Green Goo: Nanobiotechnology Comes Alive* (ETC 2003b) the ETC group takes up the crossover between nanotechnology and biotechnology. The convergence is discussed by focusing on the catastrophic scenarios that it could generate – such as 'green goo', a group of artificial organisms produced by biotechnology that go out of control.

The third event was the position adopted by Prince Charles in April 2003, which generated considerable media attention (Highfield 2003, Radford 2003). The Prince asked British scientists to consider the "enormous environmental and social" (Radford 2003) caused by nanotechnology, alluding in particular to grey goo. The speech provoked strong reactions in both political and scientific circles. Responding to these reactions, the British government commissioned the Royal Society and the Royal Academy of Engineering to carry out research on nanotechnology, including its potential benefits and risks (Royal Society 2004).

These three events set off a chain of subsequent reactions. The Greens European Free Alliance group in the European Parliament raised the question and organized a special day on the subject in Brussels on 11 June, 2003, where associations such as ETC and Greenpeace were invited to present their views. Certain Green members of Parliament, such as Caroline Lucas, have openly manifested their opposition to the risks associated with the development of nanoscience in the absence of regulation (Lucas 2003). Also worth mentioning is the large report *Future Technologies, Today's Choices* submitted by Greenpeace in July 2003, which deals with both artificial intelligence and the nanosciences (Greenpeace 2003). The document presents a balanced picture of the situation, discussing both the advantages and disadvantages of nanotechnology.

This triggered a significant and growing reaction from various bodies. In 2004, various reports have been released that deal with topics, such as the general impact of nanoscience, toxic effects, and consequence of convergence (Swiss Re 2004, Sanco 2004, EHS 2004, nanoforum 2003, CTEKS 2004). In addition, there is a significant increase of publications about possible toxic effects of nanoparticles. Also Prince Charles (2004) referred to his previous statement about nanoscience and argued that the media much exaggerated his position.

To illustrate the variety of questions that are raised we discuss four issues in more detail.

2.2 Grey and Green Goo

What stands out clearly is the grey goo 'fad' – the term is used by some as a catchword to attract the attention of readers before moving on to other dangers such as the toxicity of nanomaterials, and is mentioned by others, though rarely, as a real danger. The starting assumption is that in future we will be able to create nanomachines that can manipulate matter at the molecular scale to make new products. Often this is associated with what Drexler calls 'exponential fabrication', *i.e.* when nanomachines are able to duplicate themselves. There are in fact two ways of addressing the issue.

The first is to consider biology. Cells in fact provide a number of examples of organelles, systems that work on the molecular level, for example to propel, supply energy, synthesize, repair, and duplicate. Well before molecular biology existed, empirical knowledge of living organisms was used to produce materials (wood, wool, cotton, silk, leather, paper, *etc.*), and to manufacture food, or modify it (alcoholic fermentation, bread-making, cheese-making, *etc.*). Since the 1970s, we have been able to influence the genetic machinery to produce new, modified organisms. Some molecules, such as insulin, are now manufactured using genetically modified organisms.[4] We are a long way from being in control of the way living organisms operate, but we have been using it for a very long time. A point of note is that, as George Whitesides (2001) makes clear, the 'green goo' scenario – the biological equivalent of grey goo – has already taken place on the planetary level (in our favor!). The earth used to be a mineral world with a carbon dioxide atmosphere, but life

[4] In a liter of cell culture from which insulin is to be made, there may be 10,000 billion protein-assembling ribosomes, each working at the rate of about 10 amino acids a second.

profoundly modified this environment, completely transforming the soil, atmosphere, and climate.

The second, more general approach is that of Eric Drexler, who argues that the existence of living organisms is a proof of the feasibility of nano-industry, and often backs up his reasoning with references to biology. At the same time, he argues that natural evolution does not enable radically different systems that are not based on proteins and DNA, whereas other systems, perhaps on a different chemical basis, are conceivable and may have, for example, less constraints regarding temperature. The scientific community is working on understanding the properties of nanometric objects and on developing devices for information processing and other actions on the nanoscale. However, we are still a long away from the grey goo scenario and there are even discussions on the feasibility itself (Smalley 2001, 2004). There is a fundamental difference between these achievements and microorganisms or assemblers as they might be imagined: the degree of complexity. Nature achieved this through a long evolutionary process, and the way in which life forms operate is of such incredible complexity that it exceeds that of all other machines created by man. Past and planned projects remain incomparably more simple than those supplied by living organisms, and it is hard to imagine how they could give rise to a 'parallel biology', *i.e.* objects capable of reproducing and acting according to complex scenarios.

For the longer term, there is no scientifically grounded answer to the question 'Will it one day be possible to create nanorobots from scratch?' Responses to this question range from casting doubt on the seriousness of the author to saying 'The question is not whether it is possible but when'.

Presently, the debate tends to deal with more realistic topics and should evolve along two trends according to the time scale.

- Following a recent paper by Drexler and Phoenix (2004), there is a much lower barrier to the achievement of non-replicating nanomachines "as this is the case for macroscopical devices". Thus, the most likely medium term scenario is production of nanomachines that can fulfill a single task (nanomedicine, fabrication, depollution, weapon, *etc.*) without duplication.

- In the long term, nanotechnological convergence could lead to far greater control of the behavior of the cell on the molecular level: synthesis of different elements, manufacturing of parts of hybrid cells (living-artificial), deeply modifying life (synthetic biology), *etc.*

2.3 Nanomaterials and Nanoparticles

While the grey goo story is often used as a dramatic symbol, the risk most often mentioned in the nanoscience field is the commercialization of nanomaterials or harmful components that could 'crumble' during their use or finally degrade in the environment. Certain 'crumbs', nanometric in size, could build up in the environment without degrading, disturbing ecosystems or even having toxic effects on humans. Claims are often made about either the indestructibility of certain types or, on the contrary, their extreme reactivity, their capacity to adsorb and transport dangerous molecules, and their extreme mobility. As discussed earlier, the most extreme positions go as far as to demand a moratorium on nanomaterials pending a better understanding of their behavior.

On the one hand, being 'nano' is not enough to make a product dangerous. Materials structured at the nanometric scale or nanoparticles are in no sense a new or strange type of product created by a new high-tech industry. Indeed wood, natural textiles and many other products belong to this category. Loose nanoparticles are not unknown to us either. Nature (sprays, volcano ash, desert dust), industry (carbon black, titanium dioxide) generates large amounts of ultra-fine particles (millions of tons a year). In a way, all combustion processes are nanotechnological! In an urban atmosphere, for example, there are typically between 10 and 20 million particles in the range <100nm per liter air, which represents between 1 and 2 nanograms of matter (Oberdörster 2002). Establishing a moratorium on nanomaterials, as the ETC group demands, would be difficult since, strictly applied, it would affect many products currently on sale.

On the other hand, this reasoning alone is no basis for blind optimism. Firstly, we have historical examples of mass-marketed products that, although providing many advantages, turned out to be harmful: such as asbestos and DDT. Moreover, the fact that the environment is littered with traces of by-products of products we use, shows that any decision on mass-production has consequences. Furthermore, there are growing reasons to believe that certain nanoparticles may have a detrimental effect. For example, recent work on the toxicity of nanotubes (*e.g.* Service 2004) clearly shows harmful effects on rats and mice, which seem to be due to the indestructibility of the nanotubes in the lung (formation of granulomas). It is also claimed that unlike natural nanoparticles artificial ones are engineered to be more active and highly dispersible and thus possibly more harmful. While it is too early to extrapolate such results to indicate toxicity for humans, they do clearly show that research must be carried out.

The various reports mentioned in Section 2.2 conclude, among others:

- Nanometric particles have indeed properties that may differ from the one of the bulk material.
- The importance of carrying out additional work on toxicology, as it is not possible to predict the properties of these particles on the basis of those from materials of greater mass, and of establishing standards and procedures.
- The fact that this also concerns 'traditional' particles, such as those generated by combustion.

The key question is: How can a product be labeled as potentially dangerous on account of the nanoparticles that it might throw off into the environment during its life-cycle? To answer it, we need to know the physical and chemical properties of the material, how emitted nanoparticles will evolve in the atmosphere, and the behavior of these particles in the organism (penetration channels, elimination mechanisms, pathogenic effects). This research topic will certainly greatly expand in the years to come, and will probably teach us some surprising things about familiar products. It is likely that it will even cast a new light on the issue of urban pollution.

2.4 Privacy and Chips

For the past three decades, electronics and information technology have continually advanced, and costs have fallen considerably. This progress has led to questions being addressed ever more urgently about the growing risk of an individual losing control of information about his or her private life, where such data is digitized, transmitted, and stored with new possiblities made available for information processing from several interconnected sources. Nanotechnology, while not the only technology at issue, potentially plays an important role insofar as it enables the development of new sensors, miniaturization, the possible design of systems with low energy consumption (hence autonomous), and increases processing power.

A particularly important example is the development of RFIDs (Radio Frequency Identification Devices) that contain a transmitter and logical circuits. When queried, they can transmit information, often an 'electronic product code' with enough bits to identify every individual object manufactured in the world. In their passive form, these objects do not require batteries. Their range depends on the frequency and varies from a few centimeters to about twenty meters for passive systems, while the range is much longer for systems with a power supply. Their size, which has tended to be measured in millimeters, has been reduced to the submillimeter scale in the most recent examples. These devices were perfected during the 1970s and have gradually been implemented in a series of contexts such as access systems (badges, toll-booths) and short-range identification (goods in stock, anti-theft, identification of animals). The unit price of the devices is still in the 10 cents to a few Euros range, but prices are expected to fall in the next few years, making RFIDs hardly more expensive than a label. They would seem to have limitless potential for use as they provide considerable advantages: stock monitoring systems in companies; objects capable of informing their environment of their presence; authentication systems (access badges, means of payment, *etc.*). Moreover, RFIDs are only the first generation of communicating systems. There is much room for further development, for instance, by adding local computing power, sensors, and actuators, like the systems originally developed by Kris Pister at Berkeley and commercialized by DUST Inc.[5]

However, opposition has already been formed to limit the use of RFIDs, including CASPIAN (Consumers Against Supermarket Privacy

[5] The website of the company DUST Inc. is [www.dust-inc.com].

Identification and Numbering).[6] At the end of 2003, about thirty US associations wrote a manifesto on limiting the use of RFIDs.[7] This manifesto poses various questions that may be summarized in two points.

- RFIDs can easily be hidden and, as long as they are active, they provide information on the person carrying them, including the objects and how much money the person carries.
- Unique identification means that an object is unambiguously identified. This enables information to be cross-referenced. The most obvious example is checking against the identity of the person carrying the object (his bank card, for example), but more subtle combinations are possible using apparently insignificant information.

Associations generally propose that the use of RFIDs should be regulated, including clear labels of products containing them, full disclosure of their specifications and purpose and of the information they are carrying, a limit for data and the possibility of cross-referencing, or even the possibility of removing the RFID. Defenders of the technology point out their limited range, the ease with which the emitting signals can be stopped, the fact that the supervision of these objects ceases at the door of a shop. However, distrust has been fuelled by a series of semi-official tests carried out (or planned to be carried out) on consumers, which led to CASPIAN launching boycotts, upon which the companies involved scaled back their projects.

Recently, discussions have been started on the contexts in which RFIDs should not be used, including the first workshop on privacy and RFIDs organized by MIT on 15 November 2003.[8] There are debates on the acceptability of this technology and on technical counter-measures such as 'killing', a sort of triggered apoptosis of RFIDs. Regulatory authorities in charge of privacy protection are also considering this topic. They met in 2003 in Sidney and published a common statement.[9]

The basis for fair use of RFID are more or less set, consisting in a balance between taking benefit from RFID technology and privacy right.

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[6] The website of this group is [www.nocards.org].

[7] The document 'RFID Position Statement of Consumer Privacy and Civil Liberties Organizations' is available at [www.privacyrights.org/ar/RFIDposition.htm].

[8] The workshop website is [www.rfidprivacy.org/agenda.php].

[9] Available on the website [www.privacyconference2003.org].

However, the implementation has costs and enforcement control may not be easy. The debate is now evolving towards a more or less organized confrontation between consumer organizations, consumers who are less concerned about RFIDs, retailers, and regulation authorities.

2.5 Human Implants

A technique exists for implanting RFIDs or 'smart dust' in the human body. This is already routinely done to identify pets, and could easily be extended to humans. Tests have already been made with volunteers, including a Florida family in March 2002 and a Miami journalist in April 2003.[10] More recently this technique has been used in a Spanish nightclub and a Mexican administration.[11] In 2004, an estimated one thousand people were implanted. The product used is the Verichip™ by the company Applied Digital Solution (ADS), which also sells the Digital Angel device (not yet implantable) that interfaces with the GPS network to locate its bearer.[12] These systems have a number of potential applications:

- Marking individuals for surveillance purposes. For example, an anti-kidnapping system has already been proposed by the SOLUSAT company in Mexico,[13] a country in which the disappearance of children is a serious problem. Another use is the medical monitoring of patients for whom hospitalization is not necessary, *e.g.* Alzheimer's disease.
- Means of payment. The company ADSX offers the Veripay™ system to enable secure payments similar to a chip card, but the chip is implanted beneath the skin.[14]
- Implanted chips, which cannot be lost or easily stolen like badges, could be used as a means of access to secure premises, such that access is permitted only when the system recognizes the chip signal.

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[10] See the articles 'Family Set to Get Chipped' in TechTV [www.techtv.com/news/print/0,23102,3384016,00.html] and 'Miami journalist gets 'chipped'' in Worldnetdaily [www.worldnetdaily.com/news/article.asp?ARTICLE_ID=32286].
[11] See the website of the Baja club ('zona VIP') [www.bajabeach.es] and [www.informationweek.com/showArticle.jhtml?articleID=23901004].
[12] See the website [www.digitalangelcorp.com].
[13] The website of the company is [www.solusat.com.mx].
[14] See [www.adsx.com/news/2003/112103.html].

Such systems have provoked strong reactions. The first reason for this is concerns about where the technique could lead. All sorts of individuals could potentially be kept under surveillance this way. Another consideration is the religious aspect. There are currently a number of websites that refer to these devices as the "mark of the beast" in reference to the *Book of Revelation* (13:11, 16, 17).

> Then I saw another beast coming up out of the earth, and he had two horns like a lamb and spoke like a dragon [...]. He causes all, both small and great, rich and poor, free and slave, to receive a mark on their right hand or on their foreheads, and that no one may buy or sell except one who has the mark or the name of the beast, or the number of his name.

This quote shows us that the fears generated by these new technologies trigger emotions that may be deep-seated in the human psyche, particularly the reservoir of symbols, images, and archetypes linked to the sacred.

3. Progress on Trial

3.1 An Evolving Conception

Scientific and technical progress is traditionally considered a factor that improves our quality of life, in particular when it leads to the development of new products and services that meet society's expectations. Good examples of this are medicine and environmental protection. In a more general way, we tend to see scientific and technical progress as one of the major factors influencing the development and competitiveness of modern economies. This role is likely to increase in the future with the advent of the knowledge society, in which the capacity for innovation becomes a strategic element for both companies and countries. In this context, nanotechnology and biotechnology are set to be at the heart of a new high value-added industry, the practical implications of which extend to a large number of fields. For nanotechnology alone, the size of the potential market is measured in thousands of billions of euros per year (Roco 2001). Such are the considerations that have prompted the current race between the major trading blocks of Europe, the US and Asia to invest in this field of research.

Co-existing with this positive and widely held view of scientific and technical progress is a growing challenge to the broader philosophical and sociological concept of progress. Wagar (1969), on whose views we draw here, has pointed out that progress is a secularized religious idea, the origin of which can be found in a linear conception of time whose basis in the West is Christian theology, notably that of Saint Augustine who, in addition, insisted on the subjective conception of time. According to that idea the whole of human history can be interpreted as the fulfillment of God's design: the upward movement of humanity towards its creator, seen as the Golden Age. This conception is radically opposed to that of 'traditional societies' for which the golden age is situated at the origin of the world, where the passing of time can only result in degradation and corruption of the primitive state. The notion of progress began to be contested, implicitly at least, by the Romantic movement in the 19th century, which exulted Nature. However, it is only in the 20th century that rationality, its avatars science and technology and finally progress itself, are explicitly challenged and even put on trial (Van Doren 1967). This process was also marked by the realization that progress had none of the characteristics traditionally attributed to it: neither universal, nor continuous, nor necessary, nor unambiguous, nor linear, nor cumulative as the scientists claimed. On the contrary, authors such as Lessing, Lévy-Strauss, Popper, *etc.* stressed its local, discontinuous, and non-linear nature. The paths taken by progress are multiple, complex, and often unpredictable.

Can we still believe in progress – a progress that has become much of a paradox (Easterbrook 2003)? Regarding the progress of scientific and technical knowledge, everyone would agree on the explosion of ideas since the beginning of the 20th century and the many positive consequences, impossible to imagine a century or even a few decades ago. However, regarding material, economic, social, or moral and spiritual progress, the answer is more ambiguous. In particular, it is the mechanical link between knowledge, wealth, and happiness that has been contested. Negative effects, the 'damage of progress', are increasingly visible on both the local and global scale – witness the controversy surrounding the greenhouse effect. Beyond this, there is a growing, legitimate sense that 'we no longer control the control', to borrow a favorite expression of Etienne Klein, of phenomena and forces that science has enabled us to understand. The inextricable complexity of the real is imposed on us, with its corollary risk, as an irreducible component of human action. Finally, since Sorel in 1906 (*Illusions of Progress*), political debate on how the positive effects of progress are divided up has been a recurrent theme of writers and social movements. Initially proposed by Marxists, this issue has been taken up by the anti-globalization movement.

However, while debate and objectivity are always legitimate and often necessary, it is important to avoid 'throwing out the baby with the bathwater'. We should resist the temptation to minimize the real contribution of science and technology – and in so doing, dashing the considerable hopes that they still justify, for example in the medical field – by holding them to account for consequences for which they are not necessarily responsible. Who would be ready, on a personal level, to turn his back on science and technology?

3.2 Science and Risk: Towards a Sociological Approach

Sociologists of science and technology have proposed different models, according to the school to which one refers, for interpreting the evolution of society. One of the most productive, and perhaps the best suited to the situation of nanoscience, may be that of the great German sociologist Ulrich Beck (2001), who investigated what he calls the 'risk society'. According to Beck, modern society is in the process of moving towards a new type of society in which risk and management play a central role. This is a 'reflexive' society, the operating patterns of which are still emerging. Among the elements that characterize it, we can say – without laying claim to an exhaustive and in-depth analysis of Beck's concepts – is the fact that threats have become internal. They essentially result, not from risks linked to Nature, but from the very activities of human beings, hence the link with the fundamental themes around which our fears revolve. Knowledge, perfect technical mastery, decision-making processes – everything, or nearly everything, now contains risk, says Beck. Moreover, boundless belief and confidence in science and technology, the supposed source of inevitable progress and a mainstay of the science period, has now given way to a more modest conception. 'Science in action', to borrow the expression of Bruno Latour, has a more local, context-based character, which is accompanied by the legitimate uncertainties and doubts of a reflexive society. Finally, representative democracy, founded on the philosophical principles of Montesquieu and Locke, would gradually be replaced – even if it is obviously still the institutional model of our countries – by a deliberating democracy whose theorist would be the contemporary German philosopher Habermas.

We are now at the other end of the spectrum from the optimism of the Enlightenment, science no longer being the guarantor of progress. Now it is Nature's turn to lend reassurance, whereas to our ancestors this same Nature seemed an implacable force, whose 'master and possessor' (in the words of Descartes) they sought to be. From now on, science makes us nervous, and we are less and less convinced that technical performance has made us more free and more happy (Easterbrook 2003). Even more, Martin Rees (2003) depicts various disasters that could be brought about by science.

Given that this new situation can lead to stasis or even to rejection, it is worth seeking to understand the phenomenon. However, there are always, in varying doses, three basic components pointing back to fundamental themes, which can be compared to Jungian archetypes, around which all fears linked to science and technology seem to revolve (see Figure 1 and Farouki 2001). These three themes are closely linked and may, in certain cases, be intertwined. The only aim we have in dealing with them separately, as we do here, is to clarify the form they take and produce an analytical scheme to be used later. We will describe the form of these fundamental themes by first characterizing certain fears that are traditionally associated with them, then identifying the link that can be made with nanoscience and nanotechnology, before mentioning their link with tradition, particularly the Judeo-Christian tradition.

Analyzing these fears in this manner in no way implies that they are illegitimate or discredited. While anxiety is, for psychologists, without objective cause and foundation, fear on the other hand is always rooted in a certain reality. Although the numerous predictions of the end of the world made on the occasion of previous scientific developments have up to now been without basis, history also shows that certain fears may be confirmed by experience. Examples are Chernobyl, or the deliberate dissemination of non-degradable products that turned out to be dangerous, such as asbestos and DDT. It should also be pointed out that fear itself can be useful in the sense that, as Hans Jonas (1990) convincingly argues, it can serve as an alarm bell alerting society to consider the problem, identify the exact nature of the risks, develop a research program if necessary, and take the necessary prevention measures. Jonas describes this process as the 'heuristics of fear', and considers it a positive contribution on the socio-political level.

3.3 First Type of Fear: Loss of Control

The first theme is that of an experiment that goes wrong, or a product that after commercialization provokes irreversible negative consequences, going as far as the extinction of the human race or even the disappearance of the planet. There are three scenarios:

- A sudden event that leaves no time to react. In this case irreversibility is due to the strength of the forces unleashed over which the scientists lose control. This scenario applies in particular to processes that use high-energy sources, such as the nuclear industry or particle physics.
- Control can be lost because there is no possibility of reacting. The typical case is the dissemination of products that turn out to be harmful. Irreversibility here comes from their long life span or their ability to reproduce. In the present context, the main concern is the dispersal of fragments of nanomaterials. This situation draws credibility from the fact that it has already happened with industrial products, such as the so-called phytosanitary substances (insecticides, fungicides, *etc.*) that have been used on a large scale in intensive agriculture since the middle of the 20^{th} century. Entities capable of reproduction – all the more disturbing in that stopping release at the source is not sufficient to stabilize the situation – are relevant to living substances (micro-organisms, DNA of GMOs).
- In addition to these 'extreme' examples of loss of control, we should consider 'chronic' cases such as pollution, changes of the ozone

layer, or the accumulation of greenhouse gases. Here, the products sufficiently benefit a group of individuals, either of a geographical region or a particular generation, such that the situation continues because the people who benefit do not always perceive the disadvantages. If the perception of benefits and negative effects differs, the debate will focus as much on the evaluation of the advantages and disadvantages of the technology as on the injustice of the way risks are shared. Before the publication of the IPCC reports,[15] which pointed the way to an international scientific consensus, this was the case with the debate on greenhouse gases. The irreversibility of the situation is no longer linked solely to a given technology, which could simply be replaced to avoid the problems and associated risks. It is linked to the way 'human society' works in the broadest sense, whether this is due to economic forces or to the balance of power between countries. The solution can only lie in changing the mechanisms that regulate human society as a whole on which – since these are mainly international treaties – it is difficult find a consensus (*e.g.* agreement on CFCs or Kyoto protocol).

This loss of control concerns or panics certain people to such a degree because they believe it can provoke considerable upheavals, even the end of the world. In the traditional imagery of the West, this fear is crystallized around the notion of the Apocalypse.

The Apocalypse (etymology: unveiling, revelation – hence the *Book of Revelation*) is a fundamental theme of Judeo-Christian eschatology (Cohn 1983). It is based on a very specific view of time and the meaning of history, not shared by Eastern religion, such as Buddhism. In particular, its linear conception of time is an Augustinian notion that bourgeois society allowed to flourish in the nineteenth century and which is strongly linked to the notion of progress. The return of the golden age, at the end of the 'Adamic' cycle of humanity, is to be preceded by a period where fire and blood rain down on the earth in order to chase away the forces of darkness once and forever. The *Book of Revelation* is the key example of this type of literature. The theme has therefore been linked to God's judgment (or the Final Judgment, see below) for 2000 years.

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[15] See the IPCC website [www.ipcc.ch].

In the course of the 20th century, decline in religious belief in the West has been balanced by the growing notion that humanity might itself provoke this Apocalypse, using the ever more powerful 'arms' provided by science and technology. A number of novels take up this theme of a worldwide catastrophe provoked by humans. At the beginning of the twentieth century the theme of the Apocalypse was still related to natural disasters (volcanoes: Krakatoa (1883), La Montagne Pelée (1902); earthquakes: San Francisco (1906), Valparaiso and Messina (1908); rising waters causing a new flood; demography, with the yellow peril, *etc.*). Now, the fear of the end of civilization is justified by the self-destructive capabilities, supposedly uncontrollable, and placed at the disposal of humanity (Boia 1989). In 1929, however, the theme of the Apocalypse started to tap into other sources. That year, the *New York Times* informed its readers of the theories of eminent scientists who believed that the entire universe could accidentally flare up like a gunpowder fuse. This fear was then strengthened after the discovery, shortly before World War II, of the uranium fission reaction. There was fear that a chain reaction triggered experimentally, *e.g.* an atomic bomb, could run across the entire world. Famous scientists such as Langevin had to intervene to calm people's minds (Weart 1998).

3.4 Second Type of Risk: Abuse of Discoveries

Even if an innovation presents no risk of loss of control in one of the ways mentioned above, it may have serious consequences or turn out to be harmful if it is used in a manner that was not foreseen, particularly in the hands of ill-intentioned parties. There are several levels of concern about such abuse, depending on the person to whom the evil intent is ascribed.

The first case is an individual to whom a new product or technology, diverted from its intended use, gives increased power to cause harm. Obvious examples are the appearance of new types of criminal use of new technologies including terrorism. The distribution of strains of anthrax at the end of 2001 in the US is a good example of this; the use of Sarin gas in the Tokyo underground in 1995 by the Japanese sect Aum Shinrikyo, which, incidentally, claimed in this way to be triggering the Apocalypse, is another. Such technologies are relatively sophisticated, requiring the collaboration of at least some highly competent specialists, which makes it is easier for the security services to investigate.

A group of individuals, a private company, or a government may also use a new technology to gradually change the conditions of life for everyone. This could be a totalitarian country imposing certain practices to ensure the subservience of its subjects, a theme literature has exploited on several occasions (*Brave New World* by Aldous Huxley; *1984* by George Orwell). But reality may be much more subtle and banal. The geopolitical situation today may lead to a particular surveillance or control system being adapted in a fully democratic manner to counter risks that are deemed intolerable, such as certain forms of criminal behavior or terrorism. Also, a new technology might be promoted in the name of moral aims, such as feeding the population and fighting hunger and malnutrition, as has been done, for instance, to promote GMO's.

The theme that underlies all the fears, and which is explicitly structured around the notions of good and evil, is that of the Sorcerer's Apprentice.

The Sorcerer's Apprentice is a classic literary theme, often featuring in works of a fantastic nature. The central idea is that a scientist, free from all moral scruples, exploits the natural forces he has discovered to ends that are not exclusively good, betraying the implicit mandate he has from society to carry out his research. Not only is the Sorcerer's Apprentice shown to be irresponsible, at a certain point he loses control of the forces he has unleashed. Moreover, the scientific and technological resources at his disposal mean that he is capable of triggering the Apocalypse himself (see above), such that it is no longer seen as human fate imposed by the will of God. The ill-fated action of the scientist may even be deliberate. Popular characters such as Dr. Faust symbolize the mad scientist who has, so to speak, entered into a pact with the devil. Great writers, such as J.W. Goethe, H.G. Wells, M. Shelley, Th. Mann, and A. France, have regularly used the theme that is present since the fifteenth century and which inspired also theatre and opera. More recently, starting in the late 1970s, the Sorcerer's Apprentice has been associated also with the biologist who is able to manipulate life itself.

After the discoveries related to the atom, it is the reign of biology and the possibility of genetic manipulation that have led to the re-emergence of the myth of the superman. 'Progress' seems threatening: will the Sorcerers' Apprentices stop in time (Rifkin & Howard 1977)? The debate developed during the 1980s on the ethical level, leading scientists such as Testard in France to stop their research on their own initiative.

3.5 Third Type of Risk: Transgression

Developments in science and technology may also provoke reactions such as 'it's going too far' or 'somebody is trying to play God'. Everyone has their own, personal definition of the limits that humans should not exceed, whether or not this is based on a sacred view of the world. This definition draws on a mixed set of elements in which everyone finds their own meaning: scientific knowledge, precedents, cultural myths, and personal religious beliefs. These reactions, if it is felt that a transgression has taken place, may be violent even if there is no immediate danger. If these acts show a degree of uncertainty with regard to their consequences, the perception of risk may be boosted by the only partly conscious idea of 'divine punishment'.

A typical example is an experiment that allows doing what has never been done before, which in some way is a transgression in itself. There are numerous precedents, and few directors of new experimental installations could do without refuting apocalyptic scenarios. For instance, the Tokamak TFR was built at the beginning of the 70s at the French Atomic Energy Commission (CEA) in Fontenay-aux-Roses, France, to study thermonuclear fusion, a machine that was then the most powerful in the world. Some opponents of the project were afraid that the hot plasma from this machine might be the source of intense electric fields that would cause a catastrophe.

One of the most recent cases is the Relativistic Heavy Ion Collider at Brookhaven in the USA. The purpose of this collider is to study frontal collisions at very high energy between heavy ions, heating them up to temperatures close to those that existed a few fractions of a second after the big bang. Two scenarios went around the world. The first predicted the appearance of a black hole in the interaction zone that would swallow up the entire planet. The other scenario was the appearance of 'strange' particles (with reference to strangeness, a property of certain quarks) that would swallow the earth atom by atom. A scientific panel was set up to try to provide rational responses to such concerns.[16]

However, the cases that seem to have the most resonance, both on the emotional level and in terms of the ethical debate they trigger, relate to progress in biotechnology. This technology does in fact pose a potential challenge to the fundamental conception of life, the human being, and even the anthropological structure of society, like parental relationships. Cloning and experiments on stem cells have been sufficiently discussed in recent time.

Even when the potential danger is not clearly identified and it is not clear that a project will be successful, the very idea of transgressing the boundaries of forbidden knowledge seems to generate fear. The archetype of the Tree of Knowledge illustrates the religious ban on acquiring knowledge and, more importantly, releasing the 'hidden forces' of Nature. This ban is common to a number of cultural eras: the Greek myth of Prometheus, condemned to have his liver torn to shreds by the eagle of Zeus for having stolen the sacred fire of knowledge from the gods, is also linked to it. However, the Christian West has remained particularly marked by the Biblical story of the fall of Adam, the ancestor and symbol of all humanity. This fall is held to be the result of 'sin', the transgression of a major taboo: man attempted to become the rival of his Creator by gaining access to forbidden knowledge. This knowledge bears a curse, and seeking to understand the hidden forces of Nature is sacrilegious – the vain and curious desire of research, called knowledge and science, as denounced by Saint Augustine. The discovery of 'formidable hidden energies' in matter, asking only to be released in order to return the world to chaos, simply strengthened in parts of the population, often unconsciously, the feeling that in the 20th century humanity reached the extreme limit of what was permitted. The other strand of Christian tradition, to which the theology of Nature is related, considers that doing science may be part of worshiping God. However, this tradition has not been dominant in the building of popular mental imagery.

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[16] See for example [nuclear.ucdavis.edu/NPG_rhic.html].

Finally, the archetype of the Tree of Knowledge has for 16 to 18 centuries been associated with the very rich and complex mental imagery of alchemy. In this 'art', the transformation of matter (for example, so-called base metals) or, on a more subtle and profound level, the individual illumination of the 'seeker', was necessarily accompanied by a form of death, according to a psychological process that was studied in detail by Jung (1971). Re-birth, or 'resurrection', and death are therefore the two sides of the same process of radical transformation of humans and, by extension, of the world (see the theme of the Apocalypse discussed earlier). Indeed, Soddy and Rutherford had a clear understanding of the very strong link with this historical and psychological background, as they are reported to have explicitly mentioned, at the crucial moment of their discovery, the 'alchemical' nature of the transmutation of elements, at the risk of being excluded from the scientific community by using this term (Weart 1988). Around 1930, however, Rutherford did assume this responsibility by publishing a book on atomic physics aimed at a lay audience, called *The Newer Alchemist.*

4. What Can Be Done about Nanosciences?

4.1 Nanoscience and Fear

Is the emerging fear of nanoscience and nanotechnology justified? Is it a cause for concern? Is there a controversy that could threaten research and applications? How should we analyze this? What can we do?

Based on experience, the initial response of scientists, engineers, and large companies when their activities are called into doubt or simply questioned tends to be unsatisfactory and ineffective. Calling the arguments of demonstrators irrational and their position illegitimate, claiming that informing or educating the public would be enough to allay doubts and calm fears, or that it is all a plot, will never give a balanced understanding of the situation. Moreover, this type of approach is likely to lead to a standoff situation from which nothing positive can emerge. Sociologists point out that those involved in a debate always believe they have good reasons for their actions, and that their logic and 'world view' –

even when unscientific – have a fundamental legitimacy. Such an attitude accepts the existence of more than one rationality in society.

Moreover, scientific discourse can be perceived as contradictory; Jean-Pierre Dupuy (2004) speaks of the 'double language' of the scientific community. Growing media interest in the results of science and technology too often leads specialists to claim that such and such a development is a true revolution, paradigm shift, or a major disruptive technology. After all, decision-makers need to be persuaded to finance research in a context of increased financial constraints. However, as soon as fears emerge among the public, the same people deliver a toned-down version of events in an attempt to be reassuring: actually, everything is under control, the techniques are perfectly mastered, Nature has been doing that forever, *etc.* Discourse on nanoscience and nanotechnology does not break with this pattern.

To better grasp the emerging constraints linked to nanoscience and nanotechnology, it is necessary to understand that these take place in a much broader context of long-term changes in society. Over and above the specific characteristics of the field to which they apply (the 'nano-world'), these fears are only one of several elements of what is undoubtedly a profound change in society's relationship to science and technology.

Beyond this general analysis of the evolution of our societies, what can we propose to improve the way we manage the difficulties resulting from scientific and technical progress in the field of nanoscience and nanotechnology? In order to try to provide an answer to this question, a first step is to learn from other debates (nuclear, GMO's, *etc.*) in which a lack of understanding and absence of dialogue between the various parties involved (experts, public, associations) meant that these questions could not be dealt with in an optimal way. A second step is to look at the work of sociologists of science and technology for concepts, tools, and methods that will ensure that the debate is constructive, while respecting the position of all parties involved. As shown in Section 2, there is a wide variety of questions. Having identified three categories of problems that are linked to the fundamental themes of fear, we are now able to address one by one the difficulties with which we might be confronted.

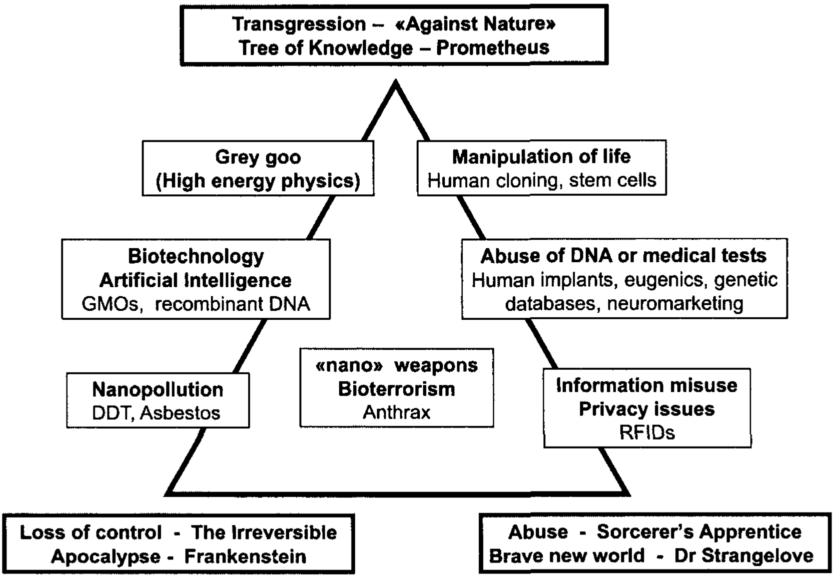

Figure 1. The three corner of the triangle represent the basic fears as discussed in Section 4. The rectangles on the corners represent the position of fears resulting from various new technologies (nanotechnologies including their convergence with other disciplines) regardless of how realistic they are. Some examples of already existing or past issues are included.

4.2 The Loss of Control: New Products

Several issues arising from nanotechnology belong to this category. The short term ones consist in avoiding losing control when a product is introduced to the market, particularly if it is dispersed into the environment, food chain, *etc.* in a manner that it is difficult or impossible to reverse. A typical example is the introduction of new materials as discussed in Section 2.3. Some of the new materials could release harmful nanoparticles in the environment. This point raises increasing concerns since the production of various nanostructured materials and nanoparticles is expected to rise drastically, sometimes from almost zero, like nanowires and carbon nanotubes, and some of them could be aimed at a mass market. Another case could be 'processed' food. A close issue is the GMOs, whose opponents seem to fear, firstly, that GMOs can in certain cases be harmful to health, which so far has no scientific foundation in the discussed cases, and secondly, that they modify the genomes of natural species when disseminated, which does seem to be unavoidable and irreversible. What would the application of a principle of reasoned precaution involve in such situations?[17]

There are four important elements to be considered.

- Firstly, it would be useful to establish mechanisms for approving the marketing of products that pose potential risks. A reasonable balance would have to be found between the dynamic forces of innovation, which must continue to be encouraged, and protection of the population and the environment. Numerous standards and regulations exist, one of the best known is the approval process for medicines. The questions that need to be answered are: (1) Is the existing mechanism sufficient? (2) What processes need to be established to regulate the release of new products? These questions, which have already been raised with regard to nanomaterials, are far from trivial, as we have shown above. However, they are urgent because innovations are numerous and varied and the products are sometimes hidden.
- Moreover, a monitoring and alert mechanism, flexible but effective, could also be introduced, taking its cue from the medicine surveillance network for drugs.
- Callon's suggestion is to establish 'hybrid forums', major deliberating mechanisms to manage controversies over scientific and technological innovations (Callon *et al.* 2001). Such spaces for debate and interaction between a wide range of parties, including scientists, industrial corporations, engineers, institutions, associations, and the public, must have clear rules setting out, in particular, how the work of the forum relates to the real decision-making process. While few of the decisions would simply literally reproduce the conclusions adopted by the forum – even if they are the result of a true consensus – these conclusions must be taken into account in the decision-making process, in a manner that is transparent from the outset. The

[17] We understand this principle as calling for prudent action – not immobilization – when there is strong scientific uncertainty and possible irreversible and unacceptable consequences.

hybrid forum, according to Callon, must be a space where those taking part can explore options and learn together, a process in which the identity of participants may change or be built up over time. Popular knowledge would not be discredited and considered illegitimate but, on the contrary, respected and taken into consideration. Finally, the hybrid forum enables setting-up a procedure for managing controversy. Free and open debate between all parties concerned, such that all opinions can be heard and respected, might help avoid rejection as a point of principle, which, for the most part, is due to a lack of prior discussion or a clear perception of the benefit of the innovations. This point could be important because, unlike other innovations discussed later, one can be exposed without having any control on that or any direct benefit, such as when a nanomaterial is introduced in a product to simplify its manufacturing but without any gain for the customer. Nevertheless this process will have limitations. Indeed, a specific feature of nano-products is that there are a huge variety of innovations and it is hard to decide which one should be discussed. For instance, it would be difficult to organize a public debate for any new textile commercialized.

- Finally, specific research is required to reduce scientific uncertainty as much as possible. Risk is now a normal part of our technoscientific society, as Beck has pointed out, and the society must learn to adopt a questioning attitude towards its own practices and productions, characterized in particular by the fact that research always accompanies action. One question that will be increasingly asked is what type of research should be encouraged to optimize the mechanisms discussed in the two previous points. There are at least three aims: (1) enough background knowledge to define criteria allowing assessing toxicity; (2) a clear view of how the products are degraded in the environment; (3) a better knowledge of the fate and behavior of nanoparticles in the environment.

4.3 The Loss of Control: An Experiment that 'Goes Wrong'

In addition to experiments that should not be undertaken for ethical reasons, one can consider cases where an experiment could 'go wrong'. As discussed at the end of Section 2.2, the most realistic scenarios are related to the convergence of nano and biosciences. A good illustration is the synthetic biology projects at the Institute of Alternative Biological Energies, based in Maryland.[18] The target is to create new types of organisms with an artificial genome, such that they are, for instance, capable of manufacturing hydrogen or isolating carbon dioxide. The team's idea is to start from what already exists and carry out modifications, so it is strictly speaking not a synthetic bacterium. It is not known if, and even less how, it would be possible to create a living cell from its components which, placed together, do not assemble themselves spontaneously to create a living bacterium. If the project successfully creates 'efficient' bacteria, masses in the order of the worldwide CO_2 emission would have to be produced and released in the environment, *i.e.* billions of tons, since a bacterium could absorb a carbon mass comparable to its own weight. Tests of samples could also lead to the dissemination and possible fast expansion of the new species. There are similar fears, particularly in France about GMO's open field experiments. Uncontrolled military experiments, terrorist use, and long-term grey goo scenarios belong to the same category.

The issue is how to manage an efficient regulation system that could authorize or forbid experiments or projects that could be risky. First, some limitations must be taken into account.

- It is impossible to define a 'dangerous zone' within the realm of research topics. For instance there is no 'grey goo development program' but plenty of experiments aiming at a better understanding and control of assembly, information processing, and chemistry at the molecular level, most of which aim at the design of better products, better drugs, *etc.* In addition many of the risky ideas may come from unexpected convergence of innocuous ideas.
- Research is globalized. How can one stop a research program – supposing that is fully justified – if research continues elsewhere on the planet? The intense competition between nations and multinational corporations in the military and economic field makes it vain to hope

[18] See the website of the Institute [www.bioenergyalts.org].

to be able to stop research from which certain parties expect decisive advantages in the global competition for power and domination.

An efficient control system should meet the three following conditions.

- There is a need to invent and implement social and/or institutional mechanisms to control research, while avoiding any drift towards 'obscurantism'.[19] The organization of research should set the responsibility of various actors. Governments, funding agency, and scientists must consider the long-term consequences of their research. Bodies such as ethics committees and foresight groups are likely to provide a valuable input. Debates should be organized between supporters of such experiments, which will often tend to underestimate, or even ignore the negative effects of their own work, and a panel of scientists with different opinions. The way in which research is organized and financed should provide a first check on this, since the investor is in principle required to make a judgment. However, the trend in most modern research systems is just the opposite: there are numerous supporters who may, in addition, have intricate links, meaning that no-one has the necessary overall view. The responsibilities are diluted and the interests of the various parties may diverge.
- The general public must also be involved. The goal is to enable constructive debate about matters relating to science and technology, including questioning certain issues, without being identified with one of the supposed enemies of progress. What are therefore the uncertainties? What are the real and perceived risks? What are the advantages and disadvantages, for whom and when? Is there a 'real' controversy within the scientific community itself? What interests are at stake? Controversy may never be irreversible, but nor is the technical purpose set in stone. Even when there is not controversy, strictly speaking, or imminent danger, these forums for debate and discussion would provide honest, competent, and argued information. It is

[19] By this we refer only to the systematic refusal without arguments of all research, and not the act of contesting and challenging certain scientific and technical activities. The latter does not, in a democracy, constitute a subversive action; it rather facilitates a legitimate debate within society about innovations that society will have to manage, and the disadvantages of which it could possibly have to suffer.

essential to separate the real and the imaginary, so that we can concentrate on the 'real' questions. For example, from our point of view, the fear of nanotechnology using quantum effects is largely unfounded. This point of view needs to be expressed, justified, and if necessary criticized in an open manner. On the other hand, the question of linking nanotechnologies with complexity or biology is a subject that cannot be easily brushed aside.

- Only an international consensus, on very precise issues and backed up with monitoring and control mechanisms, could arrive at such a result. In a first step, the experiences of various regulation mechanisms should be shared between actors to find at least a common consciousness of underlying issues; in a second step, progress should be made towards a deeper international integration.

4.4 Abuse of Discoveries

This difficulty concerns the need to avoid, as far as possible, the abuse of scientific discoveries and technological innovations. Progress in nanotechnologies and their convergence with other techniques may offer various occasions of abuse. This may concern privacy, as discussed in Section 2.4, and the spread of biometric techniques and DNA tests. For instance, last century's eugenics may return through new (bio)technologies, perhaps in another form that replaces the concept of race with predisposition to a given disease. Finally, one theme that has re-emerged is the development of new arms based on nanotechnologies, for example in the form of micromachines, as a natural extension of biological weapons.

In such a society, to understand innovation we need a new model, such as proposed by Callon *et al.* (2001). The traditional approach, now superseded and inoperative, required a pre-defined technical object, with a set of features, released into a society that would demonstrate a lower or higher degree of acceptance of the innovation, and would occasionally put up resistance that it would be necessary to overcome. In models proposed by sociologists of science and technology, *e.g.* by Callon and Latour, the technical object has its technical and social characteristics negotiated and produced simultaneously. It is interesting that this model presents analogies with the debates that are taking place around RFIDs and possible technical characteristics such as 'killing' discussed in Section 2.4. The spatial extension of the invention would take place thanks to a complex process of 'translation' within a network of participants, among which the innovator must above all find allies, who will then have their own interests and reasons for propagating its use. Once more, the globalization of research considerably limits the real impact of any local or national action. Only an international consensus promises to achieve what has already been accomplished, for instance, for chemical and bacteriological weapons.

Aside from the fact that the notion of 'abuse' may be relative, it will always be difficult to arrive at a consensus because diverging interests are likely to be at stake. For example, some parties, such as producers and distributors, will stress the considerable advantages to be gained through the systematic use of RFIDs for managing and tracing certain products, while others, in particular consumers and citizens, may see their use as putting individual liberties at risk. An intrusive technology may result of a trade off between a service and more safety and privacy protection. Examples of these questions are extensive video monitoring coupled with biometry, database of genetic fingerprints, *etc.* The trade off may be an unstable equilibrium between groups having strongly opposite opinions.

There is no absolute truth in this matter, and both points of view can be defended. In a democracy, only society as a whole is able to identify what is real progress, as far as it is concerned; it is a political question, in the best sense of the term. In this context, the consensus of the majority, which will be expressed in legislation, is forged by dialogue among the participants in the debate. Such negotiation supposes, on the one hand, a role for delegation and mediation – hence procedures for choosing representatives and spokes-persons – and, on the other hand, the role of arbitrator and decision-maker to be played by political leaders. It requires transparent information and decision-making procedures, which are, rightly or wrongly, contested in various technical and scientific fields, such as nuclear energy and GMOs. Moreover, some research or development projects (*e.g.* rebuilding a pathogenous bacteria to investigate a disease that has disappeared for centuries) clash to such an extent with the shared interests and/or fundamental values of our societies that they are prohibited.

4.5 Transgression

The long-term goal of nanoscience is the understanding of how Nature works at the molecular level. Up to now Nature is still 'protected' by the barrier of complexity so that even a deep understanding of each part does not lead to the understanding of the whole. An additional trend is that information technologies are spreading everywhere so that Nature and human beings could be parts of a gigantic information system. That type of evolution drastically affects the relationship between humanity and Nature, as in the following cases.

- As discussed in Section 2.2, nanoscience could lead to the manipulation of life. Traditional biotechnology is already capable of this, but the new factor, it is imagined, would be a vast increase of human manipulation of living matter in an unprecedented way, that may go as far as the creation of hybrids, monsters, chimeras or other 'unnatural' beings, such as in Crichton's novel *Prey*.
- Another question is the limit of humankind. The questions already arises with issues such as stem cells or human cloning that are both related to the control of DNA configuration in a cells. More generally the body could eventually be considered as a complex machine that can be fixed in case of failure and modified or even enhanced. Similarly the impact of understanding and modifying the brain will raise new issues such as the meaning of responsibility and feelings when they are understood in terms of circuitry and 'wetware'.
- In the shorter term, the mixing of the information technology and life is a kind of shock. The introduction of external devices in the body, as discussed in Section 2.5, is considered a violation that causes stronger reactions than an external RFID attached to clothes or skin. Other technology such as brain imagery, *e.g.* neuromarking, or DNA analysis for nonmedical purpose rise similar issues.

Often such research can also bring benefit, for instance, for health, as it is argued for stem cell research. Nevertheless, even if the market is the right regulation system for many new technologies, some cases mentioned above need external regulation. Two important points must be considered.

- As with today's medicine and biotechnology, the issues must be addressed by external ethics committees or regulation authorities, if possible before development. Here again, there is a limitation due to the globalization of research. Unlike 'dangerous experiments', there is no risk if common rules are adopted worldwide. However, a more permissive country could attract most of the research forbidden elsewhere and take benefit of that in the long term.
- As already discussed above, public awareness and debates well in advance are required for at least three reasons: (1) It is a useful tool to prepare various arguments that could be taken into account by regulation authorities. (2) The impact of some of the research is so large that science and the public must keep close to avoid a divide. (3) The hype, unconscious declaration, and success of some science fiction movies blur the distinction between reality and fiction. It is important to provide the information required to have a sane opinion.

5. Conclusion

Nanosciences and nanotechnologies are a rapidly growing field that already generates many hopes within the scientific and technological community of future discoveries, developments, and solutions to a number of societal problems. Simultaneously, fears of possible negative and uncontrolled impacts on humans and the environment are also developing steadily. In this chapter, we propose a typology to classify these fears, which are shown to be associated with images, metaphors, and symbols deeply rooted in the Western religious tradition. However, we think that it is necessary, and urgent, to discern between the hype, notably due to the media coverage of the field, and reality. Strangely enough, the idea that there might be a problem with nanotechnologies first emerged amongst the community of experts and promoters of this field, at a time when the general public was not even aware of the existence/emergence of a nanoworld. Is it only initially a media phenomenon?

Whatever the answer, we may have the opportunity, perhaps for the first time in the history of science and technology, to consider simultaneously the developments of new scientific knowledge and engineering capabilities with its impact on society and the environment and, thus, to take in time appropriate decisions 'to keep everything under control'. In a potentially controversial context, political decision-makers have the responsibility, with the active participation of scientists and engineers, to initiate, stimulate, and organize the public debate. Their objective should be to clarify the actual issues at stake, putting aside purely imaginary ones which rather belong to science fiction, as well as to identify methodologies to tackle these issues and to implement regulations, where necessary, to 'master' the development of nanotechnologies.

The difficulty of this task stems from the wide variety of (nano)-objects, topics, and issues associated with the expressions 'nanosciences' and 'nanotechnologies'. Indeed, nanoparticles, molecular robots, radio-frequency identification devices, *etc.*, raise different questions and call for specific solutions. The possible toxicity of nanoparticles, which may be released massively in the environment, poses a different problem than the wide commercial diffusion of RFIDs, which may endanger the privacy of personal information, even in a democratic society.

In this chapter, we make a number of proposals to tackle these difficult issues. We underline the importance of the role assigned to the public and, more generally, to all concerned social actors in any debate about science and technology. Callon's hybrid forums appear worth considering seriously. Foresight exercises would also be very useful to build scenarios taking into account properly both the likely developments of sciences and technologies and societal needs, expectations, and fears. Before testing them, we do not know if the proposals in fact enable effective management of the controversies that could emerge. The case of nanosciences could in this respect be exemplary, since the concerns and fears that it provokes have been raised even before its actual development. Consequently, those working in this field, in first place the scientists and engineers, have the option of including these legitimate questions in the very core of their research and innovation.

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CHAPTER 13

LIVING WITH UNCERTAINTY: TOWARD THE ONGOING NORMATIVE ASSESSMENT OF NANOTECHNOLOGY

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We are concerned with the new type of uncertainty that is brought about in consideration of singular events, like the future effects of nanotechnology, and characterized by the existence of cognitive barriers leading to paralysis of action in decision-making. We argue for application of the methodology of *ongoing normative assessment*. Such a methodology is a balanced solution between waiting until it is too late, if the effects are dangerous, and acting when it is yet too early, if the consequences of the developing technology have not yet been determined.

1. Introduction: Nanotechnology's Metaphysical Research Program

It is often asserted that the starting point of nanotechnology was the classic talk given by Feynman (1959), in which he said: "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom [...] It would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance." Today's champions of nanotech add: "We need to apply at the molecular scale the concept that has demonstrated its effectiveness at the macroscopic scale: making parts go where we want by *putting* them where we want!" (Merkle 2003).

This cannot be the whole story. If the essence of nanotechnology were that it manipulates matter on the atomic scale, no new philosophical attitude different from the one to other scientific disciplines would be necessary. Indeed, chemistry has been manipulating matter on the atomic scale for at least the past two centuries. We believe there is indeed some kind of unity behind the nanotech enterprise and the NBIC convergence (Roco & Bainbridge 2002); but that this unity lies at the level of the 'metaphysical research program' that underpins such convergence. It is at this level that nanoethics must address novel issues.

Let us recall that Karl Popper, following the lead of Emile Meyerson (1927), defined the notion of metaphysical research program as a set of ideas and worldviews that underlie any particular scientific research agenda. The positivist philosophy that drives most of modern science (and much of contemporary philosophy) takes 'metaphysics' to be a meaningless quest for answers to unanswerable questions. However, Popper showed that there is no scientific (or, for that matter, technological) research program that would not rest on a set of general presuppositions about the structure of the world. To be sure, those metaphysical views are not empirically testable and they are not amenable to 'falsification'. However, this does not imply that they are not of less importance or that they do not play a fundamental role in the advancement of science. Those who deny metaphysics simply render it invisible, and it is very likely that their hidden metaphysics is bad or inconsistent. To the amazement of those who mistook him for a positivist, Karl Popper claimed that the philosopher or historian of science's task was twofold: first, unearth and make visible the metaphysical ideas that lie underneath scientific programs in order to make them amenable to criticism; second, to proceed to a critical examination of those metaphysical theories, in a way that is different from the criticism of scientific theories, since no empirical testing is here possible, but nevertheless rational.

Our claim is that the major ethical issues raised by the nanotech enterprise and the NBIC convergence are novel and that they originate in the metaphysical research program on which such convergence rests. In order to substantiate this claim, we submit that the origin of the NBIC convergence is to be sought in another classic conference, the one John von Neumann gave at Caltech (1948) on complexity and self-reproducing automata.

Turing's and Church's theses were very influential at the time, and they had been supplemented by cyberneticians Warren McCulloch and Walter Pitts' major finding on the properties of neural networks (Dupuy 2000b, pp. 68-69). Cybernetics' credo was then: every behavior that is unambiguously describable in a finite number of words is computable by a network of formal neurons – a remarkable statement, as von Neumann recognized. However, he put forward the following objection: is it reasonable to assume as a practical matter that our most complex behaviors are describable in their totality, without ambiguity, using a finite number of words? In specific cases it is always possible: our capacity, for example, to recognize the same triangular form in two empirical triangles displaying differences in line, size, and position can be so described. But would this be possible if it were a matter of globally characterizing our capacity for establishing 'visual analogies'? In that case, von Neumann conjectured, it may be that the simplest way to describe a behavior is to describe the structure that generates it. It is meaningless, under these circumstances, to 'discover' that such a behavior can be embodied in a neural network since it is not possible to define the behavior other than by describing the network itself. To take an illustration:

> The unpredictable behaviour of nanoscale objects means that engineers will not know how to make nanomachines until they actually start building them. [*The Economist*, March 2003]

Von Neumann thus posed the question of complexity, foreseeing that it would become the great question for science in the future. Complexity implied for him, in this case, the futility of the constructive approach of McCulloch and Pitts, which reduced a function to a structure, thus leaving unanswered the question of what a complex structure is capable.

It was in the course of his work on automata theory that von Neumann was to refine this notion of complexity. Assuming a magnitude of a thermodynamic type, he conjectured that below a certain threshold it would be degenerative, meaning that the degree of organization could only decrease, but that above this threshold an increase in complexity became possible. Now this threshold of complexity, he supposed, is also the point at which the structure of an object becomes simpler than the description of its properties. Soon, von Neumann prophesied, the builder of automata would find himself as helpless before his creation as we feel ourselves to be in the presence of complex natural phenomena (Dupuy 2000b).

At any rate, von Neumann was thus founding the so-called *bottom-up approach*. In keeping with that philosophy, the engineers will not be any more the ones who devise and design a structure capable of fulfilling a function that has been assigned to them. The engineers of the future will be the ones who know they are successful when they are surprised by their own creations. If one of your goals is to reproduce life, to fabricate life, you have to be able to simulate one of its most essential properties, namely the capacity to complexify.

Admittedly, not all of nanotech falls under the category of complexity. Most of today's realizations are in the field of nanomaterials and the problems they pose have to do with toxicity. However, as a recent report by the European Commission says, "the powerful heuristic of Converging Technologies will prove productive even if it is or should be realized to a small extent only" (Nordmann 2004). The effects that pose ethical problems are not only the effects of technology *per se*, but also the effects of the metaphysical ideas that drive technology, whether technological realizations see the light of day or not. We are here mainly interested in these. Among them the novel kind of uncertainty associated with an ambition or a dream to set off complex phenomena looms large.

2. Towards a Novel Concept of Prudence

In her masterly study of the frailties of human action, Hannah Arendt brought out the fundamental paradox of our time: as human powers increase through technological progress, we are less and less equipped to control the consequences of our actions. From the start, a long excerpt is worth quoting, as its relevance for our topic cannot be overstated – and we should keep in mind that this was written in 1958:

> [...] the attempt to eliminate action because of its uncertainty and to save human affairs from their frailty by dealing with them as though they were or could become the planned products of human making has first of

> all resulted in channeling the human capacity for action, for beginning new and spontaneous processes which without men never would come into existence, into an attitude toward nature which up to the latest stage of the modern age had been one of exploring natural laws and fabricating objects out of natural material. To what extent we have begun to *act into nature*, in the literal sense of the word, is perhaps best illustrated by a recent casual remark of a scientist who quite seriously suggested that '*basic research is when I am doing what I don't know what I am doing'*.
>
> This started harmlessly enough with the experiment in which men were no longer content to observe, to register, and contemplate whatever nature was willing to yield in her own appearance, but began to prescribe conditions and to provoke natural processes. What then developed into an ever-increasing skill in *unchaining elemental processes*, which, without the interference of men, would have lain dormant and perhaps never have come to pass, has finally ended in a veritable art of *'making' nature*, that is, of creating 'natural' processes which without men would never exist and which earthly nature by herself seems incapable of accomplishing [...]
>
> The very fact that natural sciences have become exclusively sciences of process and, in their last stage, *sciences of potentially irreversible, irremediable 'processes of no return'* is a clear indication that, whatever the brain power necessary to start them, *the actual underlying human capacity which alone could bring about this development is no 'theoretical' capacity, neither contemplation nor reason, but the human ability to act* – to start new unprecedented processes whose outcome remains uncertain and unpredictable whether they are let loose in the human or the natural realm.
>
> In this aspect of action [...] processes are started whose outcome is unpredictable, so that *uncertainty rather than frailty becomes the decisive character of human affairs*. [Arendt 1958, pp. 230-232; our emphasis]

No doubt that with an incredible prescience this analysis applies perfectly well to the NBIC convergence, in particular on two scores. Firstly, the ambition to (re-)make nature is an important dimension of the metaphysical underpinnings of the field. If the NBIC converging technologies purport to take over Nature's and Life's job and become the engineers of evolution, it is because they have redefined Nature and Life in terms that belong to the realm of artifacts. See how one of their most vocal champions, Damien Broderick (2001, p. 116), rewrites the history of life, or, as he puts it, of 'living replicators':

> *Genetic algorithms* in planetary numbers lurched about on the surface of the earth and under the sea, and indeed as we now know deep within it, for billions of years, replicating and mutating and being winnowed via the success of their expressions – that is, the bodies they *manufactured*, competing for survival in the macro world. At last, the entire living ecology of the planet has *accumulated, and represents a colossal quantity of compressed, schematic information.*

Once life has thus been transmogrified into an artifact, the next step is to ask oneself whether the human mind could not do better. The same author asks rhetorically, "Is it likely that nanosystems, designed by human minds, will bypass all this Darwinian wandering, and leap straight to design success?" (p. 118).

Secondly, as predicted by von Neumann, it will be an inevitable temptation, not to say a task or a duty, for the nanotechnologists of the future to set off processes upon which they have no control. The sorcerer's apprentice myth must be updated: it is neither by error nor by terror that Man will be dispossessed of his own creations but by design.

There is no need for Drexlerian self-assemblers to come into existence for this to happen. The paradigm of *complex, self-organizing systems* envisioned by von Neumann is stepping ahead at an accelerated pace, both in science and in technology. It is in the process of shoving away and replacing the old metaphors inherited from the cybernetic paradigm, like the ones that treat the mind or the genome as computer programs. In science, the central dogmas of molecular biology received a severe blow on two occasions recently. First, with the discovery that the genome of an adult, differentiated cell can be 'reprogrammed' with the cooperation of maternal cytoplasm – hence the technologies of nucleus transfer, including therapeutic and reproductive cloning. Secondly, with the discovery of prions, which showed that self-replication does not require DNA. As a result, the sequencing of the human genome appears to be not the end of the road but its timid beginning. Proteinomics and complexity are becoming the catchwords in biology, relegating genomics to the realm of passé ideas.

In technology, new feats are being flaunted every passing week. Again, the time has not come – and may never come – when we manufacture self-replicating machinery that mimics the self-replication of living materials. However, we are taking more and more control of living materials and their capacity for self-organization and we use them to perform mechanical functions.

Examples are plenty. To give just one: In November 2003, scientists in Israel built transistors out of carbon nanotubes using DNA as a template. A Technion-Israel scientist said, "What we've done is to bring biology to *self-assemble an electronic device* in a test tube [...] The DNA serves as a scaffold, a template that will determine where the carbon nanotubes will sit. That's the beauty of using biology" (Chang 2003).

From a philosophical point of view the key issue is to develop new concepts of prudence that are suited to this novel situation. A long time ago Aristotle's *phronesis* was dislodged from its prominent place and replaced with the modern tools of the probability calculus, decision theory, the theory of expected utility, *etc*. More qualitative methods, such as futures studies, 'Prospective', and the scenario method were then developed to assist decision-making. More recently, the precautionary principle emerged on the international scene with an ambition to rule those cases in which uncertainty is mainly due to the insufficient state of our scientific knowledge. We believe that none of these tools is appropriate for tackling the situation that we are facing now.

From the outset we make it explicit that our approach is inherently normative. German philosopher Hans Jonas cogently explains why we need a radically new ethics to rule our relation to the future in the "technological age" (Jonas 1985). This "Ethics of the Future" (*Ethik* für *die Zukunft)* – meaning not a future ethics, but an ethics *for* the future, for the sake of the future, *i.e.* the future must become the major object of our concern – starts from a philosophical aporia. Given the magnitude of the possible consequences of our technological choices, it is an absolute obligation for us to try and anticipate those consequences, assess them, and ground our choices on this assessment. Couched in philosophical parlance, this is tantamount to saying that when the stakes are high, as in predicting the future, none of the normative ethics that are available is up to the challenge. Virtue ethics is manifestly insufficient since the problems ahead have very little to do with the fact that scientists or engineers are beyond moral reproach or not. Deontological doctrines do not fare much better since they evaluate the rightness of an action in terms of its conformity to a norm or a rule, for example to the Kantian categorical imperative: we are now well acquainted with the possibility that 'good' (*e.g.* democratic) procedures lead one into an abyss. As for consequentialism – *i.e.* the set of doctrines that evaluate an action based on its consequences for all agents concerned – it treats uncertainty as does the theory of expected utility, namely by ascribing probabilities to uncertain outcomes. Hans Jonas argues that doing so has become morally irresponsible. The stakes are so high that we must set our eyes on the worst-case scenario and see to it that it never sees the light of day.

However, the very same reasons that make our obligation to anticipate the future compelling, make it impossible for us to do so. Unleashing complex processes is a very perilous activity that both demands certain foreknowledge and prohibits it. Indeed, one of the very few unassailable ethical principles is that *ought* implies *can.* There is no obligation to do that which one cannot do. However, we do have here an ardent *obligation* that we can*not* fulfill: anticipating the future. We cannot but violate one of the foundations of ethics.

What is needed is a novel approach to the future, neither scenario nor forecast. We submit that what we call *ongoing normative assessment* is a step in that direction. In order to introduce this new concept we need to take a long detour into the classic approaches to the problems raised by uncertainty.

3. Uncertainty Revisited

3.1 Shortcomings of the Precautionary Principle

The precautionary principle triumphantly entered the arena of methods to ensure prudence. All the fears of our age seem to have found shelter in the word 'precaution'. Yet, in fact, the conceptual underpinnings of the notion of precaution are extremely fragile.

Let us recall the definition of the precautionary principle formulated in the French Barnier law: "The absence of certainties, given the current state of scientific and technological knowledge, must not delay the adoption of effective and proportionate preventive measures aimed at forestalling a risk of grave and irreversible damage to the environment at an economically acceptable cost" (1995). This text is torn between the logic of economic calculation and the awareness that the context of decision-making has radically changed. On one side, the familiar and reassuring notions of effectiveness, commensurability and reasonable cost; on the other, the emphasis on the uncertain state of knowledge and the gravity and irreversibility of damage. It would be all too easy to point out that if uncertainty prevails, no one can say what would be a measure proportionate (by what coefficient?) to a damage that is unknown, and of which one therefore cannot say if it will be grave or irreversible; nor can anyone evaluate what adequate prevention would cost; nor say, supposing that this cost turns out to be 'unacceptable', how one should go about choosing between the health of the economy and the prevention of the catastrophe.

One serious deficiency, which hamstrings the notion of precaution, is that it does not properly gauge the type of uncertainty with which we are confronted at present. The report on the precautionary principle prepared for the French Prime Minister (Kourilsky & Viney 2000) introduces what initially appears to be an interesting distinction between two types of risks: 'known' risks and 'potential' risks. It is on this distinction that the difference between prevention and precaution is said to rest: precaution would be to potential risks what prevention is to known risks. A closer look at the report in question reveals 1) that the expression 'potential risk' is poorly chosen, and that what it designates is not a risk waiting to be realized, but a hypothetical risk, one that is only a matter of conjecture; 2) that the distinction between known risks and, call them this way, hypothetical risks corresponds to an old standby of economic thought, the distinction that John Maynard Keynes and Frank Knight independently proposed in 1921 between risk and uncertainty. A risk can in principle be quantified in terms of objective probabilities based on observable frequencies; when such quantification is not possible, one enters the realm of uncertainty.

The problem is that economic thought and decision theory underlying it were destined to abandon the distinction between risk and uncertainty as of the 1950s in the wake of the exploit successfully performed by Leonard Savage with the introduction of the concept of subjective probability and the corresponding philosophy of choice under conditions of uncertainty: Bayesianism. In Savage's approach, probabilities no longer correspond to any sort of objective regularity present in nature, but simply to the coherent sequence of a given agent's choices. In philosophical language, every uncertainty is treated as *epistemic* uncertainty, meaning an uncertainty associated with the agent's state of knowledge. It is easy to see that introduction of subjective probabilities erases Knight's distinction between uncertainty and risk, between risk and the risk of risk, between precaution and prevention. If a probability is unknown, all that happens is that a probability distribution is assigned to it subjectively. Then further probabilities are calculated following the Bayes rule. No difference remains compared to the case where objective probabilities are available from the outset. Uncertainty owing to lack of knowledge is brought down to the same plane as intrinsic uncertainty due to the random nature of the event under consideration. A risk economist and an insurance theorist do not see and cannot see any essential difference between prevention and precaution and, indeed, reduce the latter to the former. In truth, one observes that applications of the 'precautionary principle' generally boil down to little more than a glorified version of 'cost-benefit' analysis.

Our situation with respect to new threats is different from the above-discussed context. The novel feature this time is that although uncertainty is objective, we are not dealing with a random occurrence either. This is because each of the future great discoveries or of the future catastrophes must be treated as a *singular event*. Neither random, nor uncertain in the usual epistemic sense, the type of 'future risk' that we are confronting is a monster from the standpoint of classic distinctions. Indeed, it merits a special treatment, which the precautionary principle is incapable of giving.

When the precautionary principle states that the 'absence of certainties, given the current state of scientific and technical knowledge, must not delay *etc.*', it is clear that it places itself from the outset within the framework of epistemic uncertainty. The assumption is that we know we are in a situation of uncertainty. It is an axiom of epistemic logic that if I do not know P, then I know that I do not know P. Yet, as soon as we depart from this framework, we must entertain the possibility that we do not know that we do not know something. In cases where uncertainty is such that it entails that uncertainty itself is uncertain, it is impossible to know whether or not the conditions for application of the precautionary principle have been met. If we apply the principle to itself, it will invalidate itself before our eyes.

Moreover, 'given the current state of scientific and technical knowledge' implies that a scientific research effort could overcome the uncertainty in question, whose existence is viewed as purely contingent. It is a safe bet that a 'precautionary policy' will inevitably include the edict that research efforts must be pursued – as if the gap between what is known and what needs to be known could be filled by a supplementary effort on the part of the knowing subject. However, it is not uncommon to encounter cases in which the progress of knowledge comports an increase in uncertainty for the decision-maker, a thing inconceivable within the framework of epistemic uncertainty. Sometimes, to learn more is to discover hidden complexities that make us realize that the mastery we thought we had over phenomena was in part illusory.

3.2 Society is a Participant

From the point of view of mathematics of complex systems one can distinguish several different sources of uncertainty. Some of them appear in almost any analysis of uncertainties; others are taken into account quite rarely.

Presence of tipping points, *i.e.* such points on the system's landscape of trajectories that trigger an abrupt fall of the system into states completely different from the states that the system had previously occupied, is one of the reasons why uncertainty is not amenable to the concept of probability. As long as the system remains far from the threshold of the catastrophe, it may be handled with impunity. Here cost-benefit analysis of risks is bound to produce a banal result, because the trajectory is predictable and no surprises can be expected. To give an example, this is the reason why humanity was able to blithely ignore, for centuries, the impact of its mode of development on the environment. However, as the critical thresholds grow near, cost-benefit analysis, previously a banality, becomes meaningless. At that point it is imperative not to enter the area of critical change at any cost, if one, of course, wants to avoid the crisis and sustain the smooth development. We see that for reasons having to do, not with a temporary insufficiency of our knowledge, but with the structural properties of complex systems, economic calculation is of little help.

We now turn to another source of uncertainty that appears in the case of systems in whose development participates the human society. Technology here is just one example. To these systems the usual techniques for anticipating the future, as discussed in the next section, are inapplicable. The difficulty comes from the fact that, in general, any system where the society plays an active role is characterized by the impossibility to dissociate the observed part of the system ('the sphere of technology') from the observer ('society at large'), who himself is influenced by the system and must be viewed as one of its components. In a usual setting, the observer looks at the system that he studies from an external point, and both the observer and the system evolve in linear physical time. The observer can then treat the system as independent from the act of observation and can create scenarios in which this system will evolve in linear time. Not so if the observer can influence the system and, in turn, be influenced by it (Figure 1). What evolves as a whole in linear time is now a conglomerate, a composite system consisting of both the complex system and the observer. However, the evolution of the composite system in the linear time becomes of no interest for us, for the act of observation is performed by the observer who is a part of the composite system; the observer himself is now *inside the big whole*, and his point of view is no more an external one. The essential difference is that the observer and the complex system enter into a network of complex relations with each other, due to mutual influence. In science such composite systems are referred to as self-referential systems. They were first studied by von Neumann in his famous book on the theory of self-reproducing automata, which consequently gave rise to a completely new direction of mathematical research.

According to Breuer's theorem, the observer involved in a self-referential system can never have full information on the state of the system. This is a fundamental source of uncertainty in the analysis of complex systems that involve human action. We should take very seriously the idea that there is a "co-evolution of technology and society"

(Rip *et al.* 1995). The dynamics of technological development is embedded in society. The consequences of the development of nanotechnology will concern society as well as technology itself. Technology and society shape one another. One can then prove mathematically that the society cannot know with certainty where the technological progress will take it nor make any certain predictions about its own future state.

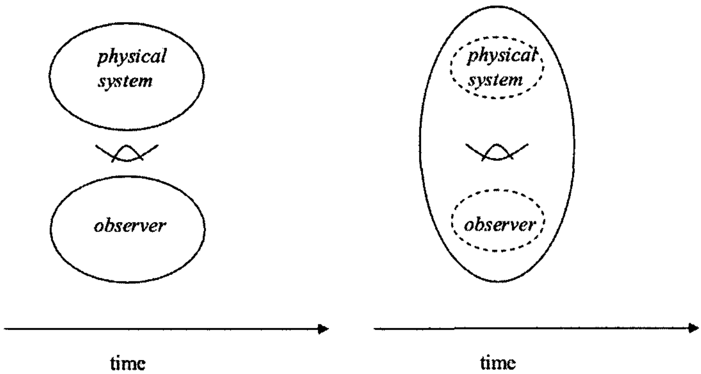

Figure 1. An external observer and an observer-participant.

3.3 Projected Time

It is a gross simplification to treat the sphere of technology as if it developed only according to its internal logic. Political decision-making and the opinion of the society influence research. The decisions that will be made or not, such as various moratoria and bans, will have a major impact on the evolution of research. Scientific ethics committees would have no *raison d'être* otherwise. If many scientists and experts ponder over the strategic and philosophical questions, it is not only out of curiosity; rather, it is because they wish to exert an influence on the actions that will be taken by the politicians and, beyond, the peoples themselves.

These observations may sound trivial. It is even more striking that they are not taken into account, most of the time, when it comes to anticipating the evolution of research. When they are, it is in the manner of control theory: human decision is treated as a parameter, an independent or exogenous variable, and not as an endogenous variable. Then, a crucial causal link is missing: the motivational link. It is obvious that human decisions that will be made will depend, at least in part, on the kind of anticipation of the future of the system, this anticipation being made public. And this future will depend, in turn, on the decisions that will be made. A causal loop appears here, that prohibits us from treating human action as an independent variable. Thus, research and technology are systems in which society is a participant.

By and large there are three ways of anticipating the future of a human system, whether purely social or a hybrid of society and the physical world. The first one we call *Forecasting*. It treats the system as if it were a purely physical system. This method is legitimate whenever it is obvious that anticipating the future of the system has no effect whatsoever on the future of the system.

The second method we call, in French, '*Prospective*'. Its most common form is the scenario method. Ever since its beginnings the scenario approach has gone to great lengths to distinguish itself from mere forecast or foresight, held to be an extension into the future of trends observed in the past. We can forecast the future state of a physical system, it is said, but not what we shall decide to do. It all started in the 1950s when a Frenchman, Gaston Berger, coined the term '*Prospective*' – a substantive formed in analogy with 'Retrospective' – to designate a new way to relate to the future. That this new way had nothing to do with the project or the ambition of anticipating, that is, *knowing* the future, was clearly expressed in the following excerpt from a lecture given by French philosopher Bertrand de Jouvenel (1964):

> It is unscholarly perforce because there are no facts on the future. Cicero quite rightly contrasted past occurrences and occurrences to come with the contrasted expressions *facta* and *futura*: *facta*, what is accomplished and can be taken as solid; *futura*, what shall come into being, and is as yet 'undone', or fluid. This contrast leads me to assert vigorously: '*there can be no science of the future.*' *The future is not the realm of the 'true or false' but the realm of 'possibles'*.

Another term coined by Jouvenel that was promised to a bright future was '*Futuribles*', meaning precisely the open diversity of *possible fu-*

tures. The exploration of that diversity was to become the scenario approach.

A confusion spoils much of what is being offered as the justification of the scenario approach. On the one hand, the alleged irreducible multiplicity of the 'futuribles' is explained as above by the *ontological indeterminacy* of the future: since we 'build', 'invent' the future, there is nothing to know about it. On the other hand, the same multiplicity is interpreted as the inevitable reflection of our inability to know the future *with certainty*. The confusion of ontological indeterminacy with epistemic uncertainty is a very serious one. From what we read in the literature on nanotechnology, we got the clear impression that the emphasis is put on epistemic uncertainty, but only up to the point where human action is introduced: then the scenario method is used to explore the sensitivity of technological development to human action.

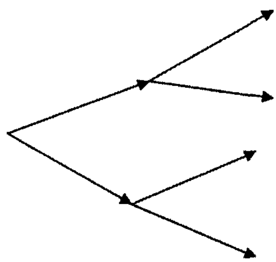

Figure 2. Occurring time.

The temporality that corresponds to Prospective or the scenario approach is the familiar decision tree. We call it *occurring time* (Figure 2). It embodies the familiar notions that the future is open and the past is fixed. In short, time in this model is the usual linear one-directional time arrow. It immediately comes to mind that, as we have stated above, linear time does not lead to the correct type of observation and prediction if the observer is an *observer-participant*. This is precisely the case with the society at large and its technology, and, consequently, one must not expect a successful predictive theory of the latter to operate in the linear occurring time.

We submit that occurring time is not the only temporal structure we are familiar with. Another temporal experience is ours on a daily basis. It is facilitated, encouraged, organized, not to say imposed by numerous features of our social institutions. All around us, more or less authoritative voices are heard that proclaim what the more or less near future will be: the next day's traffic on the freeway, the result of the upcoming elections, the rates of inflation and growth for the coming year, the changing levels of greenhouse gases, *etc*. The *futurists* and sundry other prognosticators know full well, as do we, that this future they announce to us as if it were written in the stars is, in fact, a future of our own making. We do not rebel against what could pass for a metaphysical scandal (except, on occasion, in the voting booth). It is the coherence of this mode of coordination with regard to the future that we have endeavored to bring out, under the name of projected time (Figure 3).

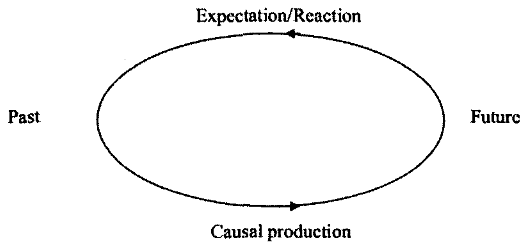

Figure 3. Projected time.

To return to the three ways of anticipating the future, the foresight method can be said to be a view of an independent observer from outside the physical system. Counter-argument to it is that in reality the observer is not independent and has a capacity to act as to produce causal effects on the system. The second way of anticipation, 'Prospective', or its version such as the scenario approach, is a view on the system where the observer is not independent any more, but the view itself is still taken from outside the system. Thus, the one who analyzes and predicts is the same agent as the one who acts causally on the system. As explained in the previous section, this fact entails a fundamental limit on the capacities of the anticipator. What is needed, therefore, is a replacement of the linear occurring time with a different point of view. This means taking seriously the fact that the system involves human action and requiring that predictive theory accounts for this. It is only such a theory that will be capable of providing a sound ground for non-self-contradictory, coherent anticipation. A *sine qua non* must be respected for that coherence to be the case: a *closure condition*, as shown on the graph. Projected time takes the form of a loop, in which past and future reciprocally determine each other. It appears that the metaphysics of projected time differs radically from the one that underlies occurring time, as counterfactual relations run counter causal ones: the future is fixed and the past depends counterfactually upon the future.

To foretell the future in projected time, it is necessary to seek the loop's *fixed point*, where an expectation (on the part of the past with regard to the future) and a causal production (of the future by the past) coincide. The predictor, *knowing that his prediction is going to produce causal effects in the world*, must take account of this fact if he wants the future to confirm what he foretold. Therefore the point of view of the predictor has more to it than a view of the human agent who merely produces causal effects. By contrast, in the scenario ('prospective') approach the self-realizing prophecy aspect of predictive activity is not taken into account.

We will call *prophecy* the determination of the future in projected time, by reference to the logic of self-fulfilling prophecy. Although the term has religious connotations, let us stress that we are speaking of *prophecy* here in a purely secular and technical sense. The prophet is the one who, prosaically, seeks out the fixed point of the problem, the point where *voluntarism achieves the very thing that fatality dictates*. The prophecy includes itself in its own discourse; it sees itself realizing what it announces as destiny. In this sense, as we said before, prophets are legion in our modern democratic societies, founded on science and technology. What is missing is the realization that this way of relating to the future, which is neither building, inventing or creating it, nor abiding by its necessity, requires a special metaphysics, which is precisely provided by what we call projected time (Dupuy 1989, 1992, 1998, 2000a).

4. Cognitive Barriers

4.1 The Description of the Future Determines the Future

If the future depends on the way it is anticipated and this anticipation being made public, every determination of the future must take into account the causal consequences of the language that is being used to describe the future and how this language is being received by the general public, how it contributes to shaping public opinion, and how it influences the decision-makers. In other terms, the very description of the future is part and parcel of the determinants of the future. This self-referential loop between two distinct levels, the epistemic and the ontological, is the signature of human affairs. Let us observe that this condition provides us with a criterion for determining which kinds of description are acceptable and which are not: the future *under that description* must be a fixed point of the self-referential loop that characterizes projected time.

Any inquiry on the kind of uncertainty proper to the future states of the co-evolution between technology and society must therefore include a study of the linguistic and cognitive channels through which descriptions of the future are made, transmitted, conveyed, received, and made sense of. This is a huge task, and we will limit ourselves here to two dimensions that seem to us of special relevance for the study of the impact of the new technology: the aversion to not knowing, and the impossibility to believe. A third such dimension that we do not discuss here is the certainty effect studied by Tversky and Kahneman. This effect consists in a practical observation that certainty exaggerates the aversiveness of losses that are certain relative to losses that are merely probable.

4.2 Aversion to Not Knowing

In 1950s, soon after Savage's work, a debate on the subjective probabilities was initiated by Maurice Allais. Allais intended to show that Savage's axioms are very far from what one observes, in economics, in practical decision-making contexts. Soon an example was proposed, a version of which is known under the name of Ellsberg paradox (Ellsberg

1961). The key idea of Allais and, later on, of Ellsberg is that there exists aversion to not knowing. Not knowing must be understood as the opposite of knowing, negation of a certain ascribed property, and must be differentiated from the unknown or ignorance. Ignorance presupposes that something can possibly be known, while here we are concerned with a situation of not knowing and not being able to know, because of the game conditions or because of some real-life factors. Aversion to not knowing can take the form of aversion to uncertainty in situations where uncertainty means epistemic uncertainty according to Frank Knight's distinction between risk and uncertainty. However, as a general principle aversion to not knowing exceeds the conceptual limits of Savage's theory.

The Ellsberg paradox is an example of a situation where agents would irrationally prefer the situation with some information to a situation without any information, although it is rational to prefer to avert from information. Consider two urns, A and B (Figure 4). It is known that in urn A there are exactly ten red balls and ten black balls. About urn B it is only said that it contains twenty balls, some red and some black. A ball from each urn is to be drawn at random. Free of charge, a person can choose one of the two urns and then place a bet on the color of the ball that is drawn. According to Savage's theory of decision-making, urn B should be chosen even though the fraction of balls is not known. Probabilities can be formed subjectively, and a bet shall be placed on the subjectively most likely ball color. If subjective probabilities are not fifty-fifty, a bet on urn B will be strictly preferred to one on urn A. If the subjective probabilities are precisely fifty-fifty then the decision-maker will be indifferent. Contrary to the conclusions of Savage's theory, Ellsberg argued that a strict preference for urn A is plausible because the probability of drawing a red or black ball is known in advance. He surveyed the preferences of an elite group of economists to lend support to this position and found that his view was right and that there was evidence against applicability of Savage's axioms. Thus, the Ellsberg paradox challenges the appropriateness of the theory of subjective probability.

We shall also say that the Ellsberg paradox challenges the usual assumption that human decision-makers are probability calculators. Indeed, had one given himself the task of assessing the problem with urns from the point of view of probabilities, it would be inevitable to make use of the Bayes rule and thus conclude that urn B is the preferred choice. But, as shown by Ellsberg, aversion to not knowing is a stronger force than the tendency to calculate probabilities. Aversion to not knowing therefore erects a cognitive barrier that separates human decision-maker from the field of rational choice theory.

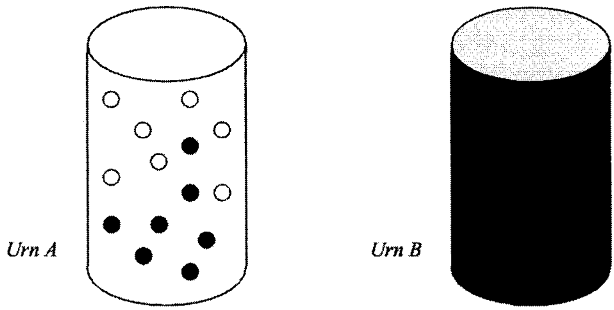

Figure 4. The Ellsberg paradox.

4.3 Impossibility of Believing

Let us return to the precautionary principle. By placing the emphasis on scientific uncertainty, it misconstrues the nature of the obstacle that keeps us from acting in the face of catastrophe. The obstacle is not just uncertainty, scientific or otherwise; it is equally, if not a more important component, the impossibility of believing that the worst is going to occur. Contrary to many the basic assumption of epistemic logic, one can know that P but still not believe in P.

Pose the simple question as to what the practice of those who govern us was before the idea of precaution arose. Did they institute policies of *prevention,* the kind of prevention with respect to which precaution is supposed to innovate? Not at all. They simply waited for the catastrophe to occur before taking action – as if its coming into existence constituted the sole factual basis on which it could be legitimately foreseen, too late of course. We submit that there exists a deep cognitive basis for such a behavior, which is exhibited by human decision makers in a situation when they know that a singular event, like a catastrophe, stands right behind the door. In these circumstances arises a cognitive barrier of the impossibility to believe in the catastrophe.

To be sure, there are cases where people do see a catastrophe coming and do adjust. That just means that the cognitive barrier in question is not absolute and can be overcome. We will introduce further a method that makes such overcoming more likely. However, by and large, even when it is known that it is going to take place, a catastrophe is not credible. On the basis of numerous examples, English researcher David Fleming identified what he called the "inverse principle of risk evaluation": the propensity of a community to recognize the existence of a risk seems to be determined by the extent to which it thinks that solutions exist (Fleming 1996). There is no subjective or objective probability calculus here; knowing that P but not believing in P has a different origin.

What could this origin be? Observe first that the aversion to not knowing and the impossibility to believe do not go unconnected. Both are due to the fact that human action as cognitive decision-making process vitally depends on having information. Cognitive agents cannot act without having information that they rely upon, and the experience from which they build analogies with a current situation. Consequently, a fundamental cognitive barrier arises, which is that if an agent does not have information or experience, then he does not take action, a situation that for an outsider appears as paralysis in decision-making. Aversion to not knowing is caused by the cognitive barrier but the agent, like in the Ellsberg paradox, is forced to act. He then chooses an action which is not rational but which escapes to the largest degree the situation of not having information. Were the agent allowed not to act at all, as in real life situations, the most probable outcome becomes the one of paralysis. When the choice is between the relatively bad, the unknown, and doing nothing, the last option happens to be the most attractive one. If it is dropped and the choice is just between the relatively bad and the unknown, relatively bad may turn out to be the winner. To summarize, we argue that a consequence of the cognitive barrier is that if in a situation of absence of information and of the singular character of the coming event there is a possibility not to act, this will be the agent's preference.

Standing face to face with a catastrophe or a dramatic change in life, most people become paralyzed. As cognitive agents, they have no information, no experience, and no practical know-how concerning the singular event, and the cognitive barrier precludes the human decision-maker from action.

Another consequence of the cognitive barrier is that if an agent is forced to act, then he will do his best to acquire information. Even though it may later be found out that he had made wrong decisions or his action had not been optimal, in the process of decision-making itself the cognitive barrier dictates that the agent collects as much information as he can get and acts upon it. Reluctance to bring in available information or, yet more graphically, refusal to look for information are by themselves special decisions and require that the agent consciously chooses to tackle the problem of the quality and quantity of information that he wants to act upon. If the agent does so, *i.e.* if he gives himself the task to analyze the problem of necessary vs. superficial information, then it is comprehensible that the agent would refuse to acquire some information, as does the rational agent in the Ellsberg paradox. However, if the meta-analysis of the preconditions of decision-making is not undertaken, then the agent will naturally tend to collect at least some information that is available on the spot. Such is the case in most real life situations. Consequently, the cognitive barrier entails that the directly available information is viewed as relevant to decision-making; if there is no such information, then the first thing-to-do is to look for one.

Cognitive barrier in its clear-cut form applies to situations where one faces a choice between total absence of information and availability of at least some knowledge. The reason why agents have no information on an event and its consequences is usually that this event is a singular event. Singular events, by definition, mean that the agent cannot use his previous experience for analyzing the range of possible outcomes and for evaluating particular outcomes in this range. To enter into Savage's rational decision-making process, agents require previous information or experience that allow them to form priors. If information is absent or is such that no previous experiential data is available, the process is easily paralyzed. Contrary to the prescription of the theory of subjective probabilities, in a situation of absence of information real cognitive agents do not choose to set priors arbitrarily. To them, selecting probabilities and even starting to think probabilistically without any reason to do so appears as purely irrational and untrustworthy. Independently of the projected positive or negative outcome of a future event, if it is a singular event, then cognitive agents stay away from the realm of subjective probabilistic reasoning and are led to paralysis.

Now, our immediate concern becomes to offer a way of functioning, which is capable of bringing the agents back to operational mode from the dead end of cognitive paralysis.

5. Methodology of Ongoing Normative Assessment

The methodology that we propose is different from a one-time probabilistic analysis that is devoted to constructing a range of scenarios, all developing in the linear time which forks into a multitude of branches, and choosing 'the best', whatever the criterion. Our method does not rest on the application of an *a priori* principle, such as the Precautionary Principle. We submit that no principle can do the job of dealing with the kind of uncertainty that the new technological wave generates. What we propose can be viewed as a practice, rather than a principle, as a *way of life* or a procedural prescription for all kinds of agents: from a particular scientist and a research group to the whole of the informed society, telling them how to proceed with questions regarding the future, on a regular basis in course of their usual work.

Our methodology is a methodology of ongoing normative assessment. It is a matter of obtaining through research, public deliberation, and all other means, an image of the future sufficiently optimistic to be desirable and sufficiently credible to trigger the actions that will bring about its own realization. The sheer phrasing of the methodology suggests that it rests on the metaphysics of projected time, of which it reproduces the characteristic loop between past and future. Importantly, one must note that these two goals, for an image to be both optimistic and credible, are seen as entering in a contradiction. Yet another contradiction arises from the requirement of anticipating a future state early enough, when its features cannot yet be seen clearly, and not waiting until it is too late, when the future is so close to us that it is unchangeable. Both contradictions hint at a necessary balance between the extremes. It is not credible to be too optimistic about the future, but cognitive paralysis arises when the anticipated future is irreparably catastrophic. It is not credible to announce a prediction too early, but it becomes, not a prediction but a matter of fact, if waited for too long. The methodology of ongoing normative assessment prescribes to live with the uncertain future and to follow a certain procedure in continuously evaluating the state of the analyzed system.

The methodology of ongoing normative assessment can also be viewed as a conjunction of inverse prescriptions. This time, instead of an optimistic but credible image of the future, one should wish to obtain at every moment of time an image of the future sufficiently catastrophic to be repulsive and sufficiently credible to trigger the actions that would block its realization. As shown in the discussion of projected time, a closure condition must be met, which takes here the following form: a catastrophe must necessarily be inscribed in the future with some vanishing, but non-zero weight, this being the condition for this catastrophe *not* to occur. The future, on its part, is held as *real*. This means that a human agent is told to *live with* an inscribed catastrophe. Only so will he avoid the occurrence of this catastrophe. Importantly, the vanishing non-zero weight of the catastrophic real future is not the objective probability of the catastrophe and has nothing to do with an assessment of its frequency of occurrence. The catastrophe is altogether inevitable, since it is inscribed in the future: however, if the methodology of ongoing normative assessment is correctly applied, the catastrophe will not occur. A damage that will not occur must be *lived with* and treated *as if* inevitable: this is the aporia of our human condition in times of impending major threats.

To give an example of how ongoing normative assessment is applied in actual cases, we cite the Metropolitan Police commissioner Sir John Stevens, who, speaking about terrorist attacks in London as reflected in his everyday work, said in March 2004, "We do know that we have actually stopped terrorist attacks happening in London but [...] there is an *inevitability* that some sort of attack will get through but my job is to make sure that *does not* happen" (Stevens 2004).

Each term in the formulation of the methodology of ongoing normative assessment requires clarification. We start with the word *ongoing*.

The assessment that we are speaking about implies systems where the role of the human observer (individual or collective) is the one of observer-participant. As discussed in Section 3.2, the observer-participant does not analyze the system that he interacts with in terms of linear time; instead, he is constantly involved in an interplay of mutual constraints and interrelations between the system being analyzed and himself. The temporality of this relation is the circular temporality of projected time: if viewed from an external, Archimedes' point, influences go both ways, from the system to the observer and from the observer to the system. The observer, who preserves his identity throughout the whole development and whose point of view is 'from the inside', is bound to reason in a closed loop temporality, the only one that takes into account the mutual character of the constraints. Now, if one is to transpose the observer's circular vision back into the linearly developing, occurring time, he finds that the observer cannot do all his predictive work at one and only one point of occurring time. Circularity of relations within a complex system requires that the observer constantly revise his prediction. To make sure that the loop of interrelations between the system and himself is updated consistently and does not lead to a catastrophic elimination of any major component of either the system in question or of the observer himself, the latter must not stop addressing the question of the future at all times. No fixed-time prediction conserves its validity due to the circularity and self-referentiality of the complex system.

We now address the next term in the formulation of our methodology, *normative* assessment. A serious deficiency of the precautionary principle is that, unable to depart from the normativity proper to the calculus of probabilities, it fails to capture what constitutes the essence of ethical normativity concerning choice in a situation of uncertainty. We argue that judgments are normative but that this normativity, applied to the problem of the future, takes on a special form.

We refer to the concept of 'moral luck' in moral philosophy. Let us first illustrate with an example why probabilistic reasoning does not lead to any satisfactory account of judgment. Imagine that one must reach into an urn containing an indefinite number of balls and pull one out at random. Two thirds of the balls are black and only one third are white. The idea is to bet on the color of the ball before seeing it. Obviously, one should bet on black. And if one pulls out another ball, one should bet on black again. In fact, one should *always* bet on black, even though one foresees that one out of three times on average this will be an incorrect guess. Suppose that a white ball comes out, so that one discovers that the guess was incorrect. Does this *a posteriori* discovery justify a retrospective change of mind about the rationality of the bet that one made? No, of course not; one was right to choose black, even if the next ball to come out happened to be white. Where probabilities are concerned, the information as it becomes available can have no conceivable retroactive impact on one's judgment regarding the rationality of a past decision made in the face of an uncertain or risky future. This is a limitation of probabilistic judgment that has no equivalent in the case of moral judgment.

Take another example. A man spends the evening at a cocktail party. Fully aware that he has drunk more than is wise, he nevertheless decides to drive his car home. It is raining, the road is wet, the light turns red, and he slams on the brakes, but a little too late: after briefly skidding, the car comes to a halt just past the pedestrian crosswalk. Two scenarios are possible: either there was nobody in the crosswalk, and the man has escaped with no more than a retrospective fright. Or else the man ran over and killed a child. The judgment of the law, of course, but above all that of morality, will not be the same in both cases. Here is a variant: the man was sober when he drove his car. He has nothing to reproach himself for. But there is a child whom he runs over and kills, or else there is not. Once more, the unpredictable outcome will have a retroactive impact on the way the man's conduct is judged by others and also by the man himself. Therefore, moral luck becomes an argument proving that ethics is necessarily a *future ethics*, in Jonas's sense as described earlier, when it comes to judgment about a future event. However, the implementation of that future ethics is impeded in practice by the very inevitability of the uncertainty of the future. This is the ethical aporia we started with.

Is there a way out? Hans Jonas's credo is that there is no ethics without metaphysics. Only a radical change in metaphysics can allow us to escape from the ethical aporia. The major stumbling block of our current, implicit metaphysics of temporality turns out to be our common conception of the *future as unreal*. From the human belief in free will – 'we may act otherwise' – is derived the conclusion that the future is not real, in the philosophical sense: 'future contingents', *i.e.* propositions about actions taken by a free agent in the future, *e.g.* 'John will pay back his debt tomorrow', are held to have no truth value. They are neither true nor false. If the future is not real, then it is not something that we can have cognizance of. If the future is not real, then it is not something that projects its shadow onto the present. Even when we know that a catastrophe is about to happen, we do not believe it: we do not believe what we know. If the future is not real, there is nothing in it that we should fear, or hope for. From our point of view, the derivation from free will to the unreality of the future is a sheer logical fallacy.

Like the car driver, but on an entirely different scale, human society taken as a collective subject has made a choice in the development of its potential capabilities that brings it under the jurisdiction of moral luck. It may be that its choice will lead to great and irreversible catastrophes; it may be that it will find the means to avert them, to get around them, or to get past them. No one can tell which way it will go. Judgment can only be retrospective. However, *it is possible to anticipate, not the judgment itself, but the fact that it must depend on what will be known once the 'veil of ignorance' covering the future is lifted.* Thus, there is still time to insure that our descendants will never be able to say *'too late!'* – a too late that would mean that they find themselves in a situation where no human life worthy of the name is possible.

Retrospective character of judgment means that, on the one hand, application of the existing norms for judging facts and, on the other hand, evaluation of new facts for updating the existing norms and creating new ones, are two complementary processes. While the first one is present in almost any sphere of human activity, the second process prevails over the first and acquires an all-important role in the anticipation of the future. What is a norm is being revised continuously, and at the same time this ever-changing normativity is applied to new facts. It is for this reason that the methodology of ongoing assessment requires that the assessment be normative and that the norms themselves be addressed in a continuous way.

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CHAPTER 14

GREAT UNCERTAINTY ABOUT SMALL THINGS

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Public debates about nanotechnology are often conducted in terms of mere possibility arguments (MPAs). These arguments come in two variants. According to the negative variant, since the development of nanotechnology can have certain specified negative effects, that development should not be supported. According to the positive variant, since the development of nanotechnology can have certain specified positive effects, it should be supported. The 'can' of these arguments is difficult to disambiguate, and meaningful probabilistic analysis of these statements is in most cases impossible. Therefore, other analytical tools have to be developed in order to deal rationally with mere possibility arguments. In this chapter, two such tools are introduced, namely the test of alternative effects and the test of alternative causes.

1. Introduction

Much of the public discussion about nanotechnology concerns possible risks associated with the future development of that technology. It would therefore seem natural to turn to the established discipline for analyzing technological risks, namely risk analysis, for guidance about nanotechnology. It turns out, however, that risk analysis does not have much to contribute here.

The reason for this is that the tools of risk analysis have been tailored to deal with other types of issues than those presently encountered in connection with nanotechnology. Risk analysis was developed as a means to evaluate well-defined dangers associated with well-known technologies, such as the risk that a bomb explodes accidentally or that exposure to a specific chemical substance gives rise to cancer (Rechard 1999, Hansson 1993). The characteristic activity of risk analysts is to estimate the probabilities of such events. Elaborate methodologies have been developed to estimate probabilities of events that depend on complex chains of technological events, such as nuclear accidents, or on biological processes that are only partially known, such as chemical carcinogenesis.

These methodologies are not of much help when we are dealing with the issues commonly associated with nanotechnology. Critics of nanotechnology typically refer to unrealized possibilities, such as that nanotechnological devices can be used for eavesdropping and other privacy intrusions, that nanorobots can replace soldiers, that nanodevices can be implanted to control a human being, or that self-replicating nanosystems may eventually replace the human race instead of serving us. These are certainly serious concerns, but nobody knows today whether or not any of these types of nanodevices will ever be technologically feasible. Neither do we know what these hypothetical technologies will look like in case they will be realized.[1] Therefore, discussions on such dangers differ radically from how risk analysis is conducted. The tools developed in that discipline cannot be used when so little is known about the possible dangers that no meaningful probability assessments are possible.

In the terminology of risk analysis, the possible dangers of nanotechnology should be treated as uncertainties rather than risks. The distinction between risk and uncertainty derives from decision theory. By decision-making under risk is meant that we know what the possible outcomes are and what are their probabilities. In decision-making under uncertainty, probabilities are either not known at all or only known with insufficient precision (Knight 1935, pp. 19-20; Luce & Raiffa 1957, p. 13). In most decision-theoretical treatments of uncertainty, it is assumed that, besides probabilities, most other features of the situation are

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[1] These technologies have been characterized in terms only of their functional, not their physical characteristics. On functional characterization of technologies, see Kroes & Meijers 2002.

well-defined and known. In real life it is not unusual to encounter situations of *great uncertainty*. By this is meant that other types of information than probabilities are lacking as well. Hence, in decision-making under great uncertainty we may be unaware what the options are that can be chosen between, what the possible consequences of the options are (and not only the probabilities of these consequences), whether or not information from others (such as experts) can be relied upon, or how one values (or should value) different outcomes (Hansson 1996).

The effects of future, yet unrealized technologies are in most cases subject to great uncertainty. Nanotechnology is an unusually clear example of this. As already mentioned, the technological feasibility of the nanoconstructions under ethical debate is in most cases uncertain. Furthermore, many of the possible future nanotechnologies are so different from previous technologies that historical experience provides very little guidance in judging how people will react to them. The development and use of new technologies is largely determined by human reactions to them, which have their influence via mechanisms including markets, politics, and social conventions (Rosenberg 1995).

It is not only the negative but also the positive effects of nanotechnology and other future technologies that are subject to great uncertainty. The most fervent proponents of nanotechnology have argued that it can solve many of humanity's most pressing problems: Nanotechnology can make cheap solar energy available, thus solving the energy problem. Nanoscale devices injected into the bloodstream can be used to attack cancer cells or arterial plaques, thus eradicating major diseases. Synthetic human organs can be constructed that replace defective ones. According to leading cryonics companies, nanotechnology will be used to bring back cryopreserved persons to life.[2] These predictions are all subject to great uncertainty in the same way and for the same reasons as the more dire predictions referred to above. However, whereas expounders of the positive predictions seem fully aware of the uncertainty inherent in the negative predictions, and vice versa, both groups tend to de-emphasize the uncertain nature of their own predictions.

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[2] See *e.g.* http://www.alcor.org.

In dealing with the usual topics of risk analysis, namely reasonably well-defined event types and event chains, experts in particular fields of science and engineering, such as toxicology, structural mechanics, nuclear technology, *etc.* can provide much of the information that is needed to assess the risks and guide decision-making. In issues of great uncertainty, such as the positive and negative effects of future nanotechnology, the problem-solving potential of such specific knowledge is smaller. Instead, issues such as the structure and validity of arguments will be more important. These are issues for philosophers specializing in informal logic and argumentation analysis. Therefore, uncertainty analysis offers a promising, although unexplored, area for applied philosophy. It is the purpose of the present contribution to introduce a systematic approach to one central topic in uncertainty analysis that is particularly relevant for debates on nanotechnology, namely the critical appraisal of arguments referring to the (mere) possibility of positive or negative future developments.

2. Mere Possibility Arguments

Public debates about future technologies are often conducted in terms of what future developments are *possible*. Nanotechnology is a typical example of this. Opponents of nanotechnology claim that we should refrain from developing it since it *can* lead to disastrous outcomes. Its most enthusiastic proponents maintain that we must develop it since it *can* solve many of the problems that are plaguing humanity. I will use the term *mere possibility argument* (MPA) to denote an argument in which a conclusion is drawn from the mere possibility that the choice of an option, behavior, or course of action may lead to, or be followed by, certain consequences.

Clearly, the 'can' of some MPAs is accessible to disambiguation. Consider the following dialogue:

I: "It would be wise of you to stop smoking. Otherwise the cigarettes can kill you."

II: "But there are thousands or things that could kill me, and I cannot quit all of them. In the last few months, the newspaper contained articles saying that eggs, meat, milk, and I think even more foodstuffs can be deadly. I cannot stop eating all of these."

I: "There is a big difference. These food-related dangers are all quite uncertain. But scientists have shown that about half of the smokers die prematurely because of smoking."

Here, the first speaker puts forward an MPA, which the second speaker tries to neutralize (with a type of argument that we will return to in section 4). The first speaker then substantiates the argument, by transforming it from an MPA to a probabilistic statement. This is a common argument pattern. When MPAs are put under attack, their proponents often try to reconstruct them to make them more conclusive.

Although the disambiguation (and probabilistic reconstruction) of MPAs is an important form or argumentation, the focus of the present chapter is on argumentation that remains on the level of mere possibilities. There are two reasons for this. First, it is a judicious research strategy to study argumentation on the MPA level before ways to go beyond that level are introduced. Secondly, in nanotechnology it is often not possible to go beyond the MPA level of argumentation.

There are two major variants of MPA arguments:

The mere possibility argument (MPA), negative version:
A can lead to *B*.
B should not be realized.
Thus, *A* should not be realized.

The mere possibility argument (MPA), positive version:
A can lead to *B*.
B should be realized.
Thus, *A* should be realized.

To exemplify the negative version, let *A* be the development of nanotechnology and *B* the emergence of new technological means for mind control. To exemplify the positive version, again let *A* be the development of nanotechnology, but let *B* be the construction of nanodevices that efficiently remove arterial plaques.

It is important to realize that argumentation based on mere possibilities need not be faulty. There are situations in which it seems reasonable to let an MPA have a decisive influence on a decision. Suppose that on a visit to an arms factory, a person takes up a just finished pistol, puts it against his head, and shows intention to pull the trigger, just for the fun of it. Then someone says: 'Do not pull the trigger. You never know, it can be loaded.' Although there is no reason at all to believe that the pistol is loaded, it would seem reasonable to heed the warning.

However, there are also many cases in which it is rational to reject a mere possibility argument or consider it overruled. Suppose, for instance, that someone wants to stop research aimed at constructing nanodevices capable of carrying drugs to their target organ and releasing them there. The argument given for stopping this research is the MPA that these devices may turn out to have severe toxic effects that will only be discovered after they have been in use for many years. This argument is much less persuasive than the argument in the previous case that the pistol might be loaded, for the simple reason that we also need to take into account the possibility that such devices can be used to cure diseases more efficiently than currently available therapies.

A major problem with MPAs is that an unlimited number of them can be created. Due to the chaotic nature of causation, mere possibility arguments can be constructed that assign extreme positive or negative consequences to almost any action that we can take. As one example of this, almost any action that we take *can* give rise to social conflicts that in the end provoke a war. However, this applies to all actions (and omissions). Therefore, in the absence of reasons to consider it more credible for some of the options we are considering than for others, this is an unspecific (or background) uncertainty that should be excluded from most decision-guiding deliberations. Generally speaking, we need to distinguish between unspecific MPAs that can mostly be disregarded and more specific MPAs that need to be considered in relation to the particular issue under discussion. This distinction can be made by considering other possible future technologies than that under discussion, and determining whether or not the MPA is equally applicable to (some of) them as to the technology for which it was proposed.

A systematic analysis of MPAs is needed in order to protect us against at least two (sometimes overlapping) fallacies. The first of these consists in acting or reasoning on the basis of the previously formulated possibilities only, *i.e.* on the MPAs that have been brought to our attention rather than on those that are specific to the situation. The second fallacy consists in making a biased selection of MPAs, so that one pays attention to those MPAs that support one's own preconceived viewpoint, but neglects those that speak against it.

In order to avoid such mistakes, and facilitate a rational use of MPAs, two tests will be introduced in the following two sections. The two tests are both based on existing patterns of argumentation, and they can be seen as systematizations of these patterns. They both aim at clarifying whether or not a proposed MPA is relevant for its intended purpose.

3. The Test of Alternative Effects

An MPA can be defeated by a counterargument showing that we have at least as strong reasons to consider the possibility of an effect that is opposite to the one originally postulated.

> *Negative MPA, defeated by alternative effect:*
> *A* can lead to *B*.
> *B* should not be realized.
> Thus, *A* should not be realized.
> However:
> *B′* is not less plausible than *B* in the case of *A*.[3]
> It is at least as urgent to realize *B′* as not to realize *B*.
> Thus, *A* should be realized.[4]

[3] This holds if, in the case of *A*, either (i) *B′* is at least as plausible as *B*, or (ii) *B′* and *B* cannot be distinguished in terms of plausibility. Therefore, this clause does not require that the MPA be reconstructed in terms of plausibility (which would, arguably, be a way to reintroduce probabilities through the backdoor). The function of this clause is instead to prevent the use of MPA level argumentation when there is contravening probabilistic or quasi-probabilistic information.

[4] Strictly speaking, if it is *equally* urgent to realize *B′* as not to realize *B*, then the argument does not suffice to conclude that *A* should be realized, only to invalidate the argu-

Positive MPA, defeated by alternative effect:
A can lead to *B*.
B should be realized.
Thus, *A* should be realized.
However:
B′ is not less plausible than *B* in the case of *A*.
It is at least as urgent not to realize *B′* as to realize *B*.
Thus, *A* should not be realized.

For a simple example, consider the argument that the development of new nanotechnology (*A*) may lead to the construction of devices that can be implanted into the human brain, and then used to control behavior (*B*). This is a negative MPA. In evaluating it, we also need to look into alternative uses of this technology, such as the implantation of devices with which disabled persons can regain motor control and sensory contact with their body.

The *test of alternative effects* consists in searching for defeating arguments of these forms. For an example, consider the argument against nanotechnology that is based on the possibility that flying robots, the size of insects, may be developed, and that these can be used for purposes of military attack (Altmann 2001). A possible counterargument can be based on an alternative effect of that technology: If flying robots can be developed, then it is equally possible that they can be used for intelligence purposes. Under the assumption that mutual access to reliable intelligence reduces the risk of war, this may contribute to the avoidance of military conflict.[5]

In this case it would be natural for the person who put forward the first MPA to modify it by pointing out that insect-sized robots could be used for attack, not only by states but also by terrorists. To this, however, it could be retorted that the employment of such robots for intelligence

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ment that *A* should not be realized. The corresponding *caveat* applies to the other defeating arguments outlined in this and the following section.

[5] This is not an uncontroversial assumption. Note however that the original MPA relies on another controversial assumption, namely that access to more efficient weapons increases either the risks or the consequences of war.

purposes could radically reduce the capabilities of terrorist organizations to hide away. It is not obvious whether or not the argument referring to military uses of flying nanorobots can ultimately be reconstructed in a form that resists the test of alternative effects. This is not the place to resolve this controversy. What is important, however, is that the application of this test will induce a careful analysis of the MPA and its presuppositions.

4. The Test of Alternative Causes

The other major way to defeat or weaken an MPA is to show that the postulated cause *A* is not decisive for the possibility that *B* will occur. As we noted above, if *B* is not a specific effect of *A*, but equally possible in the absence of *A*, then it should be excluded from consideration. Therefore, counterarguments against MPAs can be constructed along the following lines:

> *Negative MPA, defeated by alternative cause:*
> *A* can lead to *B*.
> *B* should not be realized.
> Thus, *A* should not be realized.
> However:
> *B′* is not less plausible in the case of not-*A* than *B* in the case of *A*.[6]
> It is at least as urgent to not to realize *B′* as not to realize *B*.[7]
> Thus, *A* should be realized.

> *Positive MPA, defeated by alternative cause:*
> *A* can lead to *B*.
> *B* should be realized.
> Thus, *A* should be realized.
> However:

[6] As a special case, *B′* and *B* can be identical.
[7] This line can be omitted if *B′* and *B* are identical.

> B' is not less plausible in the case of not-A than B in the case of A.
> It is at least as urgent to realize B' as to realize B.[8]
> Thus, A should not be realized.

The test of alternative causes consists in searching for defeating arguments of this type. For example, consider the argument against nanotechnology that it can give rise to a 'nano divide', *i.e.* growing inequalities between those who have and those who do not have access to nanotechnology. This argument is equally plausible for any new technology that has a potential to improve certain aspects of our lives. We already have, on the global level, large 'divides' in terms of sanitation, food technology, medical technology, ICT, *etc.* It can reasonably be argued that any new technology (including technologies that will receive more resources if we refrain from funding nanotechnology) will expectedly follow the same pattern. Therefore the 'nano divide' is a non-specific effect that does not seem to pass the test of alternative causes.

For another example, consider the statement, sometimes used as an argument in favor of nanotechnology, that it can provide us with means for cheap desalination. The problem with this argument is that we do not know what technologies (if any) can be used to achieve this aim. In particular, we do not know if nanotechnology or some other technology (such as biotechnology) will most probably provide the solution. The prospect of finding means for cheap desalination can possibly be used as an argument for furthering scientific and technological development in general. However, in the absence of a credible outline of a technological solution it cannot be used as an argument for furthering a specific technology such as nanotechnology.

5. Conclusion

The systematic application of the two tests introduced above helps us to avoid the two fallacies mentioned in Section 2. Both tests involve a search for new, analogous MPAs, thereby rectifying the fallacy of rea-

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[8] This line can be omitted if B' and B are identical.

soning only on the basis of previously formulated possibilities. Furthermore, in both cases this search focuses on finding new MPAs that constitute arguments against the given MPAs, thereby providing a remedy against the fallacy of only considering MPAs that point in one direction, namely that of one's preconceived opinions.

In combination, the two tests will eliminate many untenable MPAs. This makes it possible to focus discussions on a smaller number of such arguments that can then be subjected to a more detailed analysis.[9] The two tests should only be seen as a first beginning. In order to analyze more fully the discourse on nanotechnology (or other subjects dominated by issues of great uncertainty), an extensive study of actual argumentation is needed, as a basis for a much more comprehensive discussion of the validity of the various arguments in actual use.

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9 In Hansson 1996 some criteria are given for identifying serious cases of high-level consequence-uncertainty, including novelty, lack of spatial and temporal limitations, and interference with complex systems in balance. These criteria can also be used in the evaluation of MPAs.

CHAPTER 15

BRIDGING THE GAPS: SCIENCE FICTION IN NANOTECHNOLOGY

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This chapter argues that narrative elements from the science fiction (SF) literary genre are used in the discourse of Nanoscience and Technology (NST) to bridge the gap between what is technically possible today and its inflated promises for the future. The argument is illustrated through a detailed discussion of two NST texts. The chapter concludes by arguing that the use of SF narrative techniques poses serious problems to the development of a critical analysis of the ethical and social implications of NST.

1. Introduction

In 1997, Francis Collins, the spokesperson for the US Human Genome Project (HGP), claimed that, "the project's Ethical, Legal and Social Implications (ELSI) program [was] unique among technology programs in its mandate to consider and deal with these issues alongside the development of the technology" (cited in McCain 2003, p. 112). Recent assessments of its impact have been far from celebratory (*e.g.* Evans 2002, Huijer 2003, McCain 2003). Indeed, it is claimed that the ELSI program insulated the HGP from criticism rather than facilitating negotiations between scientists and non-scientists (Huijer 2003, p. 488).

Against this background, when Mihail Roco, a key promoter of nanoscience and technology (NST)[1] in the U.S. and director of the National Nanotechnology Initiative (NNI), claims that societal implications have been an integral component of the NNI from the start and argues that the National Science Foundation (NSF) "has made support for social, ethical and economic research studies a priority" (Roco 2003a, p. 185), it is reasonable to wonder to what extent this represents a genuine invitation to the agora[2] or a façade that merely disguises science's traditional agoraphobia. As Nik Brown has recently argued, "The 'post-normal science' thesis [...] which sees science increasingly dependent on wider political and public aspirations should, it appears, be received with caution" (Brown 2003, p. 18). However, notwithstanding these reservations, it would be wrong to dismiss the opportunities created by the current social and political exigencies requiring technoscience to explore the ethical and social implications of its activities. Even if it is just a façade, it represents a surface that at the very least can be tagged with critical graffiti.

Having said this, it would be equally problematic to think that the deliberative space in which discussions of the social and ethical implications of nanotechnology are unfolding, or will unfold, is an empty one. At the moment, this space is being structured by a form of extrapolation that draws on narrative elements from the science fiction (SF) genre. In this chapter, I argue that there are important limitations associated with

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[1] There is a simple economic logic related to my use of the acronym NST in lieu of the expression 'Nanoscience and Technology': the acronym is shorter than the phrase – both the acronym and the referent are borrowed from Wood *et al.* (2003, p. 5). In addition, there are also two theoretical points to be made. As Wood *et al.* note, the use of NST to refer to "a new branch of science" alerts us to the fact that there is a concerted effort to bring together disparate scientific practices or to locate one's existing research program under a fashionable and money worthy umbrella (*ibid.*). This should not be taken to mean, however, that there is consensus on the meaning of NST itself. As I note below in the body of the text, controversy remains. Second, by grouping science and technology together, the term problematizes traditional models of linear knowledge transfer from state supported research in fundamental science to technological applications. On the relationship between nanoscience and nanotechnology, see Wood *et al.* 2003, pp. 5-17, and Fogelberg 2003. For a broader analysis of the relationship between science and technology, see Nowotny *et al.* 2001.

[2] Nowotny *et al.* (2001, p. 183) argue that science has "moved centre-stage in what we call the *agora* – the space in which market and politics meet and mingle, where the articulation of private emotions and meanings encounter the formation of public opinion and political consensus". See also Ravetz 1999.

trying to understand the ethical and social implications of NST within this discursive space, and that an understanding of these limitations must precede or should be taken into account in a more reflexive debate on NST.

First, I consider the implications of arguing that SF is not an external but an internal aspect of NST discourse. Following this, I show that the central metaphor in NST discourse – nanotechnoscientists as master builders – provides a semantic link to SF narrative elements. This link allows NST authors to extrapolate by drawing on SF world-building techniques. I, then, provide a detailed analysis of this process by examining the key role that the SF literary device of the *novum* plays in two NST texts.[3] A number of scholars have already drawn attention to the important function that the SF literary device of the *novum* plays in NST discourse, especially Milburn (2002) and Marshall (2004) and to a lesser extent Miksanek (2001) and Landon (2004). What my discussion adds to these is a more detailed textual analysis of the functioning of the *novum* and an exploration of the implications of these discursive strategies for debates on the ethical and social implications of NST.

The first text is Drexler's *Engines of Creation*, the second an edited book on the convergence of nano, bio, information technology and cognitive science (NBIC), *Converging Technologies for Improving Human Performance*. It is edited by Mihail C. Roco and William S. Bainbridge, both active promoters of NST.[4] Although many in the NST community might argue that Drexler's vision is both dated and outside the mainstream, the editors of and contributors to the second text are very much part of the NST mainstream. In bringing these two texts together, I show

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[3] I would like to make clear that by no means does my focus on narrative features and discursive strategies, in this chapter, exhaust NST as a social, cultural, economic, and political phenomena. A more comprehensive treatment of NST, which is beyond the scope of this paper, would include dimensions such as cultural practices in the laboratory, the policing of disciplinary boundaries, funding sources, national policy cultures, *etc.*

[4] Roco is senior advisor to the NSF and chair of the Nanoscale Science, and Engineering and Technology Subcommittee (NSEC) of the National Science and Technology Committee (NSTC). He was one of the key architects of the launch and is current director of the multiagency NNI and remains a tireless promoter of NST. Bainbridge is Deputy Division Director at the Directorate for Computer and Information Science Engineering (CISE) whose program responsibilities include nanoscale science and engineering.

that there are more similarities than would be initially expected, not necessarily in terms of their substantive claims but in terms of the formal narrative structures through which their claims are engendered.[5] This is followed by a discussion of the limitations associated with the framing of ethical and social implications by current NST discourse. In the conclusion, I consider some further implications of the way NST discourse mobilizes the future.

2. Science Fiction and Nanoscience and Technology

Technoscientists in the NST field frequently draw on SF in order to construct a binary opposition that is deployed to police the boundary (Gieryn 1999) between science and non-science. A well-known instance is the debate initiated by Gary Stix (1996), a staff writer for *Scientific American*, who wrote a highly critical piece on Eric Drexler's agenda for nanotechnology.[6] Amongst other things, as Milburn notes, Stix compares "Drexler's writing to the scientific romances of Jules Verne and H.G. Wells, suggesting that 'real nanotechnology' is not to be found in these science fiction stories" (Milburn 2002, p. 265). However, as Fogelberg and Glimell argue in their analysis of the debate, one of the key issues at stake is the meaning of scientific practice (Fogelberg & Glimell 2003,

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[5] Theoretically and methodologically, my analysis is framed by a conception of scientific knowledge that locates scientific knowledge production in discursive formations that incorporate both discursive and non-discursive elements (Foucault 1992, López 2004) and that require the mobilization of a variety of social and cultural resources (Callon 1986, Gieryn 1999). In this context, discourse is not understood as the distorted, or more or less accurate, representation of reality: discourse is one of the social forces that contribute to the constitution of reality. The two texts chosen for analysis have been selected not because they constitute a sample or a representation of the entire NST field, but because they are both key attempts to mobilize a variety of social actors through their broad vision of the NST field, and they are strategically well placed to do so: the Drexler text because it inaugurated the field and the NBIC text because of its proximity to the NNI, which has been central to the development of a NST program in the US. They are, to use Callon's term, two good examples of "translations" (Callon 1986).

[6] Later, I discuss Drexler's vision of nanotechnology in some detail; for the moment, it is enough to say that he foresees the development of self-replicating molecular machines that will make possible the production of bulk material from the nano to the macro scale. This vision is held and promoted by the *Foresight Institute* (www.foresight.org) that Drexler co-founded.

pp. 10-12). Drexler's more speculative extrapolative approach, based on theoretical computational modeling, is seen to be at odds with the experimentally based work that is taken to be the hallmark of good science.[7]

My purpose in examining the relationship between SF and NST is not to explore how SF is invoked to criticize NST for its 'unscientific excesses' or to address the mediating role that SF, as an object external to science, might play between the scientific community and the public at large in popular culture.[8] Instead, I argue that narrative elements from the SF genre are not external to but contribute to the constitution of NST discourse itself. By drawing attention to the shifting and permeable border between science and SF in NST, it is not my intention to either put in question the scientific credentials of nanotechnoscientists by insinuating that they are not doing 'real science' or, more generally, to undermine the credibility of science due to its reliance on narrative techniques found in fiction. As Donna Haraway argues,

> Not only is no language, including mathematics, ever free of troping; not only is facticity always saturated by metaphoricity; but also, any sustained account of the world is dense with storytelling. 'Reality' is not compromised by the pervasiveness of narrative; one gives up nothing except the illusion of epistemological transcendence, by attending closely to stories. [Haraway 1997, p. 64]

Science is not possible despite narrative but precisely because of it. However, not all narratives are the same; they draw on different naratological devices. Discourses that extrapolate technoscientific developments into the future, through SF narrative elements, contain assumptions about, amongst other things, the nature of being, the dynamics of historical change, the aspirations of citizens, and the relationship between society, culture and technoscience. With this in mind, I will now discuss more specifically how SF narrative elements are incorporated into NST.

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[7] See Milburn 2002, for further examples of the science fiction/fact opposition.

[8] See Hamilton 2003, for an excellent discussion of these dynamics in the context of biotechnology.

Definitions of NST are highly contested (Fogelberg & Glimell 2003, pp. 5-26). This is due to its status as an 'emergent science', that is to say a science whose truth claims remain to be settled by scientific or public consensus (Hamilton 2003, p. 268).[9] What is more, given the heterogeneous and interdisciplinary nature of the NST field,[10] it is not likely that definitional closure will be achieved soon. Definitional problems also arise because NST, as we shall see below, is radically future oriented; thus, it is also defined by how its potential is refracted towards competing futures (Wood *et al.* 2003, p. 3).

However, a minimum definition would draw attention to the significance of its length scale:

> One nanometer (one billionth of a meter) is a magical point on the dimensional scale. Nanostructures are at the confluence of the smallest of human-made devices and the largest molecules of living things. Nanoscale science and engineering here refer to the fundamental understanding and resulting technological advances arising from the exploitation of new physical, chemical and biological properties of systems that are intermediate in size, between isolated atoms and molecules and bulk materials, where the transitional properties between the two limits can be controlled. [Roco cited in Ratner & Ratner 2003, p. 7]

The 'newness'[11] of the nanoscale refers to the difference between the macroscopic and nanoscopic properties of materials. To take Ratner and Ratner's (2003) example, although a metric ton, a kilogram, and gram of gold all have the same physical properties, the same is not true when one scales down to the nano length. Gold's color, melting point, and chemical properties are different at the nano length scale as a result of the nature of atomic interactions and the fact that these are not averaged out as they are in bulk material. In other words, "Nano gold doesn't act like bulk gold" (Ratner & Ratner 2003, p. 2). Thus as Roco and Bainbridge

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[9] Hamilton (2003) uses the Latourian terminology to describe biotechnology, but it is even more applicable to NST.

[10] See Wood *et al.* 2003 for a useful overview. On the challenges of interdisciplinarity in current integrative attempts in NST, see Schummer 2004.

[11] The newness must be approached with care because of the diversity of the field. As Wood *et al.* (2003, p. 10) argue with respect to material sciences, "Many advances that are being ascribed to nanotechnology could equally be regarded as an incremental development of existing technologies"; see also Atkins 2002.

argue, "The nanoscale is not just another step toward miniaturization, but a qualitatively new scale. The new behavior is dominated by quantum mechanics, material confinement in small structures, large interfaces, and other unique properties" (2001, pp. 4-5).[12]

When these unique properties are combined with the prevalent and dominant metaphor[13] that reigns in NST discourse – nanostructures as the *building blocks* of matter and the nanotechnoscientist as the *master builder* – we can begin to appreciate the radical transformative powers that NST not only denotes but also connotes.[14] For instance, the Nobel laureate for physics, Horst Stormer, suggests that when we are empowered by nanotechnology to "play with the ultimate toy box of nature – atoms and molecules [...] the possibilities to create new things appear limitless" (cited in NSTC 1999, p. 1). Indeed it is not infrequent to encounter references to NST's radical transformative powers. For instance, claims such as "By anyone's measure, nanotechnology is the next big thing. In fact, according to government R&D planners, nanotechnology is nothing short of the next Industrial Revolution" (Schultz 2000, p. 41) are rather common.

In fact, these claims are foundational for analyses of the ethical, legal, and social implications that have been initiated by the NST community itself.[15] One might even argue that the fact that the social implications have been central to the NNI represents not so much a belief in the legitimacy of submitting NST to social and ethical analysis as much as the conviction that NST is like no other technoscientific practice in its ability to impact and transform both the social and natural world. As

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[12] These new behaviors and properties are initially expected to broadly impact, amongst others, the fields of materials science, electronic and optoelectronics, and the biomedical sciences (Wood *et al.* 2003, pp. 10-16).

[13] The role of metaphors in the organization of knowledge domains has been recognised by philosophers, historians, and sociologists of science for some time. See López 2003, chap. 1, for an overview.

[14] In focusing on this metaphor, I am not arguing that it is an 'accurate' representation of the field, rather I am registering its contemporary ubiquity and prominence. It is important also to note that the metaphor not only attempts to 'represent' heuristically the work of NST but also its social function. A comparison with competing and less successful competitors would be highly instructive but cannot be undertaken within the context of this paper.

[15] See Roco & Bainbridge 2001, 2003.

Wood *et al.* argue in their review of the emerging field, "Nanotechnology is being heralded as a new technological revolution, one so profound that it will touch all aspects of human society" (2003, p. 1).

Yet, while it is certainly the case that there have been important developments that make possible the manipulation of matter with precision at the nanoscale, as commentators have also noted, NST is only here as a trace of a future yet to be produced (Fogelberg & Glimell 2003, Milburn 2002, Wood *et al.* 2003). Even NST's most energetic promoters have to admit that "nanotechnology is still in its infancy, because only rudimentary nanostructures can be created with some control" (Roco & Bainbridge 2001, p. 1). There is a rather significant gap between what can be achieved with NST today and what is imagined that will be achievable in the future; predictions of revolutionary transformations seem premature.

This gap, of course, is not specific to NST and can be found in other fields. It is typically sutured rhetorically through hype that not only mobilizes meaning but also social, political, and economic resources by promising breathtaking advances, miracle cures, and virtually unimaginable wealth.[16] However, in the case of NST the hype is different. For instance, although biotechnology hype promises wealth, global food abundance, and intimations of immortality through genetic therapy and enhancement, NST's hype promises more! By drawing on the metaphor of the nanotechnoscientist as the master builder and NST as the toolbox that makes possible the manipulation of the fundamental stuff that makes up the world, NST claims nothing less than to be able to rebuild the world. This ultimate conceit, which feeds NST's molecular speculations, is elegantly captured by the title of the U.S. National Science and Technology Council brochure on nanotechnology: 'Nanotechnology: Shaping the World Atom by Atom' (NSTC 1999).

It is instructive to compare the semantic suppleness associated with the metaphors used in the HGP with those deployed in NST. The HGP promised to produce a 'plan', 'blueprint', 'encyclopaedia', or a 'program' of life (Rothman 1998, p. 25). In all instances its vision of the future was limited by the frontier between the organic and the inorganic.

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[16] For the role of hype in the promotion of 'revolutionary' technologies see Brown 2003 and William-Jones & Corrigan 2003.

However, NST's 'shaping–the–world–one–atom–at–a–time' metaphor makes it possible to transcend this boundary: Nobel laureate and nanotechnoscientist Richard Smalley claims, "Nanotechnology is the builder's final frontier" (cited in NSTC 1999, p. 1).

Recognizing the centrality of the world-building metaphor is important because its semantic connotations also make it possible for NST discourse to draw on narrative elements from the SF literary genre that is, in part, characterized by its ability to produce radically different future or parallel worlds. This creates the discursive conditions for what, following Landon, we can call SF thinking. SF thinking

> generates the rhetoric that bridges the gap between the givens of science and the goals of the imaginary marvelous, the emphasis always on 'explaining' the marvelous with rhetoric that makes it seem plausible, or at least not yet impossible. [cited in Gerlach & Hamilton 2000, p. 465]

By incorporating SF thinking, NST discourse overcomes the gap between what is possible today and what might be possible in the future.[17] This is achieved by using extrapolative narrative techniques that are well established in the genre. In other words, or in other worlds, it is able to solve the tension inherent in claiming that we are already living in a nano-era while also recognizing that the dawning of the nano-era depends on much that has yet to happen.

3. Mainstream and Periphery in Nanoscience and Technology

Although Drexler is credited with having coined the term 'nanotechnology', it is undeniable that his status in the field is problematic. As noted above, he is one of the targets of the science fiction/fact opposition deployed to locate certain NST activities outside the boundary of real science. It is frequently argued that his vision of nanotechnology remains peripheral and outside the mainstream. As evidence for this, one might point to the fact that his agenda has certainly not been explicitly endorsed

[17] On SF thinking, see Csicsery-Ronay 1991 and Gerlach & Hamilton 2000.

by the NNI.[18] Still, even though his book, *Engines of Creation*, may be frequently criticized, it has also introduced a generation of scientists and engineers to a nanotech 'futurescape'. Thus even a staunch critic such as Smalley,[19] who believes that there are insurmountable objections to Drexler's proposed molecular assemblers, has conceded that Drexler "has had tremendous effect on the field through his books" (cited in Milburn 2002, p. 280). Moreover, the disagreement between Smalley and Drexler is not about the revolutionary or social transformative impact of NST (*i.e.* its capacity to rebuild the world):

> Smalley acknowledges that nanotechnology, even in the more modest form of his own nanotubes of carbon, eventually 'may change the future of humankind' and that nanotechnology from chemistry on a nanometer-scale 'may make even Drexler blush'. [Fogelberg & Glimell 2003, p. 19]

In making these points, it is not my intention to shore up Drexler's scientific credibility or to undermine those of his opponents. Rather, it is to note that we should not allow the controversies over the viability, or not, of molecular assemblers to obscure the similarities that exist in terms of how SF narrative elements are used to negotiate the gap between current technoscientific capabilities and their future development.[20]

In *Engines of Creation*, Drexler introduces us to a future where molecular manufacturing will be capable of making

> virtually anything from common materials without labor, replacing smoking factories with systems as clean as forests. They will transform technology and the economy at their roots [...] They will indeed be engines of abundance. [Drexler 1990, p. 63]

Engines of health, or cell repair machines, will cure disease and prolong life; other engines will contribute to the launching of a new space program. All of this, and more, will be possible on the journey towards a

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[18] Ralph Merkle, closely associated with the *Foresight Institute*, however, did testify in the congressional hearings that lead to the launch of the NNI in 2001 (Milburn 2002, p. 277).

[19] See Smalley 2001 for his initial critique. For recent exchanges between the two, see Drexler & Smalley 2003.

[20] In a different context, Milburn 2002 very skillfully demonstrates that the boundary between mainstream and periphery in NST discourse is more porous than is often supposed.

positive-sum society that will culminate in an "open future of wealth, room and diversity, [where] groups will be free to form almost any sort of society they wish, free to fail or set a shinning example for the world" (Drexler 1990, p. 237). The only problem is that these "engines of creation" or molecular assemblers have yet to be produced. Still, Drexler's writing narrates their coming as unavoidable.

The arrival of assemblers is to follow a path already initiated by current bio and molecular technology. Protein machines will combine the cutting and pasting abilities of enzymes with the programmability of ribosomes to produce new nanoscale non-protein materials that will in turn be used to create second-generation nanomachines or *universal assemblers*. When these assemblers are combined with the astronomical computing power of nanocomputers, the knowledge of molecular and atomic architecture collated by nano-reverse-engineering-machines or *disassemblers*, and the ability to self-replicate in order to achieve economies of nanoscale, the nano-era will finally be upon us (Drexler 1990, pp. 3-20).[21]

If we leave aside the technical argument regarding the viability of molecular assemblers, there are a number of narrative devices that make nanomachines both credible and inevitable in Drexler's text. Following SF convention, his text constructs a "sublime chronotope" in which the action unfolds (*i.e.* the romance of how molecular assemblers will rebuild the world). SF critic Istvan Csicsery-Ronay, Jr. defines the sublime chronotope as a "literary 'space-time' where fictional things work according to their own particular laws of time and space. SF works generally depict one or more special chronotopes that are wonderfully strange and ultimately vast and powerful" (Csicsery-Ronay 1996, p. 386).[22] In Drexler's text, the chronotope has two dimensions: synchronic (*i.e.* at one point in time) and diachronic (*i.e.* across time or historical). Synchronically, Drexler's nano-chronotope invites us to see a world that has been thoroughly overhauled and reconstituted through the tropes of the atomic, the molecular, and the machinic. Diachronically, he narrates an

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[21] Recently, Drexler has denied the need for self-replication (Phoenix & Drexler 2004).

[22] Csicsery-Ronay points to related concepts in SF author and critic Samuel R. Delany's account of "paraspaces" (1995, p. 168) and literary critic Brian McHale's "narrative zones" (1987, p. 5).

'engine' of historical change that links the past with a de-familiarized present. This present promises the future, as the acorn promises the oak.[23]

In synchronic mode, the chronotope is woven through the narration of a space that is both familiar and alien. It is our world but its landscapes, scale, structures, rules, and action are all atomic. If Marx claimed that "Value [...] does not have its description branded on its forehead; it rather transforms every product of labor into a social hieroglyphic" (cited in Graham 2002, p. 236), Drexler might argue that value is inscribed as an atomic hieroglyphic. Indeed, he begins his book by claiming that "throughout history, variations in the arrangement of atoms have distinguished the cheap from the cherished, the diseased from the healthy" (Drexler 1990, p. 3), and he goes on to write, "Our ability to arrange atoms lies at the foundation of technology. We have come far in our atom arranging, from chipping flint for arrowheads to machining aluminum for spaceships" (*ibid.*).

Framed by Drexler's nano-chronotope, human interaction with nature and the development of technology is nothing more than the attempt to manipulate atoms, initially clumsily but increasingly with more precision (*i.e.* bulk versus molecular technology). The chronotope that stages the plot in *Engines of Creation* not only invites us to reconsider our relationship vis-à-vis nature, it also demands that we develop a molecular conception of our bodily selves: "The ill, the old and the injured all suffer from misarranged patterns of atoms, whether misarranged by invading viruses, passing time or swerving cars. Devices able to rearrange atoms will be able to set them right" (*ibid.*, p. 99).

The figure of 'the machine' is the second key discursive element in the chronotope. Drexler argues that there is no more incontrovertible evidence of the viability of nanomachines or molecular assemblers than the existence of protein machines or ribosomes that assemble proteins in our cells (*ibid.*, p. 6). Thus, "molecular machines in the cell demonstrate that molecular machines work" (*ibid.*). A little later in the text, he first

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[23] This of course corresponds to the SF narrative device of the future history which provides a 'logical' historical explanation for the movement from the author's real time to the future (Csicsery-Ronay 1996, p. 386); see also James 1996, pp. 54-94.

redefines life as a "special structure" which is governed by the "machinery of life" (*ibid.*, p. 17) and adds, "The history of life is the history of an arms race based on molecular machinery" (*ibid.*, p. 26).

By combining a world where reality is reduced to myriads of atomic configurations and the bonds that hold or fail to bind them together, where technology is crude or precise atomic manipulation, health a harmonious atomic arrangement and disease an atomic cacophony, with vital molecular machinery as the basis of life, Drexler's text re-ontologizes the world. In doing so, he creates a sublime chronotope that provides an ideal habitat for his nanomachines because they straddle the two significant dimensions of this new domain, *i.e.* the atomic and the *machinic.* Grab your atomic force microscopes. We have entered the age of assembler and the book of the world is written in the language of atomic bonds.

4. The Breakthrough as the *Novum*

The synchronic dimension of the chronotope is traversed by a diachronic or historical vector. It narrates how we have arrived at the stage where the assembler revolution is already contained in our present, making it inevitable. Drexler claims that it is possible to isolate the principles of change whose explanatory domain span "molecules, cells, beasts, minds, and machines [and] should endure even in an age of biotechnology, nanomachines and artificial minds" (*ibid.*, p. 21). After identifying molecular replicators – *i.e.* RNA, viral genes, human genes, *etc.* – as the chronotope's principal historical actors (*ibid.*, p. 25), he argues that through the evolutionary mechanisms of mutation and selection there is a continuity between *The Rise of the Replicators* (RNA molecules) and the rise of all other things that populate the earth:

> Mutation and selection of genes has, through long ages, filled the world with grass and trees, with insects, fish and people. More recently other things have appeared and multiplied – tools, houses, aircraft, and computers. And like the lifeless RNA molecules, this hardware has evolved. [*Ibid.*, p. 30]

He further embeds the production of 'hardware' within evolutionary semantics by arguing that the principles of engineering can be understood in terms of mutation and selection: "In engineering, enlightened trial and error, not the planning of flawless intellects, has brought most advances" (*ibid.*, p. 31).

If synchronically we have seen how the atomic and machinic nano-chronotope provides an ideal space for molecular assemblers, diachronically the chronotope locates the engineer as the hero whose practice embodies the principles of change that govern the nano-chronotope. Moreover, by inserting the engineer in the context of evolutionary trans-historical forces, the molecular-assembler revolution becomes unstoppable. Thus, it is not surprising that he concludes his book by interrogating the present with questions that originate in the future:

> If we succeed (and if you survive) then you may be honored with endless questions from pesky great-grandchildren: 'What was it like when you were a kid, back before the Breakthrough?' and 'What was it like growing old?' and 'What did you think when you heard the Breakthrough was coming?' and 'What did you do then?' By your answers you will tell once more the tale of how the future was won. [*Ibid.*, p. 239]

This is not only a call for 'nano-engineers of the world to unite' and take their place in a world historical event that has already been determined, it also provides the key to the functioning of the chronotope.

What Drexler's text achieves, unwittingly or not, is a narrative that re-ontologizes the past, present, and future. This is achieved by rebuilding the world synchronically and diachronically around the *Breakthrough*, the arrival of the molecular assembler. The narrative process whereby a single element is used as the axis around which a future alternative world is generated is a key discursive element of SF. Though there is much debate of the status of SF as a genre, there is some consensus on the centrality of the device of the *novum*:

> A *novum* is a deliberately introduced change made to the world as experienced by author and reader, but a change based on scientific or other logic; it is such a significant part of the SF that the *novum* frequently determines the subsequent narrative. [James 1994, p. 108, italics added]

The novum is a variation of the "What if…" question that is used as a world-building device by extrapolating the potential ramifications of the interruption to reality contained in the question (*e.g.* time travel, artificial intelligence, a parallel universe, molecular assembly). The assembled world derives its coherence not from the logic or validity of the *novum* itself but from the way all its dimensions have been processed by the machinery of the *novum*. This is precisely the discursive scaffolding that underpins Drexler's sublime chronotope and in turn provides the stage that projects nanotechnology into the future, or retracts the future into the present. In other words, this is how Drexler bridges the gap between what is possible now and what he envisions will be possible in the future. Without this SF discursive device, Drexler's vision of nanotechnology could not be assembled.

5. NBIC Convergence

Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science is a published report that derives from a 2001 workshop sponsored by the NSF and the Department of Commerce (DOC). Since then a number of NBIC meetings have taken place. The report is of interest for a variety of reasons. First, it is the most recent and sustained effort to construct a broad vision of NST by making NBIC central to the achievement of a variety of technoscientific, social, economic, and political goals. Moreover, given the scope and transdisciplinary nature of the NNI, and the variety of agencies that it mobilized, a broad integrative vision is likely to remain a crucial element in future national NST initiatives.[24] Second, the editors and contributors are drawn from NST's mainstream. For Mihail Roco, a key figure in the NNI, NBIC represents a continuation of the work already begun.[25] Finally, both editors have consistently championed 'analyses of ethical and social implications'; consequently, it provides an ideal site to read the framing of these questions within NST discourse.

[24] It could indeed be argued that NST, properly speaking, does not exist outside of this type of national initiative.
[25] See for instance Roco 2004.

NBIC supporters argue that the impetus for convergence is driven by "the integration and synergy of the four technologies (nano-bio-info-cogno) [that] originate from the nanoscale, where the building blocks of matter are established" (Roco & Bainbridge 2003, p. vii). The integration between bio and nano is possible because the unity of matter at the nanoscale means that the structure of both organic and inorganic materials is determined by the same fundamental principles. Consequently, it becomes possible for technology to "harness natural processes to engineer new materials, biological products, and machines from the nanoscale up to the scale of meters" (*ibid.*, p. 2). The integration and synergies between info nano and bio are diverse. On the one hand, the enhancement of computing power (*i.e.* speed and memory) is expected to derive from new nano-engineered materials as well as from novel architectures in the form of quantum and biological (DNA based) computing (Theis 2001; Ratner & Ratner 2003, pp. 130-39; Wood *et al.* 2003, pp. 19-24). On the other hand, developments in NST and biotechnology themselves depend on computer based modeling and visualization made possible by the digitalization of molecular processes (Johnson 2003, Thacker 2004, Roco 2003b).

The integration of the cognitive science component is tied to the development of the "Human Cognome Project" whose goal would be to map "the structure and function of the mind" (Bainbridge 2003, p. 97). It is argued that cognitive science would be able to explain "the mind and human behavior" by understanding their "physico-chemical- biological processes at the nanoscale" (Roco 2003c, p. 301). This would be made possible by the convergence of bio, computer, and nanotechnology (Roco & Bainbridge 2003, p. 12). In turn, the ability to enhance cognition and communication, as a result of the accrued knowledge, would make new scientific and technological discoveries possible. Ultimately, the multiple synergistic pathways in NBIC herald a new renaissance

> based on a comprehensive understanding of the structure and behavior of matter from the nanoscale up to the most complex systems yet discovered, the human brain. Unification of science based on unity in nature and its holistic investigation will lead to technological convergence and a more efficient social structure for reaching human goals. [*Ibid.*, p. 1]

It is interesting to note that amongst the goals reported in the volume are items that would not be out of place even in Eric Drexler's nano-chronotope. If Drexler entices us with visions of abundance, a contributor to the NBIC volume defines poverty as a technological challenge and predicts that intelligent machines will "eradicate poverty and usher in a golden age for all humankind" (Albus 2003, p. 293). Indeed, such will be the magnitude of the wealth produced that "new economic theories based on abundance may emerge to replace current theories based on scarcity" (*ibid.*, p. 292).

Engines of Creation, as noted above, presents the possibility of harnessing the design principles and mechanisms of biological molecular machines to create nanomachines capable of producing inorganic materials. In similar fashion, Roco and Bainbridge report that "fundamental knowledge about molecular-level processes essential to the growth and metabolism of living cells may be applied, through analogy, to development of new organic materials" (Roco & Bainbridge 2003, p. 11). If the previous two scenarios are conceivable in a Drexlerian world, the next one, brain-to-brain communication, is nudging towards SF, even by Drexler's standards (Drexler 1990, p. 234). The NBIC program foresees the development of *The Communicator*, a device that will

> enhance individual attributes and remove barriers to group communication such as [...] user's physical disabilities, language differences, geographic distance and disparity in the knowledge possessed by group members [...] Improving group interactions via brain-to-brain and brain-machine-brain interfaces will also be explored. [Albus *et al.* 2003, p. 276]

For Roco and Bainbridge, brain-to-brain communication provides a stepping stone towards a networked society capable of sustaining "a global intelligence" (Roco & Bainbridge 2003, p. 22) where "humanity would become like a single distributed and interconnected 'brain' based on new core pathways of society" (*ibid.*, p. 6). There are more examples that could be cited, but the point is not to isolate individual objects or scenarios that appear to be plucked out of SF novels, but to understand how NST discourse can circulate such inflated future currency as current technoscientific tender.

Not unlike Drexler's book, the NBIC text embeds its promissory notes in a sublime chronotope that re-ontologizes the world both synchronically and diachronically. In synchronic mode, the NBIC-chronotope is constituted as a continuous and unified space-time, which stretches from the nanoscale to the scale of meters and beyond (*ibid.*, p. 2). The coherence of this space is underwritten by the unity of matter at the nanoscale and is thus regulated by a hierarchy of causality that operates from the bottom up (*ibid.*). The fundamental properties of matter are determined by its constituent molecular dynamics. Phenomena such as memory, emotion, and thought are to be explained by reference to a hierarchy that privileges the nanoscale organization of atoms and constructs a causal explanatory pathway that links nanostructures to the structure of DNA that in turn extends the link to the interaction of neurons in the brain (*ibid.*, p. 13). The great chain of being begins at the bottom but does not end with the body or the brain.

In the NBIC-chronotope, the conceptualization of the brain serves to fuse what would seem to be different phenomenological domains (*i.e.* the material and the social-cultural), allowing NBIC to expand its ontological prospecting claims. The brain is operationalized as a communicative and information processing system; social interaction and group behavior are defined by the same operators. This opens the way to re-ontologizing the brain's neural network as the cognitive 'nanostructure' of social life through which the bottom-up causal hierarchy can be replicated in the social and cultural domains. Thus, the ability to enhance these functions (*i.e.* information processing and communication) by drawing on a cognitive science leveraged by bio, nano, and information technology makes it possible to conceive of the "improvement of collective behavior and productivity" (Roco 2003b, p. 82). It is in this sense that convergence would lead to devices like the *Communicator* that would provide the basis for a "more efficient social structure for reaching human goals" (Roco & Bainbridge 2003, p. 1) and even for envisioning the "bond of humanity driven by an interconnected virtual brain of the Earth's communities searching for intellectual comprehension and conquest of nature" (Roco 2003b, p. 93).

Fuelling this vision of the ability to manage everything from the nanoscale to the interactions of humanity as a whole is an explicit and profound reductionism that arises from the conviction that "all disciplines share a common ability to work at the molecular and nano length scales using information technology and biology concepts" (Roco 2003b, p. 93). As a result, "partisans" who argue for the "independence of biology, psychology, and the social sciences [...] against 'reductionism', asserting that their fields had discovered autonomous truths that should not be reduced" are utterly self-defeating (Roco & Bainbridge 2003, p. 13).[26] Underpinning this reductionism is an ontology in which distinct phenomenological domains lack domain-specific principles of organization, thus "a networked society of billions of human beings" is to the human being what "a human being is to a single nerve cell" (*ibid.*, p. 22). Consequently, a "collective social system may be compared to a larger form of a biological organism" (*ibid.*).

The unification of the natural and social sciences would make possible the development of an explanatory regime capable of encompassing "collective behavior in physics, chemistry, biology, engineering, astronomy, and society" (Roco 2003b, p. 84). Indeed, in a chronotope where every internal ontological border is disassembled to its constituent molecular configurations, it becomes possible to conceive of a "predictive science of society and to apply corrective actions based on the convergence ideas of NBIC", and to re-ontologize culture as the product of the brain's physiology thus leading to the dual evolution of human culture and physiology (Roco & Bainbridge 2003, p. 22).

Underpinning the NBIC-chronotope are two distinct but interlinked tropes: 'communication' and 'unity'. That the ontologization of DNA as an informational code and the conceptualization of the genome as a biological computer (Thacker 2004, p. 40) makes it possible to think of molecular intervention in terms of reprogramming, is already well established.[27] By asserting the unity of matter at the nanoscale and erasing the distinction between the organic and inorganic, NST is able to extend the informational paradigm to all matter:

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[26] In a logic which can only be understood as oxymoronic, elsewhere Roco argues that reductionism characterizes those disciplines that refuse the holistic reductionism of NBIC (Roco 2003b, p. 93). See Csicsery-Ronay 1996, for the role of the oxymoron in SF.

[27] See Kay 2000 and Thacker 2004, for accounts of the development of DNA as an informational entity.

> Programmable matter is a technical approach to the physical world in which the distinction between information and materiality is effaced. For nanotech, the entire apparatus of nanomachines [...] is itself built out of the same molecular and atomic elements that compose the physical world. Nanotech's ultimate engineering fantasy – that of the nanocomputer or a computer hardware apparatus that is assembled from atoms – is a direct example of its will to materialize information. [Thacker 2004, p. 138]

NBIC incorporates society and culture into this informational logic by conceptualizing the brain itself as the programmable matter that underpins social behavior and interaction. Thus there is no longer an outside of the NBIC chronotope. The corollary to this unified world is the existence of a common molecular syntax: once deciphered, it will make just about anything possible. It is this universal machine language of matter that allows the conversion between bits, atoms, neurons, and genes and the seamless integration of people, technologies, societies, and humanity.

If synchronically it is the ontological unity of the social and natural world arising from a common molecular grammar that makes NBIC convergence inevitable, diachronically it is the ontologization of the history of humanity as a transhistorical quest for improvements in human performance. This is presented diagrammatically with a table which begins with the development of the cell, body, brain, *etc.* includes universities, printing, the industrial revolution, *etc.* and inexorably moves to NBIC in order to predict "societal and business reorganization" and even "evolution transcending human cell, body and brain" (Roco & Bainbridge 2003, p. 23). This historical trajectory opens up the space for a new type of historical actor, a new renaissance man or woman, the scientist engineer, capable of mastering the unified language of the world, in others words capable of punctuating the current equilibrium by completing a process that has already begun: NBIC convergence.

The sense of inevitability, however, is the product of how the gap between the present and future has been overcome. Like Drexler's text, the NBIC text draws on the narrative device of the *novum* (*i.e.* NBIC convergence) that constructs a discursively coherent world that stretches from the past to the future. However, the price of coherence is that everything must be traced back to the interruption that the *novum* introduces.

Thus, all of history converges towards the *novum* that in turn gives birth to the future. In the narrative developed in the NBIC text, every dimension of the world, both diachronic and synchronic, has been processed through the NBIC filter and colored by the trope of convergence and unity. Thus, the principles governing the structure of organic and inorganic matter converge, the technologies of different disciplines converge, the natural sciences converge, the natural and social sciences converge, individuals and technology converge, individuals converge into networks, societies converge, and humanity finally becomes unified. Environmental degradation, poverty, disease, cultural misunderstanding, war, *etc.* can all be solved through NBIC convergence. The NBIC world is akin to a hall of mirrors with NBIC convergence at the center: though stretched, contorted, and deformed, every reflection refers back to the principle of NBIC. It is precisely this that makes the extrapolated future credible.

6. SF in NST: Bridging too many Gaps

The reasons why the device of the *novum* fails to generate a propitious context for the consideration of the ethical and social implications of NST are the very same reasons that explain its success and centrality as a narrative device in the literary genre of SF. In the later, its function is the construction of a coherent and plausible world that is separated from our own world in time and/or space. This is achieved by making the *novum* the crucible on which all aspects of the extrapolated world are forged. It functions through a viral logic by replicating itself in all the principal phenomenological domains of the chronotope. The price of plausibility and coherence is unidimensionality – *i.e.* organizing the structure of the world around one principle.[28] This constructed world in turn provides the ontological stage in which the characters are embedded and the plot unfolds. However, when this same narrative technique is used in NST discourse to extrapolate from current technoscientific abilities to the future, a number of problematic effects are produced.

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[28] The unidimensionality refers to the principles of construction of the chronotope but not SF literature itself.

First, SF literature typically incorporates a historical account, or future history, that explains how the fictional world has come about. It normally contains the period before, during, and after the *novum*. If the narrated world is to be credible, the relationship between the three periods must be one of inevitability. This sense of historical necessity is also reproduced, as I have shown above, when the *novum* structures NST discourse. Thus, as a result of how their respective *nova* have generated the diachronic and synchronic dimensions of their sublime chronotopes, Drexler's and Roco and Bainbridge's accounts create a sense of inevitability. However, if the inevitability of these processes are accepted, then there is logically and discursively a rather limited role for ethical reflection or analysis of social implications.

Second, to the extent that the *novum* used to extrapolate a future world is a technoscientific innovation, as is the case in NST discourse, then the extrapolation will take on a technological determinist logic. Technological determinism explains social, cultural, political, and economic change in terms of technoscientific development. However, this logic is a poor operationalization of the dynamics between technoscience and society. The framing of technoscience as the explanatory cause of social phenomena fails to register the complex processes that embed technoscientific practice in specific social, cultural, political, and economic relations. Indeed, as the body of scholarship developing around the social studies of science reveals, technoscience is a social achievement dependent on, for instance, economic rationalities, contests for legitimacy and authority, micro-interactions in the laboratory, social organization, and the development of social networks (Gieryn 1999, Latour & Woolgar 1986). Thus, technoscientific practice relies on the simultaneous production and/or mobilization of social, economic, political, and cultural conditions through which it is invested with legitimacy and effectivity (Latour 1986, Turnbull 2000). The specific ways in which these social processes are negotiated will open up certain developmental pathways while closing off others. It is for this reason that Latour claims that technologies "far from primarily fulfilling a purpose […] start by exploring heterogeneous universes that nothing, up to that point, could have foreseen and behind which trail new functions" (Latour 2002, p. 250). The extrapolative structure of the *novum* erases the contingencies inherent in technoscientific development by projecting it along a linear developmental path that will most certainly be frustrated. As Brown (2003, p. 4) argues, "In the short term we tend to completely overestimate the practical capabilities of technologies. In the longer-term we tend to get it wrong altogether, with technologies occasionally taking us completely by surprise". This becomes particularly problematic when these developmental paths are invested, as they are within a technological determinist logic made possible by the *novum*, with the ability to resolve all manner of social, cultural, and political problems. Potential non-technological solutions become marginalized and are not pursued.

However, the most fundamental shortcoming of deploying the *novum* as a device for framing discussions on the ethical and social implications of NST is that the *novum* bridges far too many gaps![29] It not only bridges the technical gap, but also the social and ethical gaps by generating a (fictional) future social world which contains beneficent social implications with only minor ethical complications. As we saw above, the technologies extrapolated from molecular assemblers and NBIC convergence promise a future of prosperity, peace, and physical well-being. Framed in this way, not to promote these technologies and their alleged beneficent social impacts becomes politically negligent if not utterly unethical. However, this momentum towards action obscures the fact that the credibility of the beneficent social implications and the lack of serious ethical conundrums are secured by the narrative structure of the *novum*, not through a critical analysis of social outcomes or serious ethical or normative discussion.

Moreover, the *novum* also assigns the social sciences and humanities the function of analyzing and contributing to the management of the social processes necessary to arrive at the proposed future. In this way, they are divested of their potential critical role. For instance, social scientists are asked to analyze public opinion with a view to overcoming public resistance through the effective communication of nano-benefits and promises: *i.e.* by including the public in the political economy of desire and hope generated by the *novum*.[30] They are also asked to aid nano-

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[29] Mnyusiwalla *et al.* (2003) draw attention to the gap between NST and ethics.
[30] See Bainbridge 2002 and Thompson 2001.

development by analyzing the mechanisms and procedures which will streamline processes of nano-innovation.[31] In all these contexts, social scientists and humanities scholars are not invited to test the assumptions that underpin the social future generated by the *novum*. Thus, it becomes difficult to envision how a truly critical space is to develop.

Moreover, the totalizing utopian vision produced by the *novum* invites similarly generated counter-visions. The latter deploy the structure of the *novum* much as do the former; they differ only in the malevolent logic with which the narrative is invested.[32] Consequently, it is extremely likely that the production of dystopian NST futures may arise not so much from technophobia, fear-mongering, or inadequate knowledge but from the difficulty of criticizing the seemingly impenetrable utopian futures projected through the *novum*. In this context, the most effective critical maneuver is to insert a dystopian virus into a pro-NST program and use its *novum* to assemble a dystopian future.

An understanding of this phenomenon is particularly important because it is the dystopian *novum* that has drawn the attention of popular culture and has, as argued by Marshall (2004), contributed as much to the development of NST as has its utopian counterpart. However, for many of the reasons listed above, in the context of the utopian *novum*, the dystopian register fails as a constructive critique of the social and ethical consequences at stake in NST.[33]

7. Conclusion

In this chapter, I have argued that the relation between SF narrative elements and NST is not external but internal. This is due to NST's radical future orientation, which opens up a gap between what is technoscientifically possible today and its inflated promises for the future. I have argued that this gap is bridged by linking the dominant metaphor in NST discourse – the nanotechnoscientist as the *master builder* – to SF narra-

[31] See Carroll 2001 and Crow & Sarewitz 2001.

[32] See for instance Joy 2000 and Drexler's own account of Grey Goo (Drexler 1990, pp. 171-190).

[33] I am grateful to one referee who drew these very important points to my attention.

tive techniques used to build future or parallel worlds. I have examined these techniques in detail in two NST texts: Drexler's *Engines of Creation* and Roco and Bainbridge's text on NBIC convergence. I have tried to show how narrative techniques are used in order to extrapolate credible and plausible futures through a synchronic and diachronic re-ontologization of the world.

I have not been concerned with exploring whether this type of narrative process is incompatible with scientific practice. I have, however, identified a number of obstacles that it poses for a critical discussion of ethical and social implications. First, both the sense of inevitability and technological determinism, associated with the *novum,* tend to erode the necessity of analyses of ethical and social implications. Second, I have drawn attention to the fact that the *novum* does more than merely bridge the technical gap; it also bridges the ethical gap by narrating a desirable fictional social world organized around the extrapolated technology. This contains the moral imperative to realize the extrapolated society while simultaneously cloaking the extent to which the plausibility of the extrapolated society is a function of the narrative device of the *novum.* In this context, the role for the humanities and the social sciences is to facilitate the development of the technology rather than to critically engage with it. Finally, I have suggested that the radical immunity to critique that is constructed through the *novum* creates an ideal medium for dystopian counter visions that in turn display many of the same shortcomings in their apocalyptic rendering of NST. I would argue that an understanding of these discursive tendencies must be borne in mind in the attempt to open up a space for a more open and critical analysis of the ethical and social implications of NST.

However, in highlighting how SF narrative elements in NST discourse fail to facilitate effective critical engagement, I am not arguing that SF as a literary genre is not a suitable vehicle for critical reflection on technoscientific developments.[34] It is necessary to be clear about the fact that the existence of SF narrative elements in NST discourse does

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[34] For accounts of the critical potential associated with SF, see Csicsery-Ronay 1991, Delany 1984, Elkins 1979, Gerlach & Hamilton 2000, Jameson 1982, Milburn 2002, Thacker 2000, and Suvin 1979.

not make the latter a work of literary SF. What is more, SF as a literary genre is, in fact, better at opening up a space for critical reflection than is the NST discourse described and analyzed in this chapter. In other words, ironically literary SF succeeds where NST discourse fails. This is because, as SF writer and critic Samuel R. Delaney argues, "Science fiction is not about the future; it uses the future as a narrative convention to present significant distortions of the present" (1984, p. 47). Similarly, Frederick Jameson (1982) argues that these distortions serve to defamiliarize the present and open up the exploration of alternative social, cultural, and political arrangements. The plausibility of the extrapolated 'future' in SF need only be sufficient to stage the exploration of scientific, political, social, and cultural questions in dramatic form. As a result, SF is

> less concerned with the 'objective' factors that give rise to a specific future, less concerned with forecasting or describing possible future societies, than [...] with presenting a specific future and discovering what it means to act in specific ways in terms of the belief that those ways of acting are necessary for accepting, rejecting or doubting the principles upon which a particular future social order rests. [Elkins 1979, p. 24]

Thus, the 'future' in SF is only a dramatic device for exploring the present. In contrast, NST discourse confuses the effect of the 'future' produced by the *novum* and its related narrative strategies for the future itself. It confuses the suspended disbelief that is evoked by a world organized around a single principle as a vehicle for a dramatic enactment with foresight. Whereas in SF the extrapolated future is a stepping-stone for critical reflection, in NST discourse the extrapolated future is the endpoint of the reflection.

Given the range of techniques, tools, instruments, machines, algorithms, materials, hardware, processes, projects, disciplines, actors, economic interests, and governance agendas that are included under the rubric of NST, it is unlikely that the fields of NST will all develop in unison. More likely than not they will produce varied ethical, legal, and social implications that will have to be monitored and analyzed as they unfold in different social, cultural, political, and economic contexts. An ethical lag is only a problem if we lack the social and political institutions to restrain technoscience when we deem it necessary. A necessary corrective to the unrealistic task of trying to understand the ethical and social implications of NST as if they were one process is to ask ourselves: Does it make sense to group all our macro-technologies in the same way? Moreover, if it is true that the extrapolated future made possible by SF narrative speaks more to the present than the future, we might ask ourselves what are the ethical and social implications of an organization of technoscientific activity that needs to claim such clairvoyance and promise so much to merely function?

Acknowledgments

I am grateful to the two anonymous referees for their lucid and extremely helpful comments. I would like to thank Telsing Andrews who tirelessly read and commented on a number of incarnations of this chapter as well Peter Yeadon for his helpful comments and Bryn Williams-Jones who read and commented on an earlier version. This paper was first delivered at the 2004 Canadian Sociological and Anthropological Association session titled, 'On the Social and Ethical Impacts of Nanotechnology', in Winnipeg. I want to thank the other two participants in the session, Chris MacDonald and Crystal Wallin, as well as the members of the audience. However, I would especially like to thank Michael Mehta for organizing the session, acting as a discussant and for the supportive environment he created.

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CHAPTER 16

BEYOND TRUTH: PLEASURE OF NANOFUTURES

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The topic of science and the public has enjoyed increasing attention of late. Most of the literature has concerned itself with consensus emerging from a negotiation between experts and non-experts or with the nature of expertise. I argue for a shift of emphasis from truth to funding, and that pleasure and the feeling of exhilaration is a crucial aspect of science and the public. To this purpose I analyze the publications of a group of researchers working on nanotechnology.

1. Introduction

Ever since Ludwik Fleck's analysis of the role of popularization in the genesis of scientific facts, scholars have sought to explain the relation between science and the public in terms of truth, or the negotiation of truth (*e.g.* Shapin & Schaffer 1985, Latour 1987, Collins & Pinch 1998, Shapin 1994). However, prompted by changes in the funding structures for science, researchers have themselves been turning away from a concern with truth, as in a scientific theory that matches the deep structure of the material world, and towards a concern with research relevant to a market. Along with this turn, the role of scientific discourse in the public sphere has changed. This chapter probes pleasure as an appropriate conceptual term in addition to truth.

We should not be surprised by changes in the public sphere; Jürgen Habermas has shown it to have changed for centuries (Habermas 1989). I will discuss the changes taking place in the last few decades only.

Habermas thinks in terms of human beings with differing standpoints who reach some level of consensus in the public sphere by actually communicating content to each other. The public sphere is a kind of forum where consensus is somehow reached with the use of reason. Pleasure is a decidedly non-rationalist aspect of the public sphere.

The linear model that has held sway for a long time after World War II is perhaps the most simplistic of all. According to this model, truth is created in the sphere of pure science and passed on to applied science and technology. Ludwik Fleck (1979) provided the first critique of this scheme involving a notion of feedback. Fleck used the terminology of the exoteric and the esoteric sphere, where the exoteric sphere is more public understanding of science than engineering – the point being that the esoteric sphere is not isolated. Fleck concerned himself only with this one boundary: between the inner sanctum of science and the outer lay world. However, Fleck was ignored until the 1970s when the linear model came under scrutiny. In Shapin's discussion of the public sphere, it was just this boundary of the expert and the layperson that was at issue (Shapin 1990). Since then Shinn and Whitley (1985) have denoted a more complex flow of information between various groups with various degrees of expertise that Bucchi (1998) has visualized (Figure 1). The funnel shape denotes theories and results being strengthened as they move towards the 'popular stage' – in Richard Whitley's terms:

> The more removed the context of research is from the context of reception in terms of language, intellectual prestige and skill levels, the easier it is for scientists to present their work as certain, decontextualised from the conditions of its production, and authoritative. [Bucchi 1998, p. 12]

The intraspecialistic stage refers to specialist journals, such as *Physical Review*. The interspecialistic stage refers to journals intended for scientists from all disciplines, such *Nature* or *Science*. Textbooks constitute the pedagogical stage, and the popular stage might be thought of as TV programs, for example on the Discovery channel. Bucchi's main focus is on cases such as cold fusion, in which two researchers at the University of Utah held a press conference to announce their discovery, thus bypassing the intermediary stages (and thus also peer review) altogether. His focus is visualized with the bypassing large arrow.

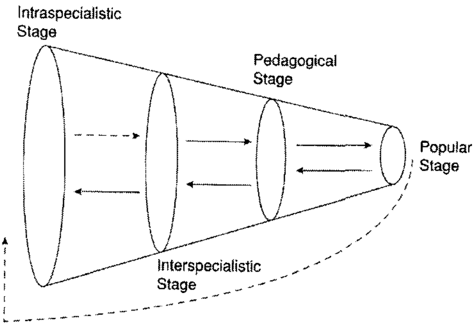

Figure 1. Bucchi's visualization of the public sphere.

Facts, truths, or knowledge is produced and passed around in this realm. It is clearly not just a one-way street going from the expert to the layperson. There is another large body of work that analyzes the way in which the expert's trustworthiness and credibility is built up, focusing on such issues as objectivity and authority. This was a major point of Shapin and Schaffer's *Leviathan* and it was taken up, for example, by Ted Porter's configuration of quantitative analysis as a technology of trust – a means of fortifying claims fending off charges of subjectivity or vested interest (Porter 1995). Daston and Galison (1992) have proposed a taxonomy of objectivity along with a periodization based on it. Hilgartner has focused on the important role of staging for the establishment of trustworthiness, in the process bringing together an increasing amount of literature on staging science. He analyzes science advisors' self-presentation and convincingly argues that "the theatrical perspective offers a means to examine how credibility is produced in social action, rather than treating it as a pre-existing property of an advisory body" (Hilgartner 2000, p. 7). This is a topic that Iwan Morus has devoted much attention to (Morus 1998). It is important for such experts to convey a good impression of their integrity and moral character in order to persuade.

All these studies are indispensable for our understanding of the role of science and the public sphere. It may well be that in the post-war period when the linear model held sway and professionals were generally revered, there was no need to consider other questions than the truth, and the trustworthiness of those who speak authoritatively about it. But in the last few decades the emphasis in science funding has moved away from a concern with filling in gaps of knowledge to the production of knowledge that is worthwhile or serviceable (the latter is Sheila Jasanoff's term). Knowledge has become more of a means to an end and less of an end in itself. This has put much more pressure on accountability. How does one ascribe value to research when the value only becomes visible at the end of a 20-year long commercialization process subject to the vagaries of the market?

Adapting to such funding realities, some scientists have turned to hype. The tremendous amount of hype surrounding nano or genomics is at least as important a part of science and the public sphere as the truth discourse is. None of the above authors pay attention to hype. I will argue that in addition to persuasion, and even suasion, science in the public sphere features also the feeling of exhilaration. This is not an indictment of scientists engaged in hype –after all they are only playing their cards well in the new game of science funding – it is merely an argument that while the truth discourse may have been appropriate at the time of the linear model, it is now wide of the mark.

Barthes' discussion of 'writerly' and 'readerly' texts may serve as a heuristic. Barthes discusses both texts for passive consumption and texts that stimulate the reader's active participation. The former may prompt pleasure (*plaisir*) and the latter a form of exuberant joy (*jouissance*). *Jouissance* calls up a violent, climactic bliss closer to loss, death, fragmentation, and the disruptive rapture experienced when transgressing limits, whereas *plaisir* simply hints at an easygoing enjoyment, more stable in its reenactment of cultural codes (Barthes 1975, p. 4). Barthes' *jouissance* may well resemble the feeling of exhilaration prompted by nanohype. But my main point is that pleasure, in all its shades, may be found in scientific texts – and also in images – and that it matters for the topic of science and the public sphere. It is not just about the fact-truth-knowledge-authority-expertise -objectivity - disinterestedness -credibility complex, but emphatically also about exhilaration, pleasure, hopes, and fears.

2. A Case Study: From Surface Physics via CAMP to iNANO

Scientific texts and images are intended for specific audiences. Some audiences are homogeneous, for example those addressed in a textbook or at a specialist conference. Other audiences are more heterogeneous. Scientists sometimes address newspaper readers that might include scientists in neighboring scientific disciplines, high school students contemplating a scientific career, decision makers in funding agencies and taxpayers.

I will analyze the publications of a scientific group in the Physics Department of the University of Aarhus, in Denmark. This Danish group is interesting because it exemplifies the changes of science in the public sphere in the last few decades – to the point where all of Bucchi's stages are involved. The main character in the plot is Flemming Besenbacher, an entrepreneurial professor of physics at the University of Aarhus. He sits on a great many committees and is generally very attentive to the political work that needs to be done to keep the funding for a lab coming. Ivan Steensgaard, a Besenbacher colleague, has worked at Bell Labs and is very experienced at generating publications in peer-reviewed scientific journals. In contrast to Besenbacher, he focuses on just this one task. Steensgaard is content to produce high quality science in a lab and leave the dealings with the outside world to others.[1]

The entrepreneurial Besenbacher has been very successful over the last two decades in creating an infrastructure within which research and many individuals thrive. It started in 1986: The entrepreneur and the more narrowly focused Steensgaard worked in surface science (the Danish term, *overfladefysik*, translates directly to the even narrower surface physics) and were fascinated with the possibilities of the newly invented instrument, the Scanning Tunneling Microscope. They teamed up with a colleague, Erik Lægsgaard, a talented radio amateur who managed to build a basic STM simply using stuff lying around in various labs. For quite a while they spun off publications investigating surfaces with an

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[1] Interviews with four members of this Danish group (Besenbacher, Steensgaard, Lægsgaard, and Vang Lauritsen) may be found on http://hrst.mit.edu. Hard copies of these interviews will be deposited in the Burndy Library.

STM. "Pay dirt", Steensgaard calls it: it almost did not matter what you did with the STM, all results were interesting and illuminating.

In Denmark there had been a tradition of spreading the tax kroners evenly among all university departments with little pressure to account for the money spent. By the late 1980s, privatization of government institutions generated capital that was to be spent in a more 'elitist' (the critics' term) fashion, by funding research centers in mutual competition and subject to much increased accountability (For an overview of the most recent developments in Danish research policy, *cf.* Lundager Jensen [1996] and Grønbæk [2001]). The grant was to run for 5 years in the first instance and could then only be renewed once – the 'sunset clause'. Renewal was dependent upon the number of publications, weighted by the status of the journal, but also upon social relevance of the research. Besenbacher networked with a view to economic and environmental relevance. He located it in two prongs:

(1) Work in collaboration with a Danish company providing catalysts for chemical industries. Catalysis is of great commercial interests; for example, a catalyst speeding up a desired chemical reaction might save millions of dollars for chemical industries.
(2) Work on de-sulfurizing catalysts promising a reduction in acid rain and general environmental improvement.

The group managed to get an extension to their grant, and so the Center ran for an entire decade, from 1992 to 2002. The Center was a success in a number of ways. It became a high-status destination for graduate students and post-docs; it raised the profile of Aarhus University; it paid salaries and expenses for many individuals; it generated some interest amongst private enterprises; and it successfully reached out to secondary education by providing projects for high school students.

By 2001 Besenbacher was worried, though. His institutional creation was about to get the axe because of the sunset clause. He fulminated against the inequity in the discontinued funding for his successful enterprise, when other kinds of staid, old-fashioned research had steady funding by default (albeit at a low level). He worked diligently behind the scenes to have the sunset rule changed, but to no avail. He had no choice but to develop a new project and compete with others to set up a new Center. Having his ear to the ground he cultivated relationships in medicine and the life sciences, thrashing out a Center to work on, *inter alia*, biocompatible materials using scanning probe microscopy. He was successful again and now heads up a new Center. The old Center was called CAMP: Center for Atomic-scale Materials Physics, a descriptive term understandable to other scientists. The name of the new center is Interdisciplinary Nanoscience Center, or iNANO. The name of the Center now is a tag intended for a larger audience than physicists, chemists, biologists, and medical scientists. Atomic-scale materials science would have been much clearer, much less ambiguous, to the academic constituencies but incomprehensible to the many others that also matter, such as government officials, members of parliament, journalists, newspaper readers, and high school students. The iNANO Center's own organization underlines the fact that discourse has to take place in a great many venues – one might say in all of Bucchi's four stages simultaneously. The Center's own pamphlet makes the point with a Venn diagram of its organization: three mutually intersecting circles of iNANO, Nanoschool, and Bachelor and Master Studies (basically research and teaching) are ringed by the institutional support: University of Aarhus; Aalborg University; Danish Ministry of Science, Technology and Innovation; Danish National Research Foundation; Danish Research Agency; Danish Technical Research Council; EU Framework Programs; Danish Natural Science Research Council; Industrial Partners. This list reveals with great clarity the many different audiences that iNANO has to contend with, the many stages for which texts and images have to be crafted.

Besenbacher has developed a much more involved publication strategy than the one involving Steensgaard. The Center now issues press releases, starting with sentences such as this: "This week, a group of scientists at the University of Aarhus has published an article in the world-leading scientific journal, *Science* magazine. With the use of a powerful microscope capable of resolving single atoms (a scanning tunneling microscope), the Denmark-based research group has discovered a new phenomenon […]".[2] They also publish in various glossy magazines in the science popularization genre. Graduate students, such as Jeppe Vang Lauritsen and Anne-Louise Stranne, have been inducted into this kind of

[2] http://www.phys.au.dk/camp/pdf/science-uk-press-release.pdf.

publication early on. Vang Lauritsen had several such articles under his belt before graduating. Both themes of social relevance, mentioned above (improved efficiency of chemical industries, and environmentally improved technologies), are at the focus of these publications. Besenbacher writes reports for various political bodies, both the local university and municipal administrations, and the national parliament. He sits on the Danish Natural Science Research Council (DNSRC), an advisory committee to the national parliament, the Folketing. This council has a dual task: administering a block grant for research and advising the Parliament on science policy. The committee writes reports and strategic assessments, which, I presume, are the most important texts for decisions of a budgetary nature. The 2003 strategic assessment for the next four years reads like a carbon copy of the entrepreneur's views: Elite centers are to be funded, the social relevance is pushed, and the importance of training the next generation for industrially relevant research is presented as the lifeblood of the Danish economy. The specter of declinism is deployed: the countries Denmark usually compares itself against (the US, Sweden, Finland, the UK, Germany) are investing money in research, and the Danish standard of living is at risk unless sufficient funding, and so on.

It is worth noticing that one of six special strategic areas of focus is nano and that authors' conflict of interest is not discussed.

The future benefit is stridently formulated in this DNSRC publication. The future tense is consistently used where one might have expected a subjunctive. Nanotechnology *will* thus offer: pharmaceuticals without side effects dosed using nanostructures; smaller and faster components for computers and communications technology; new and better building materials; new batteries and energy storage systems; new sensors; lab-on-a-chip systems; optical nanostructures for ultra fast communications; biological manufacturing of materials; and new catalytic converters for environmental purposes and for energy technology. The summary of all this takes on an almost prophetic tone: "Nanotechnology is an important area that will form the basis of the next industrial revolution."[3]

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[3] http://www.forsk.dk/snf/publ/stratplan/strategi_03_07eng.pdf.

3. Locating the Pleasure

I will argue that pleasure may be found in much of this discourse, primarily due to the exhilaration felt by contemplating a technologically enhanced future. The communication of this exhilaration is at times explicit in the texts, and I will argue that it resonates also in the images.

I will suggest the presence of such pleasure in all genres. I will first discuss newspaper articles, several illustrations of which turn up also in an iNANO pamphlet. I will then turn to the CAMP and iNANO websites that prominently feature STM movies. Finally, I will discuss an article in a peer-reviewed journal that utilizes such movies. In the course of this section I generally move from the right to the left in Bucchi's diagram, although much is clearly intended for several of Bucchi's stages simultaneously.

3.1 Newspapers and Pamphlets

In an article in the daily *Jyllandsposten,* Besenbacher displays three molecules: ribosome, bacteriorhodopsin, and molybdenum disulfide. The legends help us understand their meaning (Besenbacher 2002):

> The living cells contain fascinating nanomachines. The ribosome here is the cell's protein factory. Ribosome's atomic structure has been determined recently, also with the participation of researchers from the iNANO center.
>
> Nature is a decisive source of inspiration within nanotechnology. The bacteriorhodopsin shown here is a protein regulated by light. It works as a nanoscale pump transporting protons across the membrane encompassing living cells.

These two molecules are being represented as a nanomachine and a nanoscale pump, which is precisely the language pioneered by Eric Drexler, a mechanical engineer by training. Drexler's vision of nanoscale machines built atom by atom gained tremendous credibility with Don Eigler's images of IBM and atomic corrals written with xenon atoms and imaged with an STM (Hessenbruch 2004). And indeed, Besenbacher uses just this corral in the same article with the comment, "this image has developed into a symbol of the promise of atomic-scale control that nanotechnology yields".

Drexler's vision caused excitement by opening up a vista of assembling any kind of molecule atom by atom, as long as the final molecule was energetically stable. The tremendous difference between pushing the chemically inert xenon atoms around on a surface and the assembly of large 3D molecules was elided, and appropriately so when the aim is to inspire and enthuse. And Drexler's vision gained in force by his comparison with the DNA-RNA-protein complex. He argued that nanotechnology could assemble molecules resembling the building blocks of life in that these new molecules themselves produce new molecules. In other words, we would design new life-like systems in real life, just as artificial life was being generated on computers (Drexler 1987).

The same three molecules also grace pages 2 and 3 of a pamphlet introducing the center – and displayed on iNANO's website (Figure 2).[4] In large white letters the disciplines involved in the center are stated: physics, chemistry, medicine, molecular biology, engineering, and biology. In small letters on the left is a list of senior researchers and industrial partners.

The largest and most visible molecule is the bacteriorhodopsin which has also been incorporated into the banner of iNANO's website. Visually, it consists of two planes of red balls, connected by curled strands. The planes look more like the topic of surface science, whereas the curled strands show us that we are in the realm of biology. It is thus both appealing and eloquent about interdisciplinarity. To the left of it is the ribosome (below which is a molecule of less concern for the purposes of this chapter), and further to the left the molybdenum disulfide molecule that the CAMP group had analyzed using an STM with a view to improvements in catalysis. These four molecules fill the right half of the image. On the left half and somewhat isolated from the other four we find a DNA strand.

The intended audience for this pamphlet is wider than scientific colleagues. It is well suited for visitors to the lab, including high school students, or for distribution amongst journalists, administrators, and politi-

[4] http://www.inano.dk/graphics/iNANO-system/File-links/inano_final.pdf.

cians. It is the kind of glossy genre that assumes a distracted reader. The coloring is striking, with a blue background and each of the five molecules consisting of a major color: red, green (and brown), white, orange, and purple; the prose is crisp and to the point, introducing the theme of nano, summarizing the funding structure and mission of the iNANO center along with its research and teaching activities.

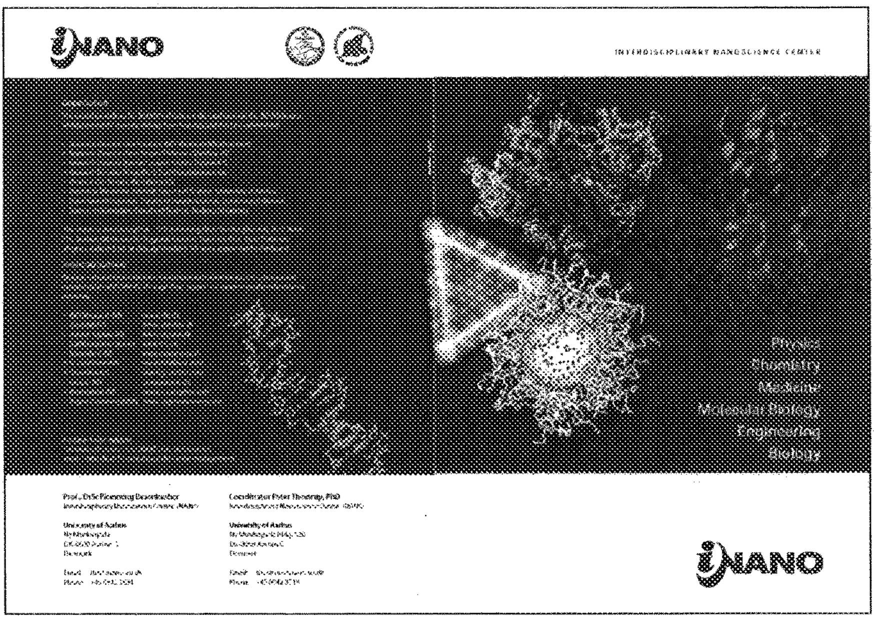

Figure 2. iNANO's five molecules.

3.2 The Sublime

The image fronting the US National Nanotechnology Initiative report issued in 1999, by comparison, is much more direct in its hype. It was also intended for a non-specific audience, also aiming to advertise nano, and with a view to supporting funding for research. Here, we have an STM-produced image of a surface but set, not against a plain blue background but the starry sky with Earth, Moon, and a falling star. The report itself explains that: "The combination of a scanning tunneling microscope image of a silicon crystal's atomic surfacescape with cosmic imagery evokes the vastness of nanoscience's potential." Alfred Nordmann has made a number of interesting suggestions about this image that may aid also in the understanding of the Danish image (Nordmann 2004). First of all, the US image juxtaposes a macrocosm and microcosm, of outer space and inner space, suggesting a continuation of the frontier dream: going where no man has gone before. Secondly, the "mystical or forbidding presence of artifacts [...] floating through space, appear[s] to defy their origin in human social practice" (2004). Nordmann suggests that it inadvertently anticipates Bill Joy's worry that the nanotechnological future may not need us. While distracting attention away from the social nature of nanoscience, it focuses our attention on to our machine-enhanced sensory modalities: the perception of the very small and the very large; a point made almost ubiquitously in popularizing literature on nanoscience with a scale of images at powers of 10, for example at meters, millimeters, micrometers, and nanometers.

In the Danish image there are no vistas of outer space and inner space. The references to the vastness of nanotechnology's potential are subtler because the original legends are now left out, but readers of the newspaper article will recognize the symbolic meaning intended for the molecules. And the molecules are certainly presented as divorced from human or social practice.

The DNA molecule in Figure 2 is slightly off to one side, presumably because, unlike the other four, it is not a molecule that the iNANO researchers have worked on. But its inclusion resonates with the promise of nanotechnology to design new molecular systems that are just as powerful as DNA and RNA – in fact the DNA molecule might be thought to be emphasized through its placement on page 2, one page before the other four. In the days of a shrinking physics budget and a growing life sciences budget, the one icon one wants to associate oneself with is the double helix of DNA (Nelkin & Lindee 1995).

And so while iNANO's visual language is subdued (just as Danish Lutheran churches are visually very restrained), it still encodes exhilaration. The phrases Besenbacher uses when addressing newspaper readers

(Besenbacher 2002) and high school students[5] show us where the decoding is meant to take us: enormous potential, as yet unknown possibilities, fantastic possibilities, and the next industrial revolution.

One may pursue the question whether the promise or hype is justified, and whether the reader is being duped by the assertions (limiting oneself to the truth discourse). But this may be an inappropriate yardstick for the science hype genre. Instead, one might ponder the importance of a genre that invites revelry in an imagined future. Such revelries have a value all of their own. To get at this issue, I will take a short detour through audience studies that have developed alternative yardsticks in opposition to the 'dominant' discourse of truth and falsity. Nick Stevenson has summarized John Fiske's argument:

> What is important about the tabloid press is not whether the articles and features it runs are actually true, but its oppositional stance to official regimes of truth. Fiske illustrates this argument by referring to a story concerning aliens landing from outer space, which he claims to be a recurrent one within tabloid journalism. The point about such stories is that they subversively blur the distinction between facts and fiction, thereby disrupting the dominant language game disseminated by the power bloc. Further, while official news attempts to ideologically mask the contradictions evident within its discourse, the tabloid press deliberately seeks to exaggerate certain norms, hereby *abnormalising* them. Fiske's argument here is that the sensationalised stories characteristic of the tabloid press produce a writerly text in that they openly invite the interpretive participation of their readers. The tabloids, like other popular texts such as Madonna and soap operas, maintain their popularity by informing the people about the world in a way that is open to the tactics of the weak. [Stevenson 2002, p. 94]

The prophetic prose and visual language of nanohype may resemble tabloid journalism in this sense (not in the sense of being true or false). Whereas technical texts tell readers what is the case, leaving little room for interpretation, especially without substantial technical training, the playful suggestions of nanohype enable the reader to imagine and to enjoy imagining. Thus Besenbacher, in addressing high school students and

[5] http://www.destination-fremtiden.dk/nanoart.asp. The name of this website translates as "destination: the future"; using the English word for destination connotes something other than the mundane.

the general public, wisely refrains from technical detail and instead invites revelries that for many readers will be pleasurable. The readers are expected to be distracted, maybe thumbing through the pamphlet during a spare moment, or reading the newspaper during breakfast. The reader is not expected to commit any facts to memory (connoting tedium) but rather to daydream.

As Colin Milburn has convincingly shown, science fiction is in the background of much nanoresearch. The Drexlerian vision has clearly taken elements from science fiction, as did Richard Feynman who gave a lecture entitled 'There's Plenty of Room at the Bottom' in 1959, a lecture which is now often (paradoxically) referred to with a view to establishing nanotechnology's scientific origins (Milburn 2002). And science fiction has this same characteristic: it invites playful revelries of the future; it prompts pleasure.

It has been suggested that a core element of science fiction is its delight in the sense of wonder, sometimes referred to as 'sensawunda' or as the sublime. Science fiction editor David Hartwell has summarized it thus:

> A sense of wonder, awe at the vastness of space and time, is at the root of the excitement of science fiction. Any child who has looked up at the stars at night and thought about how far away they are, how there is no end or outer edge to this place, this universe – any child who has felt the thrill of fear and excitement at such thoughts stands a very good chance of becoming a science fiction reader.
>
> To say that science fiction is in essence a religious literature is an overstatement, but one that contains truth. SF is a uniquely modern incarnation of an ancient tradition: the tale of wonder. Tales of miracles, tales of great powers and consequences beyond the experience of people in your neighborhood, tales of the gods who inhabit other worlds and sometimes descend to visit ours, tales of humans traveling to the abode of the gods, tales of the uncanny: all exist now as science fiction.
>
> Science fiction's appeal lies in its combination of the rational, the believable, with the miraculous. It is an appeal to the sense of wonder. [Quoted from James 1994, p. 105].

It is this sense of wonder that resonates in Besenbacher's use of words such as 'dizzying', 'unbelievably small', 'undreamt-of', 'fantastic', 'visions', 'unimaginable', 'as yet undefined', and 'ground-breaking' (Lindberg 2001, Besenbacher 2002).[6] And the images encode some of the same sense of wonder. As an aside, it would seem that science fiction is turning away from the original general trope of exploring empty space and alien worlds. Cyberpunk, one of the more recent genres of science fiction is more concerned with communication technologies, cyborgs, and technologically altered minds (*e.g.* Gibson 1984, Goonan 1994). The NNI is clued in to this development: its current mantra is NBIC (nano-bio-info-cogno) convergence. The mantra certainly refers to interdisciplinarity, but also to the sense of hype in the latest science fiction literature. This is an aside because I have not found an instance of the Besenbacher group referring to NBIC.

However, the pleasurable reading of possible futures is being constantly challenged by the discourse of truth and falsity. Just as science fiction as a genre has historically been marginalized and science fiction fandom ridiculed, so the nanovisions are under attack. Largely, this is prompted by the desire to have transparency in a political process that earmarks millions of dollars in pursuit of a vague future. But it is driven even more by the dual nature of new technology: the theme of the wizard's apprentice. Media reports on nano have picked up the Drexler vision, accelerating greatly with the publication of *Prey* by Michael Crichton, the author of Jurassic Park (Anderson *et al* 2004, *cf.* also Stephens 2004). In *Prey*, we have nanorobots instead of dinosaurs, but the theme is the same: they escape and wreak havoc upon humanity. With this publication, the pleasurable revelries of the future are turning into nightmares, thus threatening to undermine the political will for nanotechnology funding. The response in the nano-community has been to emphasize differences between actual nanoresearch and the research featured in *Prey*. Drexler himself has expressed frustration that his vision is being tarred with the brush of *Prey* (Drexler 2004).

Faced with similar hostility to nano in Danish newspapers, Besenbacher also has emphasized the need to distinguish science from "mere science fiction" (Besenbacher, quoted in Holm 2004). The blurring of the boundary between truth and fiction is desirable when that blurring leads

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[6] Also iNANO pamphlet: http://www.inano.dk/graphics/iNANO-system/File-links/ inano _final.pdf.

to exhilaration, but not if it leads to fear. Phrased thus, Besenbacher's stance appears inconsistent, but in strategic terms it is clearly not.

3.3 Movies

I will now turn to the webpages and to the STM movies. They were created during the CAMP project that ran from 1992 to 2002 and prominently displayed on the CAMP website. They are still present on the iNANO website but not with top billing. Thus, we are moving to the left in Bucchi's diagram.

Erik Lægsgaard, the designer and builder of the Aarhus STM, thinks explicitly in terms of adapting scientific instrumentation to the human senses. For example, we humans are very good at noticing a duck waddling across a lawn. We sense immediately that the background is staying fairly stable and the real change in front of us is the movement of the duck. Trees may sway, and waves in a pond may constitute movement too, but we recognize with ease that these movements always return to the original position and so we can block them out of our attention. Similarly, we can recognize diffusing single atoms against a fairly stable surface. Scientific instrumentation and computer programs have a much harder time with such recognition. Hence, Lægsgaard argues, it makes sense to make movies and use the human senses for just this kind of research. Similarly, during the development of the STM in the 1980s, Lægsgaard, a passionate radio amateur, decided to use sound in the tuning of the STM. Lægsgaard argues that it is much harder to generate a visual image of similar utility, and that the human ear is especially well suited to recognizing the kind of sound that signals a properly functioning instrument.

These movies were used in research and so the first audience was the CAMP/iNANO researchers themselves, trying to get a grip on the nanoworld. They were displayed at conferences as well, making the scientific colleagues the second audience. The websites configure a third, larger, audience. I will address pleasure in the larger audience first and get back to pleasure amongst scientific colleagues. A member of the lab, Anne-Louise Stranne has presented just such a movie with the help of six stills in a glossy science-popularizing journal. The article is structured to make the point that:

> nanotechnology is based on complete control of atoms' behavior. With complete control, a whole new world will open up providing opportunities for constructing and using materials. Individual atoms may be used as small machines moving other atoms, and it will be possible to generate electrical components from a small set of atoms. And that's just the beginning.

But to reach this promised land of technology, one must be sure that the atoms don't move or react in an uncontrolled fashion. It is here that research of atoms on surfaces enters the picture (Stranne 1999).

The movies are placed most prominently on the CAMP website, just under the banner. (They are also accessible from the iNANO website, as is Stranne's article). The movies are in yellow-orange-red, brown colors and consist of points moving along a background pattern that remains comparatively stable. We are informed in the legend and surrounding text that these are atoms diffusing along surfaces. Each still of the movie is an STM scan of the surface, and we are actually watching 30 minutes of action compressed into a few seconds, so that the motion of the diffusing atoms becomes easily recognizable. The newspaper article mentioned repeatedly above (in *Jyllandsposten*) is placed on that website and with a feedback link to its author (Flemming Besenbacher) along with one to the movies.[7]

What may the intention of placing movies on the website be? For one thing, they allow something like a voyeuristic sense of control of the nanoscale: Take a peep at the hitherto unseen world! A world that humanity has wanted to access for centuries – a world thematized in the mid-20th century by George Gamow's *Mr. Tompkins* and other science fiction authors, and more recently on US National Public Television by *The Magic School Bus*. And comprehension is easy: any viewer can discern the atom moving across the surface – quite unlike most visual scientific material. In other words, a part of the fascination with the movie consists of visual access to atomic scale: from being able to see individ-

[7] The site is constantly being reorganized and since April 1, 2004, some of these links have disappeared – but the links to the movies have always remained intact.

ual atoms move to controlling such atoms seems but a small step! As in Eigler's experiment with xenon atoms, it evokes control of the nanoworld and the pleasurable revelry of revolutionary future technologies. The pleasurable revelry is available with one click – it may reach a distracted audience such as high school students searching for something cool.

It deserves mention also that these movies were up already in 2000 when the appearance of the Internet was still largely static. I remember watching these movies then, being fascinated simply because they were on my computer screen, not on the TV. With time, the pleasure of watching just any movie on the web has obviously waned.

3.4 The Intraspecialistic Stage

I will now turn to pleasure among scientists, by examining an article in *Physical Review Letters* analyzing a movie. This audience is not presumed to be distracted, quite the opposite. Hence visuals are in plain black and white, and the mode of discourse around them is matter-of-fact without any overt references to futuristic revelries. Instead, the arguments attempt to leave as little as possible for the audience's imagination to play with. In fact, readers of scientific publications may be presumed to be on the prowl: looking for resources that they can use in their own research. Attendees at scientific conferences may also be looking to score points with the audience by asking penetrating questions. In either case, the audience is highly focused and critical of any ambiguity.

The graphs (Figure 4) are derived from the movies (Figure 3). One movie is of hexagonal assemblies of atoms upon the surface of a silver crystal.[8] The movie shows the gradual decay of these nanostructures, as the authors call them. The publication using this movie treats the movie as a means to an end (Morgenstern *et al* 1998). The display of a set of four stills gives the reader a general sense of the appearance of the movie and highlights the decay. This information is transformed into a more succinct, graphical representation of the decay. For each still of the movie (many more than the four used earlier on in their publication) the

[8] Adatoms on a Ag(111) surface.

area of the nanostructure is measured. The measurements are displayed on a graph, the axes being area and time. The resulting graph contains a continuous curve falling off to zero, symbolizing the degradation of the structure. (The same experiment is done with 'vacancy island decay', a flat hole on the surface that is then gradually filled up; hence the graph has two lines.) The point that the authors want to get to is the kinetics that causes these decays, and here they engage with the so-called Ostwald ripening model. They discuss what the measurements tell us about the model, that is to say to what extent the measurements support the model and to what extent the model assures the experimenters that their results are sensible, as opposed to, say, an artifact of the STM.

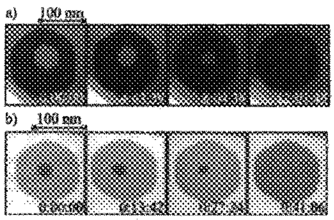

Figure 3. Four stills from a movie.

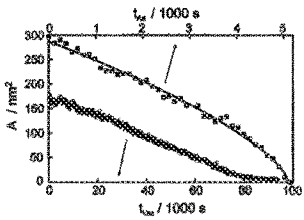

Figure 4. Graph of decay.

In other words, the movies need to be summarized into a conspectual view, most often a graph, from which even more succinct information (numbers) about the decay may be formed, such as the linearity of the decay and the gradient of the line. These numbers can then be fed into a quantitative model and the implications for the trustworthiness of each discussed. Of course, much scientific work is of this kind: a cascade of representations, summarizing information to ever-higher degrees of abstraction, the highest level of which is theory – or models (Latour 1987).

As mentioned, the audience is configured as attentive and interested. There is no color and little fireworks. The reader is expected to understand the jargon of surface physics and know how to read graphs. The Ostwald ripening theory is explained in some detail, but to follow the argument the reader must know, say, differential equations and Arrhenius plots. Some level of scientific literacy is required. The majority of the population will have no interest in this paper and would not be able to make any sense of it.

Even here the initiated may experience pleasure. There may be pleasure in deciphering highly abstract codes, in communicating at a very abstract level, and in figuring out the consequences for one's own research. And there may be pleasure in belonging to a select group of individuals that is thus enabled – especially if this group can see itself as superior in some way, such as more rational than the rest of the population. In other words, just as maps are capable of solidifying national identities, so graphs may be capable of solidifying disciplinary identities.

And there may be at least two further sources of pleasure in this publication. The authors frame the importance of the paper thus:

> The control of kinetic parameters in thin metal film growth is of utmost importance for the ability to design novel nanoscale structures.
>
> As many nanoscale surface structures are only metastable, it is important to know on what time scale material rearranges and whether these processes can be used for modifying nanostructures on surfaces.

This is indeed the nanohype theme so prominent in the popularizing literature. The Drexler dream requires control at the nanoscale, and this paper will inform you of an aspect of just that.

The second additional source of pleasure lies in the power of the STM to produce images and movies. As I have argued elsewhere (Hessenbruch 2004), the early source of surface scientists' fascination with the STM was three-fold: atomic resolution, and the imaging in real-space, and real-time. Getting images of individual atoms had been something of a holy grail in science throughout the 20th century – overlaid with the mystique of the uncertainty principle. Most people, including many scientists, understood the uncertainty principle to rule out the possibility of the imaging of individual atoms. Hence scientists also felt the pleasure of voyeurism, when seeing the first STM images. Until the 1980s, scientists had their information from such techniques as x-ray diffraction, which is powerful but sums over many atoms at a time. The information about, say, the structure of DNA was encoded in a space that differed from real space, and one space could be mapped on to the other with Fourier transforms – a mathematical technique.[9] Generations of crystallographers learnt to think in Fourier space, and the intriguing nature of STM images was that they provided images directly in real space – no need for a Fourier transform. Finally, X-ray images require the summing over longer periods of time. One cannot do snapshots of crystals using x-rays and then see how the crystal changes over time. STM movies are precisely this: they show you developments in real time. All these three factors must have rendered STM movies 'cool' to scientists, adding pleasure to the publication under discussion.

4. Conclusion

Pleasure may thus be found in all of Bucchi's stages and it should be clear that the question of truth and consensus cannot encompass all the goings-on in the public sphere. Also, the existence of esoteric texts, textbooks, popularizations and TV shows made us think of a fragmented discourse so that certain texts and images address certain audiences only, depending on their level of expertise. By contrast, I have shown that the audiences addressed are heterogeneous.

The textual and visual language is writerly, in Barthes' sense. This is quite obvious in the newspaper articles, but writerly language may even be detected in the *Physical Review Letters*. Just as Benedict Anderson has argued that maps have "penetrated deep into the popular imagination" (Anderson 1983) and contributed to the making of national identities, so a similar group identity may be enhanced by images of molecules as machines, and images of inner and outer space. Certainly, Besenbacher's PR-work is intended to tie together networks of support. Constant maintenance work is required lest parts of the network disengage, constant work is required to establish new contacts.

Latour's talk of heterogeneous networks seems apposite here: Besenbacher enrolls actants (humans and adatoms). In 1987, Latour still talked of trials of strength: the stronger network would sustain a stronger claim on truth. But the networks discussed in this chapter primarily sustain funding, not truth. And indeed Latour's recent work (*e.g.* Latour 2004)

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9 For brevity's sake the phase problem is ignored here.

has shifted towards the politics of sustaining heterogeneous networks in general – not just in order to win a struggle among versions of truth. As such, this chapter is in accord with that aspect of Latour's trajectory.

Bucchi's diagram is static in time. It doesn't allow for changes in the public sphere, a change that Habermas has documented in the long term. The development from surface physics through CAMP to iNANO indicates further changes. But to what extent is the story described here representative? Besenbacher is an exception within the Physics Department of Aarhus University. Other professors there, such as Steensgaard, do not publish popularizing articles, sit on government committees, commission nicely designed websites, or devise and write new grant proposals. They write scientific papers and communicate with their peers. These professors still live science as they did 30 years ago. However, the next generation is being trained to behave like Besenbacher. In other institutions, such as MIT or Stanford, and in other departments, such as the life and medical sciences, the practice of interdisciplinary, networking science with a view simultaneously to the market and to 'pure science' is much more common. Gibbons *et al.* (1994) have argued that science has been gradually shifting in this sense for a few decades, and this chapter adds to the evidence.

The same group of authors has more recently pointed to current science's similarity with derivatives in financial markets, such as 'futures'. Here "economic activity derived from first-order operations rooted in material production and exchange is displaced onto a second-order level where abstraction and speculation predominate [...] Innovation has acquired an urgent, even quasi-moral, stridency" (Nowotny *et al.* 2001, p. 67). "Collusions of interest [...] tread a thin line between authentic belief in the future potential and mere rhetoric of 'selling' a particular line of research to politicians and the public. Promises come first [...] in order to instill and stimulate demand which later will underpin a market" (Nowotny *et al.* 2001, pp. 37-8). Potentiality tends to take precedence over actuality. This fits nano to a tee. Nano is full of promises based upon a potential, the assessment of which is difficult, but which are elaborated upon and amplified in the media. These promises excite the imagination of industry, the public, and members of parliament, and influence research funding decisions. They also help establish new disciplinary boundaries (Guice 1999, Hedgecoe 2003). That such a centripetal force is indeed taking place under the banner of nano has been clearly demonstrated by Schummer 2004).

Now, the effect of expectations is not new. A part of Colin Milburn's argument (Milburn 2002) is that science fiction played a role in Feynman's argument about 'plenty of room at the bottom'. But this does not mean that science fiction has always played the same role. With the changes in funding structures, more and more scientists are urged or encouraged to behave like Besenbacher. The role of science fiction and exhilaration is increasing.

The policing of hype needs to change accordingly. Why insist that fears instilled by science fiction (*Prey*) must be marginalized as fiction when at the same time hopes are classified as possible fact? This opens up the question of accountability of hype. Research is supposed to be more accountable now when commercialization has replaced filling in a gap of knowledge as the yardstick, but when research gambles on future markets accountability seems hard to achieve. Can we account for some of the value of nano in the pleasure of expectation it gives, regardless of whether the promise actually comes to fruition?

At any rate, Bucchi's diagram falls short for two reasons: it is simplistic in focusing only on truth and not on the circulation of money and the selling of dreams[10]; and it ignores historical changes in science and the public sphere. Fitting the role of pleasure into Bucchi's diagram will, however, pose severe problems. The important category is not expertise but the politics of funding. Besenbacher's newspaper articles address simultaneously several of Bucchi's stages, and a politician might read it with a view to voters' interests at the next election. An investor might read it thinking of where to put his or her high-risk investments. The manager of an industrial company might read it thinking of investors wanting to invest in nanorelated research. Think tanks and government bodies deciding upon funding structures use a managerial cost-benefit language shorn of hype. Nonetheless, the very reason for funding nano is

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[10] It ignores also activities such as political lobbying and the legal discourse of intellectual property or regulation; the relevance of all of which have been demonstrated at the *Imaging and Imagining* conference in Columbia, South Carolina, March 2004.

the uncertain promise that no private company is prepared to bet on. The whole discourse of fact-truth-knowledge-authority-expertise-objectivity-disinterestedness-credibility concerns itself with what is the case, neither with what might be the case nor with revelries of what might be influencing what is.

Should we therefore abandon attempts to map science in the public sphere? I think not. Bucchi's diagram has great heuristic value. It has to be more complex to fit the realities on the ground, and it needs to incorporate temporality. In fact, the very complexity of the resulting map will likely defy its original purpose: to provide a conspectual view. But there will be pleasure in the attempt.

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CHAPTER 17

NARRATIVES FOR NANOTECH: ANTICIPATING PUBLIC REACTIONS TO NANOTECHNOLOGY

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Much information regarding nanotechnology is publicly available, but discussion of this research is currently limited to certain specialized groups: scientists, engineers, and investors, plus distinctive subcultures of nanophiles and nanophobes. There has been very little public awareness, let alone any public reaction. Nevertheless, public controversies about nanotech will soon arise. This chapter borrows an insight from cultural anthropology to explore the likely forms of public reactions. It asks whether there are general lessons and statements about public scientific controversies which are helpful to the case of nanotechnology: do we have reliable models that accurately predict public reactions to new scientific developments, or should we turn instead to limited analogies with specific episodes of public reactions? Case studies from other recent public scientific controversies, particularly cold fusion and recombinant DNA, help us explore this question.

1. Introduction

One of the ways people try to envision the future of nanotechnology is to tell stories about the past, expecting that the future will continue certain features of the past. If one tells stories which emphasize that the founders of nanotechnology *past* were heroic geniuses, for example, that kind of emphasis would bless nanotechnology *present* and *future* as a noble effort whose heroic qualities endure. Or so the storyteller would hope.

Public reactions to nanotechnology in the U.S. are more difficult to envision this way because there has been practically no history of public awareness, let alone public reaction to it. (But see Bainbridge 2004 for some ideas about research on public awareness of nanotech). In lieu of such information, we need to turn to past episodes of the arrival of new forms of science and technology, and public reactions to them: atomic energy, space science, cold fusion, stem cell research, remediation of environmental disasters, genetically modified foods, and so on. American society has had many experiences with the arrival of new technologies, and perhaps comparisons and analogies with some of them will help us anticipate public reactions to nanotechnology.

This question is compelling because, in democratic societies, non-scientists have important roles to play and stakes in the arrival of a new technology. We make science policy through legislation, litigation, lobbying, appropriations, environmental regulations, public school curriculum guidelines, and other political mechanisms in which non-experts participate. Some of the actors are experts with the finest scientific credentials, but others are people with no credentials, and still others are in between those two positions. Those who have a stake in the formation of science policy can be scientists, engineers, technicians, would-be scientists, wouldn't be scientists, science teachers, science students, policy makers with and without knowledge of science, and so on. In nanotechnology policy, some of the voices will be those of experts who work at the heart of nanotechnology. This is perfectly appropriate. But we must also take into account the voices of many other citizens. Nanotechnology is crafted by a relatively small population of experts, but public reactions to nanotech will be the work of many tens of millions.

So to anticipate those public reactions, we have to ask which histories of technology are relevant to nanotechnology, and why. How do we choose one story from the past over another for the purpose of projecting its features onto public reactions to nanotech? People may well hope that certain essential features will endure into the future, but different people will tell different stories from the past, depending on what they feel are the essential features for nanotechnology.

Furthermore, public reactions to a new technology are not necessarily determined only by the scientific merits of the technology. Extra-scientific considerations can be equally strong, including values, beliefs, symbolic communication, rhetorical tactics, and so on. We need to see that a case of a new technology can be, among other things, a drama of good versus evil, or hope versus fear, or fairness versus unfairness. Stories about nanotech too will be permeated with values, symbols, and rhetorical tactics.

To ask which stories are helpful and how, I turn to an insight from cultural anthropology, namely, Malinowski's theory of myths. I suggest that nanotechnology is likely to generate the conditions for myth-telling that Malinowski described. If so, we have to ask how we can draw insights about public reactions to nanotech from earlier cases of other technologies. Is our knowledge of other cases organized into reliable nomothetic principles, or must we match the case of nanotech to a small number of closely related case studies? The high level of hyperbole that characterizes many accounts of nanotech causes me to examine two earlier cases with similar features, namely, recombinant DNA and cold fusion. From this reasoning I extract some lessons about public reactions to nanotechnology.

2. Malinowskian Conditions and Malinowskian Stories

Eighty years ago, Bronislaw Malinowski proposed a relationship between social conditions in the present and the telling of stories about the past. Malinowski taught that people tell myths, not because they need to empirically reconstruct a true record of past events, but rather because they need to retroactively justify certain conditions in the present. The telling of myths gives legitimacy to current circumstances by tracing them to a "primeval reality" (Malinowski 1948, p. 146), or by discovering precedent – "warrant of antiquity" (p. 107) – for the way things are now. And so myths seem to be a record of past events, but they are really a reflection of the present situation (pp. 93-148).

Malinowski drew his illustrations from his ethnographic work in the Trobriand Islands of the Western Pacific. The Trobrianders prefer to justify their geographical situations by reference to a First Principle of autochthony: it is right and proper that we live where we do because this is where our ancestors emerged from underground. Indeed, a group which is satisfied with its location will point out the exact spots at which its first ancestors climbed up to the surface of the earth (pp. 111-14). But Trobriand clans and subclans sometimes occupy lands beyond their rightful territory, subduing or displacing other clans. When this happens, they violate the principle of autochthony by explaining that their own first ancestors behaved virtuously, while the other peoples' ancestors behaved improperly. Thus, a moral justification to occupy the lands of another clan (pp. 112-113). In still other circumstances, one group can justify its subjugation of another by marrying into the subjugated group, and then telling stories which exaggerate the rights that derive from those marriages (p. 115). Myth-telling for the purpose of justifying the present situation is so open-ended that it is neither consistent nor reliable, even in respect to its own First Principle. "The logic of events is not very strictly observed in the reasoning of the myth," as Malinowski gently put it (p. 113)

The sense of Malinowski's theory is that a myth is a living element which actively shapes current events, as opposed to being a record of what happened in the past (pp. 96-101). And so it makes sense that, ironically, "one of the most interesting phenomena connected with traditional precedent and charter is the adjustment of myth and mythological principle to cases in which the very foundation of such mythology is flagrantly violated" (p. 117).

This kind of story-telling is more likely to arise in some circumstances than in others. When there are "certain inconsistencies created by historical events" (p. 125); or when there are some "specially unpleasant or negative truths" (p. 136); or when one group holds power over another; or when the credibility of a form of morality is less than secure (pp. 125-126): then we can expect that myths will be told because myth-telling enables people to resolve these anomalies and unpleasantries.

To summarize Malinowski's theory of myth-telling:

(1) Myth-telling arises in certain tense circumstances, particularly when one group has to justify its treatment of another group, or when people suddenly experience profound historical changes, or when contemporary events are seen especially disturbing;

(2) Myth-telling need not answer to an accurate record of events in the past, even though it seems to be a convincing account of what happened before the present;

(3) Instead, myth-telling reflects conditions and problems in the present, which is to say that the past is reconfigured to serve the present;
(4) The result of myth-telling is to justify, legitimize, or rationalize the current circumstances in which people find themselves. Myth-telling is an exercise in coming to terms with present-day tensions.

That four-part formula is relevant and useful to public reactions to nanotechnology in the near future if we imagine any of the following Malinowskian conditions:

- That the interests of the scientists and engineers who drive nanotechnology are placed in conflict with the interests of the public;
- That the interests of some scientists are place in conflict with the interests of other scientists;
- That one part of the public finds itself in serious conflict with another part in a controversy involving nanotechnology;
- That various social or moral or political disagreements are rendered as controversies about nanotechnology, even if they have little or nothing to do with the scientific merits, or lack thereof, of research at the nanoscale;
- That large parts of the public find the consequences of nanotechnology to be puzzling, disturbing, or downright frightening;
- That large parts of the public feel that nanotechnology causes our lives to change too much too fast.

In other words, there are multiple possibilities for tension, unpleasantness, and social conflict which could bring nanotechnology into the conditions that generate myth-telling in a Malinowskian style. Those conditions will powerfully influence public reactions to nanotechnology. No doubt there will be multiple competing stories as various groups contest each other's interests. We can expect that people will tell stories about nanotech the way Trobrianders tell myths.

Now is a good time to think about this. Public awareness of nanotechnology has been minimal up to this point, so there has been very little public reaction. I see that reports on nanotech appear regularly in certain periodicals, including *Scientific American*, *Wired*, *Small Times*, *Technology Review*, and the *N.Y. Times*. I know that several million people read these publications. At the same time, however, several *hundred* million people do *not* read them, nor do they read other newspapers, magazines, or web sites which report on nanotechnology. This condition will probably not last much longer. For a short time, we have the luxury of anticipating the possible forms of public reactions to nanotechnology.

3. A Nomothetic Approach

What do we know about drawing comparisons and analogies in which past episodes stand in as surrogates for nanotech? I suggest that we have two strategies: (1) we can organize a large amount of information from many experiences by summarizing them as general insights, that is, nomothetic models which will predict our experiences with any new technology; or, (2) we can draw insights from a limited number of selectively chosen experiences which share important features with the case of nanotechnology.

The first strategy is a scientific approach in the sense that it seeks to summarize a large body of data in the form of regular laws. Its value depends heavily on the assumption that such laws have already been generated, and that the case of nanotechnology will faithfully conform to those laws. The second strategy has more modest intellectual features. It draws from a narrower base of information, and it depends strongly on which criteria are used to hypothesize that a given case study is germane to nanotechnology.

Let us begin ambitiously. The following general statements describe numerous episodes of the arrival of new technologies:

1A. When a new technology arrives, it will be so expensive that only the very wealthy can afford it, thereby exaggerating class differences. (Think of the initial days of cell phones, hand-held calculators, and air bags in cars, for example.)

1B. Shortly after a new technology arrives, mass production will great reduce the cost, thereby democratizing its availability. (Think of the second phase of cell phones, hand-held calculators, and air bags in cars.)

2A. If a new technology involves profound changes in health or medicine, some people will object that scientists and doctors are playing god. (Here one might recall organ transplants, tissue transplants, and technology-assisted reproduction.)

2B. If a new technology involves profound changes in health or medicine, some people (including patients, their doctors, and their families, plus administrators, investors and manufacturers) will fervently advocate for its use, on the grounds that patients should not suffer or die needlessly. (Here one might recall organ transplants, tissue transplants, and technology-assisted reproduction.)

3A. The best way to nurture an expensive new technology is to consign it to processes of proprietary capitalism, centered on patents and copyrights, because no one else besides proprietors and their investors will have the will or the resources to develop it, and because this will protect it from political interference. (Currently this argument is made on behalf of pharmaceutical research.)

3B. The best way to nurture an expensive new technology is through public funding and government regulation, so that potential dangers can be closely monitored, and the benefits of the new technology will become available to the largest possible number of people. (Here a good example is the Human Genome Project.)

4A. As Dorothy Nelkin pointed out, the media usually embrace a new technology enthusiastically and emphasize its promises and supposed advantages (Nelkin 1987). (Perhaps you can recall the initial accounts of cold fusion from 1988.)

4B. As Dorothy Nelkin pointed out, the media often denounce a new technology when it is seen to be imperfect, that is, when it fails to fulfill utopian expectations, even though the exact same media may have previously exaggerated its promises and supposed advantages (Nelkin 1987). (No doubt you can recall the later accounts of cold fusion.)

Notice that there is some truth in every one of these statements, but each of them can also be negated by another which is equally truthful. Furthermore, they tend to be extremely general. It is hard to say with much confidence that the case of nanotechnology will faithfully conform to any of these lessons. I surmise that these statements are not reliable general insights in a nomothetic style. On the contrary, they are platitudes: somewhat true, but too imprecise to specify the likely forms of public reactions to nanotechnology.

Like the Trobriand Islanders, we lack a consistent and reliable "logic of events", as Malinowski put it (1948, p. 113), for knowing the past for the purpose of coming to terms with the present. Instead, our visions of the past are somewhat arbitrary and unavoidably selective. A Trobriand myth-teller would find himself at home in our situation.

Then again, this is not unadulterated nihilism. Even though no case study from the past can be perfectly isomorphic with nanotechnology, a comparison can still have some real value if we confess *a priori* that it is somewhat arbitrary and selective, and then declare which features of nanotechnology we choose for selecting our comparisons.

4. Landscapes of Nanohyperbole

One feature seems to me to be especially salient to the question of public reactions to nanotechnology, namely, the climate of hyperbole which surrounds discussions of nanotech.

Vivid and exciting predictions begin with the Ur-text of nanotech, Richard Feynman's 1959 speech, 'There's Plenty of Room at the Bottom'. To cite but two examples, Feynman predicted an information technology in which "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" (Feynman 1992, p. 61); and, there could be a "mechanical surgeon" so small that it can be swallowed, after which it would maneuver through to body to the site of a lesion, and then repair the lesion (p. 64).

I emphasize that 'Plenty of Room' is cherished for its value to nanophilic hyperbole. This may well be different from its value for guiding scientific work, particularly if many scientists had independent inspirations for their research at the nano scale. Furthermore, Colin Milburn argues emphatically that Feynman's vision of tiny tools was derived from earlier works of science fiction:

> Nanotechnology is supposedly a real science *because* it was founded and authorized by the great Richard Feynman. But this origin is not an origin, and its displacement unravels the structure of its legacy. The Feynman myth would work only if it clearly had no precedents, if it was truly an

> 'original' event in intellectual history [...] Yet [...] science fiction writers had already beaten him there. [Milburn 2002, p. 283]

Whether we call it history or science or myth, or even stealing stories from fiction writers, my point is that Feynman's talk is the principal historical reference for nanophilic hyperbole.

If that was *nanoGenesis* – in the beginning Feynman said let there be nano, and there was nano – then *nanoDeuteronomy* was Feynman's 1983 speech, 'Infinitesimal Machinery'. This one was distinctly more lighthearted than 'Plenty of Room', and more precise concerning the process of arranging atoms into gadgets (Feynman 1993). As such, it did more than merely reiterate the original message. It confidently reinforced the author's vision of a world transformed by nanotechnology.

Walking in the footsteps of Feynman were the scientists who realized his vision with instruments and experiments. The *Acts of the NanoApostles* included Gerd Binnig's and Heinrich Rohrer's invention of the scanning tunneling microscope (Baro *et al.* 1984, Binnig & Rohrer 1985, 1986), and Eigler's and Schweizer's manipulation of xenon atoms to spell 'IBM' (Eigler & Schweitzer 1990).

If we stipulate that Feynman established the original outlines for nanohyperbole, and that people like Binnig, Rohrer, Eigler and Schweizer gave it credibility, then the current landscape of values and ideologies reveals several genres of thought about the value of nanotechnology. Four such genres are particularly important. The first is extreme nanophilic hyperbole, that is, an uncritical embrace of nanotech which looks ahead several decades to the arrival of nanotechnology's most amazing promises. In the words of *The Economist*, "the nano-enthusiasts [...] are recklessly setting impossibly high expectations for the economic benefits of nanotechnology" (*Economist* 2002). This genre needed an apostle like Paul to carry the good news to the gentiles, and so there arrived K. Eric Drexler, whose 1986 book, *Engines of Creation*, popularized the vivid and exciting possibilities of "the coming era of nanotechnology" as his subtitle put it (Drexler 1986). Subsequently he institutionalized his enthusiasm in the form of the Foresight Institute in Palo Alto, California. In his book and elsewhere, Drexler has emphasized one form of nanotech more than any other, namely, nano-size machines, commonly called nanobots. It is generally agreed that if these devices are to be realized, they must be preceded by some kind of machines which can reliably manufacture nanobots in very large quantities. Thus the controversy that surrounds Drexler's vision is centered not on the desirability of nanobots *per se*, but rather on the feasibility of the process of producing them.

Extremely nanophilic hyperbole includes excitement about nanobots and the assemblers that make them, as anticipated by Eric Drexler and his supporters, and it also comprises a pair of contradictory theories about the interface of technology with human anatomy. One is the expectation that medical nanotechnology will cure diseases and repair human anatomy so quickly and successfully that the normal human lifespan will be extended indefinitely. The other is the hope that all human consciousness can be uploaded into machines, thus making human anatomy unnecessary. So our bodies can stay healthy for enormous lengths of time; but our bodies are irrelevant to knowledge, thought, or spirituality. Extreme nanophilia is also represented in some works of science fiction, especially the novels of Kathleen Ann Goonan (*e.g.*, 1994, 1997, 2000).

The second family of positions on nanotechnology is a somewhat less fantastic form of optimism. As the Clinton administration gathered its various nanotech projects under the umbrella of the National Nanotechnology Initiative, it produced a series of documents that had a tone of childish enthusiasm. Invisible aircraft; computers millions of times faster than today's supercomputers; smokeless industry; and "nanoscale drugs or devices that might seek out and destroy malignant cells wherever they might be in the body": these were some of the expectations presented in the government's colorful booklet on nanotech (Amato 1999). In the detailed blueprint for the NNI, it was said that "developments in [... nanotechnology] are likely to change the way almost everything – from vaccines to computers to automobile tires to objects not yet imagined – is designed and made" (NSTC 2000, p. 13). That same document included President Bill Clinton in the team of cheerleaders. With a splash of Feynmanesque imagery, he said, "Imagine [...] shrinking all the information housed at the Library of Congress into a device the size of a sugar cube" (NSTC 2000, p. 13). The next major NNI text told us that "The effect of nanotechnology on the health, wealth, and standard of living for people in this century could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in the past century" (Roco & Bainbridge 2001, p. 2; see also Crandall 1996).

While this form of optimism has some affinities with the visionary nanophilia of Drexler and others, it is important to note the important distinctions. The U.S. government's optimism is much more concerned with immediate and near-future events, especially in materials science, medicine, information technology, and other areas in which commercial products can be delivered fairly soon. It distances itself from Drexler's agenda of nanobots and assemblers (Roco & Bainbridge 2001, p. 14), thereby insulating itself from accusations that it is merely indulging in preposterous fantasies at the taxpayer's expense.

My next category is that of measured skepticism. This genre comes from a group of science writers who recognize that important work is being done at the nanoscale, and that this work will generate profound consequences for science and society. But they also express disdain, almost contempt, for the hyperbole of extreme nanophilia. *Scientific American* is their principal venue, and the epitome of this kind of writing is Gary Stix's 1996 profile of Eric Drexler, wherein Drexler and his followers are comic eccentrics (Stix 1996). Stix's next article on nanotech was slightly kinder to Drexler, but still found ways to diminish him (Stix 2001). When *Scientific American* reported on carbon nanotubes (Minsky 2000) and molecular computing (Reed & Tour 2000), it found it necessary to suggest that stories of "microscopic robots rearranging atoms on command" might be "moonshine". "The hype", said John Rennie, "outruns the reality" (Rennie 2000). The September 2001 special issue on nanotechnology gave Drexler a chance to present his vision of nanobots (Drexler 2001), but the following article by Richard E. Smalley explained why nanobots were preposterous (Smalley 2001). And a facetious opinion piece in the same issue by Michael Shermer ridiculed the idea that "nanocryonics" will banish death (Shermer 2001).

The genre of measured skepticism is continued by other authors as well. Peter Vettiger and Gerd Binnig clearly aspire to create nanoscale computers, but they emphasize how difficult it will be do so (Vettiger & Binnig 2003). Adam Keiper writes a lucid introduction to nanotech which bifurcates all the talk of a 'nanotechnology revolution'. On the one hand there are solid advances, incrementally achieved by hard-working scientists, and on the other there are the vivid fantasies of Drexler and such (Keiper 2003). Military applications from nanotech will be remarkable, says Jürgen Altmann, but they involve so many risks that we need a series of preventive measures to prevent them from creating disasters (Altmann 2004).

I cannot prove that this position of measured skepticism resonates with the bench scientists who make nanotech real, but I have a strong instinct that they are much closer to this position than to extreme nanophilia. The enthusiasm and the funding of the NNI may please them very much, but they understand that their rewards and their careers are calibrated according to the tangible accomplishments they achieve, without reference to extraordinary predictions of great things in the distant future.

The fourth and final stance is an extreme nanophobic counter-hyperbole, approximately as intense as that of the visionary nanophiles. This last position follows the general outlines of the Frankenstein story to emphasize gloom-and-doom predictions that science is dangerous, that scientists are arrogant, and so on (see Feder 2002, Mills 2002). Its rhetorical style has several features: (1) considering that nanotech has yet to kill humans or devour the earth, its evils are projected into the future with the words *would*, *might*, *possible*, and *possibly* appearing regularly, in lieu of empirical experience of nanodangers; (2) scientists, usually unnamed, are routinely depicted as being both irresponsible and undemocratic; (3) the hypothetical horrors of nanotech are assumed to greatly exceed any possible benefits; (4) nanotech is guilty until proven innocent; and, (5) the proper response is a moratorium on research at the nanoscale.

Various combinations of these features are evident in recent articles by J. Smith and T. Wakeford (2003) and by L. Broadhead and S. Howard (2003), plus the comments by Prince Charles (Radford 2003). The most sustained commentary in this genre comes from the ETC Group of Winnipeg, Manitoba. Following several angry denunciations of the dangers of nanotech (ETC Group 2002; 2003a; 2003b), this organization called for a moratorium on commercial development of nanotech (ETC Group 2003c, 2003d, 2003e; see also Brown 2003), after which it published additional denunciations of nanotech (ETC Group 2003f, 2003g; see also Thomas 2003). The Greenpeace report on nanotech (Arnall 2003) relied very heavily on the ETC Group's position papers but, after briefly flirting with the idea of a moratorium, it recommended instead a balance of industrial self-restraint and government oversight (Arnall 2003, pp. 40-41). The Chemical Market Reporter expressed a sense of alarm in the business community that popular hostility to nanotech, regardless whether it had its basis in fact or in fiction, could poison the future of this kind of research (Lerner 2003).

The dark view of nanotech is also represented in a recent series of science fiction films, particularly *The Hulk*, *Agent Cody Banks*, *Jason X*, and *Cowboy BeBop*. A group of novels, the best known of which is Michael Crichton's *Prey* (Crichton 2002), present visions of a world radically altered for the worse by nanotechnology. (For recent commentaries on nano in science fiction, see Collins 2001, Hayles 2004, Miksanek 2001, Milburn 2002).

Another form of dramatic nanophobia comes from Bill Joy (2000, 2001) and Bill McKibben (2003). This subgenre indicates that nanotech is the centerpiece of a so-called convergence of technologies which will diminish human nature so much, in relation to high-performance machines, that our human qualities will become irrelevant: the end of humanity, so to speak.

In reviewing extreme nanophobia, I do not suggest that concern about this technology is categorically equivalent to paranoia. Vicki Colvin and others have instigated good questions about nanorisk (Rotman 2003, Tenner 2001), while Doug Brown, Barnaby J. Feder, and Candace Stuart have chronicled these discourses (Brown 2001, 2002a, 2002b, 2002c; Feder 2003a, 2003b; Stuart 2002, 2003a, 2003b). My point, rather, is that some of this concern, *e.g.*, that of the ETC Group, is so shrill that it polarizes discussions of nanotech between extreme nanophilic and extreme nanophobic hyperbole, and thereby erases the more nuanced ideologies in between. *The Economist* has noted that, unfortunately, common images of nanotech tend to arrange themselves into a bipolar division of love-nano-or-hate-nano positions (Economist 2002).

5. Malinowskian Conditions and Techno-hyperbole

If the public is going to be whipsawed between extreme forms of nanophilic and nanophobic hyperbole, we can look to past episodes of scientific or technological change which exhibited similar characteristics. I would like to present two such cases; one without Malinowskian conditions, and one with. This contrast helps us see how hyperbole intersects with such conditions.

My case of techno-hyperbole without Malinowskian conditions is the story of cold fusion from 1988. Initial reports and speculations described a technological solution to our energy problems that would deliver abundant power at miniscule cost using the simplicity of old-time technology. We would have all the energy we wanted by virtue of a plain gadget, a simple electrolytic cell, that anyone could manage. No longer would we need legions of engineers, oil-producers, bureaucrats, and policy-makers to make our electricity hum. Instead, we could do it ourselves with batteries, beakers, and liquids from the neighborhood hardware store, like a teen-age Thomas Edison. A quick fix, a cheap fix, and the simplicity of kitchen-table technology: cold fusion would be all this (Toumey 1996a, p. 98-111; Toumey 1996b).

Another story from the following day amplified that excitement by starkly contrasting old energy with new: 24 March was the date when the world learned about the Exxon Valdez oil spill. As NOVA put it, "most of the time when we think about such disasters, we're reduced to despair. But perhaps this time, from the deserts of Utah (where Stanley Pons taught at the University of Utah), somebody was offering a real answer" (NOVA 1989, p. 1).

Thus the press had a story with "drama, heroes, wizardry, and the promise of unlimited energy", said Marcel LaFollette (Heylin 1990, pp. 24-25). The heroes, the two cold-fusion scientists, were "ordinary persons who had made extraordinary accomplishments, by being different" (pp. 24-25). The promise they offered us was that "a single cubic foot of sea water could produce as much energy as ten tons of coal" (Pool 1989), which is to say that "the top few feet of water in the world's oceans contain enough [cold fusion] energy to supply the world for 30 million years" (Peat 1989).

A vivid bit of rhetorical flourish arose when Chase Peterson, President of the University of Utah, went to Washington to request $25 million for a fusion research center to develop Pons' and Fleischmann's work. One of Peterson's consultants, Ira C. Magaziner, contrasted our national character with that of the Japanese. He explained to the U.S. Congress, not very subtly, that,

> As I speak to you now, it is almost midnight in Japan. At this very moment, there are large teams of Japanese scientists in university laboratories trying to verify this new fusion science. Even more significantly, dozens of engineering company laboratories are now working on commercializing it [...] [Money for cold fusion] says that America is prepared to fight to win this time [...] I have come here to ask you, for the sake of my children and all of America's next generation, to have America do it right this time. [Crawford 1989, pp. 522-523; Huizenga 1992, pp. 50-51; Taubes 1993, p. 251]

The most succinct observation about this festival of hyperbole came from Moshe Gai, an Israeli physicist at Yale, who said, "I think cold fusion is the epitome of the American dream [...] It's the new world, it's a revolution overnight, getting rich overnight, and doing something against the understanding and against the consensus of what our scientific society is" (NOVA 1989, p. 8). Gai's insight came from a peculiar experience. He and his colleagues wanted to do a cold fusion experiment to falsify the Pons-Fleischmann hypothesis.

> And the reaction we got from the public was that [...] you scientists are [...] the only obstacle in the way of development of science. It's because of you that the dream of [...] cheap energy, will not come true. Like if we got rid of you scientists, we will have a good society [...] I was inundated by letters, telephone calls, people accusing me [of thwarting cold fusion]) [NOVA 1989, p. 7].

As Moshe Gai was a sharp voice for scientific skepticism, so Norman H. Bangerter spoke loud and clear for the opposite feeling. Said the Governor of Utah, "Knowing nothing about it, I am highly optimistic" (Taubes 1989, p. 115).

To my knowledge, there was no technophobic hostility to cold fusion. No one opposed it on the grounds that it was undesirable to produce energy through cheap and simple methods. Rather, the opposition stemmed from challenges to the veracity of the Pons-Fleischmann method for producing energy.

While hindsight shows that it was most unwise to embrace cold fusion uncritically, I emphasize here that these were not Malinowskian conditions. There were no great disparities of rank or power. The process of getting energy from cold fusion was believed to be so simple and so inexpensive that everyone would benefit in approximately equal proportion. And, when the Pons-Fleischmann hypothesis was discredited, it embarrassed some people and ruined the careers of a few, but it did not give any particular class of people great power over another class. Cold fusion was a fascinating story about science and technology, but it was no great rearrangement of our society or its economy.

6. The Case of Recombinant DNA

My other episode of techno-hyperbole is the recombinant DNA controversy of the 1970s. This case demonstrates a very different set of conditions which led to serious consequences in public reactions to a new technology.

Recombinant DNA initially earned considerable technophilic hyperbole. An article in *Scientific American* announced that "Research with recombinant DNA may provide major new social benefits of uncertain magnitude: more effective and cheaper pharmaceutical products; better understanding of the causes of cancer; more abundant food crops; even new approaches to the energy problem" (Grobstein 1977, p. 22). Jeremy Rifkin, the well-known critic of new technologies, wrote that "With the unlocking of the secrets of DNA, we will eventually be able to change the cellular structure of living beings and to create entirely new species. Biologists are already doing it with microorganisms. The Nuclear Age was the age of the physicist; the Organic Age is the age of the biologist" (Rifkin 1977).

Language like that, however, was not always wise. "The scientific facts of recombinant-DNA are complex and readily susceptible to exaggeration" (Budrys 1977, p. 19), thereby permitting a cascade of technophobic hyperbole to counter the optimistic sentiments. It was feared that "Old bugs might learn dangerous new tricks and might, if the escaped from a laboratory, demolish the intricate genetic balance that keeps all our chips in play" (Bennett & Gurin 1977, p. 44). Rifkin charged that "NIH's own maximum-security DNA-research facility" was a trailer with leaky roof and poor external security (Rifkin 1977). Jonathan King reminded others that at "the best microbiological containment facility ever build in the US, the Army Biological Warfare facility at Fort Detrick, Maryland [...] over a period of 20 years there were over 400 cases of lab workers getting serious infections from the organisms with which they worked" (King 1977, p. 635). New forms of life that might potentially be created in rDNA were called an "Armageddon virus" (Krimsky 1982, p. 309) and an "Andromeda-type virus" (Rifkin 1977). Rifkin warned that such an organism could "spread a deadly epidemic across the planet, killing hundreds of millions of people. They (*i.e.*, certain scientists) also fear that a new, highly resistant plant might be developed that could wipe out all other vegetation and animal life in its path" (Rifkin 1977).

Much of this feeling stemmed from the use of *E. coli* as the best platform for reproducing new genetic combinations. Units of DNA were extracted from viruses and other sources, and then implanted in *E. coli* because that bacterium multiplied itself very rapidly. In one particularly notable instance from 1971, a cancer researcher isolated viral DNA which was believed to be carcinogenic, and then recombined that genetic information with the genome of a strain of *E. coli* (Budrys 1977, p. 20). Many varieties of *E. coli* live within the human intestinal tract. And so there was a tangible concern that evil new forms of *E. coli* would move from genetic labs to humans' bodies (Grobstein 1977, p. 26; King 1977, p. 635; Nader 1986, p. 144). "The worst that could be imagined was a cancer plague spread by *E. coli*" (Bennett & Gurin 1977, p. 46).

When these various individual concerns were summarized in general statements about the dangers of rDNA, the language could be extraordinarily dramatic:

- "The recombinant technology circumvents all the normal barriers to exchange of genetic material between species" (King 1977, p. 635).
- Some people imagined "worldwide epidemics caused by newly created pathogens; the triggering of catastrophic ecological imbalances;

the power to dominate and control the human spirit" (Grobstein 1977, p. 22).

- "There is a class of technologies that can do great, perhaps irreversible harm. Recombinant DNA is a member of that class" (Nader 1986, p. 140).
- "Only one accident is needed to endanger the future of mankind"; "The potential dangers [of rDNA ...] pose perhaps the single greatest challenge to life that humankind has ever faced"; "science fiction's most horrible scenarios become fact" (Rifkin 1977).

Many of the warnings about rDNA came from experienced biologists who knew the research very well, and who described both the benefits and the risks of this work. But laypersons' fears of risk tended to be more intense than those of the scientists. Nonscientists were apparently more influenced by critics of rDNA research than by its advocates, with the result that they focused more on the hazards than the benefits (Krimsky 1982, p. 310). It was often noted that the original guidelines for minimizing risk, composed at the Asilomar conference of 1975, were composed by scientists deeply committed to rDNA work, with no participation or voice for external critics from public health, lab workers, or environmentalists (Grobstein 1977, p. 31; King 1977, p. 634; Nader 1982, p. 148). This enabled Rifkin to frame the rDNA debate as "a question of the public interest groups versus the scientists" (Budrys 1977, p. 21), and to capitalize on situations in which local officials in various cities and states were unaware of "secret research into recombinant DNA going on in laboratories in their communities" (Rifkin 1977). When it became known that some scientists had urged a moratorium on some forms of rDNA work in 1974, the popular interpretation of that was "if scientists were banning some research, they [the public] reasoned, then all of it must be extremely dangerous" (Bennett & Gurin 1977, p. 49).

Maxine Singer objected that "Statements implying that uncontrollable epidemic or environmental disaster is a certainty are as misleading and useless as statements implying that no possible hazard can come from the experiments" (Singer 1977, p. 632). Despite her judgment, public fears led to unpleasantness for working scientists. At Stanford Medical Center, Paul Berg had to terminate his experiment for inserting carcinogenic viral DNA into *E. coli* (Budrys 1977, p. 20). From that event came a brief moratorium on some kinds of rDNA experiments (Grobstein 1977, p. 22), followed by the Asilomar Conference of February 1975 which ranked rDNA experiments according to their potential dangers. The Asilomar document then became the basis for the NIH *Guidelines for Research on Recombinant DNA* (King 1977, p. 634; Singer 1977, p. 631).

This did not satisfy all laypersons. In Cambridge, Massachusetts, a City Councilwoman was distressed to learn that Harvard was building a P3 lab for rDNA. (P3 describes moderately risky experiments, and MIT was already running a P3 lab.) There had long been a "fragile relation" between the universities and the locals, which played out in real estate values, tax bases, and other acrimonious disagreements (Krimsky 1982, p. 298-99). The mayor of Cambridge initiated a series of hearings and investigations which emphasized the arrogance of the Harvard scientists in their dealing with the working-class residents of Cambridge. "Who the hell do the scientists think they are", asked Mayor Alfred Vellucci in June 1976, "that they can take federal tax dollars that are coming out of our tax returns and do research work that we then cannot come in and question?" (Nader 1982, p. 145). When he framed the issue this way, "the self-governance of science was concretely and symbolically threatened" (Krimsky 1982, p. 300).

During a long process of ritually humiliating the Harvard scientists, the Cambridge City Council temporarily banned "all recombinant research within the city limits" (Budrys 1977. p. 21). Later it eased that ban, and permitted rDNA work with certain specific safeguards.

By 1981, there were similar laws regulating rDNA research six cities across three states (Nader 1982, p. 151), while additional local regulations were considered in a total of nine cities in seven states (Krimsky 1982, p. 294).

You might think that finally the scientists and their universities would have clearly understood the public's concerns, but Harvard soon found one more way to embarrass itself. NIH's Guidelines for rDNA research included a procedure for NIH to certify the safety of biological vectors ('plasmids', *e.g.*, viruses) before an rDNA experiment could employ them. Charles A. Thomas, who had been on the NIH committee that composed the rDNA guidelines (and thus ought to have known better), had proceeded with not-yet-certified plasmids in his recombinant efforts to produce insulin at Harvard Medical School. He was required to terminate his experiments, and his research team was very publicly embarrassed (Wade 1977, p. 1978).

7. Lessons from the Case of rDNA

When various elements of the public make sense of nanotechnology in their own terms, will that process include the telling of lurid horror stories about evil scientists and their dangerous technology? Will public reactions to nanotechnology be as unpleasant as some of the reactions to rDNA? I suggest that the story of recombinant DNA will be relevant to nanotechnology when the following three conditions are present:

(1) *Techno-hyperbole backfire*: When some people praise nanotechnology in words and images of unrestrained nanophilic hyperbole, it would be wise to remember one of the ironic lessons from the experience of rDNA: techno*philic* hyperbole inspires the opposite reaction too, namely, techno*phobic* hyperbole. The positive predictions for rDNA frightened many people by telling them that a small group of elite experts unknown to the public would control an extraordinarily powerful method for manipulating life. This is exactly what nanotechnology might sound like too.

(2) *Malinowskian conditions*: nanotechnology, like rDNA, is likely to affect different people in different ways, and particularly to exacerbate differences of power or wealth. Some people will control the research and development, while large numbers of other people will feel that they are powerless. Similarly, nanotechnology may create profound historical changes, and it might cause people to feel that they cannot understand the existential situations in which they find themselves. And so, all three kinds of Malinowskian conditions might arise. In any of those circumstances, the stories people tell about nanotechnology will bear a burden of helping people come to terms with anomaly, conflict, inequality, and change. These pressures are not likely to engender a dispassionate appreciation of nanotechnology.

(3) *Disdain for public health and safety*: if those who make nanotechnology real are as arrogant and inconsiderate as some of the people

who brought us rDNA, then we can expect nanotechnology to be humanized as a stirring drama of virtuous laypersons versus dangerous scientists. This is especially true if the makers of nanotechnology ignore its risks to the public, or if they know those risks but underestimate them, or if they know those risks but dissemble when they ought to be candid about risks.

If all three conditions come together, I anticipate that many public reactions to nanotechnology will be at least as ugly as the initial public reaction to rDNA in Cambridge, Massachusetts. The first, techno-hyperbole backlash, is well under way. There is a large body of writing and speech which says repeatedly that nanotechnology is extremely exciting because it has great potential to rearrange our material world. I do not challenge such predictions, but I note that these visions, and the ways they are presented, can scare some people to the same degree that they thrill others. Indeed, the most frightening speculations about nanotech are the bread-and-butter of the ETC Group's rhetoric.

Next, nanotechnology is custom made for Malinowskian conditions. It is likely to create profound historical changes. And, even if it benefits everyone to some degree because of the consumer products it generates, its political economy of patents, copyrights and venture capital will give us a situation in which a limited number of people control those profound historical changes.

The third condition is yet undetermined. There has been too little public awareness of nanotechnology and its risks to craft a believable narrative of virtuous laypersons versus dangerous scientists. There have been a few extremely general warnings about the evils of nanotechnology, but no specific episodes of the makers of nanotechnology creating terrible risks to the public and then ignoring or concealing those risks, whether medical or environmental or otherwise.

Given that the first two conditions are here now, and have a momentum which is unlikely to be reversed, but that the third condition is not yet established, I suggest that the task of anticipating public reactions to nanotechnology should be focused on the last element: what risks will scientists and engineers create? How will they assume responsibility for those risks? How will they mitigate those risks? Will they candidly describe those risks and their own responsibilities for generating them? How will the public assess these risks and the experts who create them?

A little bit of recklessness or disdain will be easily magnified and transmuted into a compelling story about amoral scientists arrogantly producing terribly dangerous threats to our health and our environment. Perhaps the relevant scientific knowledge will be distorted, ignored, exaggerated, or manipulated, thereby leaving scientists feeling exasperated and powerless. Perhaps that is very unfair. But the important lesson is that hyperbole and Malinowskian conditions have already intensified the values, hopes and fears that will be shaped into public reactions to nanotechnology in the near future. It would not take much disdain for public health and safety to complete a combination of circumstances that would cause much of the public to fear nanotechnology and hate it. And then the stories that people tell about nanotechnology will take the form of myth-telling in a Malinowskian style. These dramatic narratives of existential good and evil will be most unkind to nanotech and those who create it.

8. Discussion: Cultural Dynamics of Public Reactions to a New Technology

When we see that a public controversy is an interaction between a given science and a given set of cultural values, as in the cases of cold fusion, rDNA, and probably nanotechnology, what will be the balance between the science and the cultural values? Will the quality of the science be so good and so obvious that most values, hopes, and fears will be neutralized? Or do the pre-existing values set the terms of the debate, so that they neutralize the scientific content?

In an ideal world, scientists would communicate scientific knowledge clearly and effectively to laypersons, who would then understand the knowledge and use it to make sound judgments about science policy. After Hiroshima and Nagasaki, scientists made a great effort to explain the atom to the public, thereby preparing the public to accept nuclear plants to generate electricity. During the 1950s and '60s, NASA and the media presented the basics of space science in a friendly way which enabled millions to understand it, at least at a rudimentary level. Currently the Human Genome Project devotes at least 3% of its budget to ethical, legal, and social issues, including public understanding. In these three examples, scientists and science teachers have aspired to an ideal model of communication and understanding.

In many other cases, however, the world is far from ideal. Charles Rosenberg (1966) and others have argued that science in general carries enormous secular authority, but that people often turn to science to reinforce pre-existing values and ideologies. Scientific authority is selectively appreciated and interpreted, depending on those pre-existing extra-scientific values. The sociologist Simon Locke notes that public understandings of science are not typically anchored in science as understood by scientists. On the contrary, public understanding in a scientific controversy is largely shaped by the rhetorical strategies of the competing parties, says Locke, with the result that pseudoscientific positions look much the same as scientific conclusions (Locke 1994, 1999). In my own work, I have built upon Rosenberg's insights to identify cultural values that influence public understandings of science in the U.S. and the mechanisms by which those values displace scientific knowledge (Toumey 1996a, 1996b, 1997).

As the American public comes to terms with nanotechnology, I note that: (1) general scientific literacy in this country is very poor; (2) scientific literacy for nanotechnology is practically nonexistent; and (3) certain cultural values, including strong hopes and deep fears, are likely to shape public understanding of nanotechnology. To paraphrase Rosenberg, nanotechnology will be appreciated or feared, not because of its scientific merits, but because of pre-existing extra-scientific values. Nanophilic hopes and nanophobic fears will not wait until after scientific work is completed, assessed, and disseminated. The tangible results of nanotech will be selectively appreciated and interpreted in accordance with those hopes and fears.

It is likely that public attitudes about nanotechnology, whether positive, negative, or mixed, will become more intense, more coherent, and more prominent in the very near future, as nanotechnology's tangible implications become apparent to the public. Perhaps this would not matter much if the scientific research and its applications were entirely independent of social forces, cultural values, and political decisions. But in a democratic society like ours, nonexperts have a voice in the research agenda, even if their voices affect the research indirectly. Our political system offers numerous ways for nonscientists to influence science policy, for better or for worse, and when they do they will incorporate their own cultural values into our nanotechnology policy.

9. Conclusions

Representations in the form of narratives are a way of arranging people and values into a moral order: we make sense of a new reality by putting it into stories set in the past. Those stories then enable us to say that one hero is better than another; or that one thing is the most important thing, and other things are less important; or that some features are good, while others features are evil; and so on.

Narrative representations compete with one another for credibility and historical authenticity. Different people will tell different stories about the past, depending on which features they selectively choose as the essential lessons that must be taught. For nanotechnology, the scientists and engineers who work at the heart of this research will contribute valuable stories, and perhaps will dispute each other's stories, while equally powerful narratives will come from other citizen participants who have other values to emphasize and other lessons to teach.

That nanotechnology is a blessing or a curse; that scientists can be trusted or should be feared; that all will enjoy its benefits, or that a few will control its powers: these kinds of pre-existing feelings about science will be at least as influential as the scientific merits of the research in shaping public reactions to nanotechnology. The same was true in the earlier cases of fluoridation, cold fusion, creationism-versus-evolution, embryonic stem cell research, and many more forms of science and technology.

Nanotechnology is important enough to have its own collection of histories, tales, legends, myths and anecdotes, but it is also new enough that it has to borrow information from comparisons and analogies until its own record of public reactions is established. As we anticipate those public reactions, let us recognize how they will be shaped by values and lessons that arise repeatedly in democratic societies, particularly if nanotechnology delivers Malinowskian conditions like inequalities of power and profound historical changes.

Acknowledgments

I am most grateful for comments and insights from Davis Baird, Otávio Bueno, Conny Chen, Arne Hessenbruch, George Khushf, Ashley Shew, and two anonymous reviewers. They helped me improve this chapter. I am, of course, entirely responsible for its contents.

The material in this chapter is based upon work supported by a grant from the National Science Foundation, NSF 01-157, Nanotechnology Interdisciplinary Research Team [NIRT], Philosophical and Social Dimensions of Nanoscale Research: 'From Laboratory to Society: Developing an Informed Approach to Nanoscale Science and Technology'. All opinions expressed within are the author's and do not necessarily reflect those of the National Science Foundation.

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CHAPTER 18

'SOCIETAL AND ETHICAL IMPLICATIONS OF NANOTECHNOLOGY': MEANINGS, INTEREST GROUPS, AND SOCIAL DYNAMICS

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This chapter first analyzes the different meanings of and interests in 'societal and ethical implications of nanotechnology' by such diverse groups as science fiction authors, scientists and engineers, policy makers and science managers, business people, transhumanists, the media, and cultural and social scientists. Based on the mutual semantic impact among these groups, I characterize the current state and dynamics of the debate on 'societal and ethical implications of nanotechnology' by identifying the mediators, semantic leaders, and alliances in the debate. It turns out that the debate is dominated by a visionary alliance (consisting of science fiction authors, visionary engineers, transhumanists, and business people) which is rather robust against semantic impact from other groups. I conclude from this analysis and from the cultural history of science that the most likely impact of nanotechnology on society in the near future is a public anti-scientific backlash.

1. Introduction

Along with the first visionary ideas of nanotechnology, ideas about its possible cultural and social impacts were articulated (Drexler 1986). When the U.S. National Nanotechnology Initiative (NNI) was launched in 2000, the program included from the very beginning funding for 'societal and ethical implications of nanotechnology'. Engineers and policy makers seem to have learned from the past, notably from the consumer disaster with genetically modified organism and from debates about the

Human Genome Project, that ethical and sociological reflection should accompany and not follow technological research and development. And thus they invite the cultural and social sciences to help analyze and mediate possible conflicts. That appears to be a great opportunity for cultural and social scientists to engage in partnership models with scientists and engineers such that both groups can immensely benefit from each other, for the overall benefit of the society, provided that both groups learn from each other and respect their different perspectives, goals, and problem approaches.

At the present state, however, cultural and social scientists seeking to partner with scientists and engineers to work on 'societal and ethical implications of nanotechnology' are faced with two problems that are caused by nanotechnology's immaturity. Nanotechnology's immaturity has a conceptual and a social aspect that are both relevant here. Conceptually, the lack of meaningful definitions of nanotechnology has led to the current situation that in almost all the science and engineering disciplines researchers relabel their cutting-edge work 'nano', without having much new in common and without showing any remarkable degree of interdisciplinarity (Schummer 2004a/b). In such a situation of hype, cultural and social scientists may have difficulties to decide what research projects should really count as 'nano', such that their choices might depend rather on mass media coverage and visionary promises than on the particularities of the actual research project. The prevailing articulation of nanotechnology in visionary terms is the social aspect of nanotechnology's immaturity, which brings about the second, more important problem.

Nanotechnology is not only primarily articulated in visionary terms, these visions also appear to be visions about 'societal and ethical implications' of nanotechnology. Apart from scientists and engineers, policy makers, science managers, business people, journalists, transhumanists, and science fiction authors all talk about 'societal and ethical implications' of nanotechnology. They all seem to have already strong opinions about what the 'societal and ethical implications' of nanotechnology will be, that it will radically change society, bring about a new industrial revolution, can enable anything from immortality and paradise on earth to the extinction of the human race. How could cultural and social scientists, who have no expertise in fortune telling and are, instead, bound to their scholarly standards, contribute to a debate that is dominated by such bizarre visions? How could their academic reflections compete with ideas about the 'societal and ethical implications' of nanotechnology that are meant to stir the innermost hopes and fears of people? It seems that, because of nanotechnology's immaturity, it is either too early or too late for cultural and social scientists to become engaged in the debate.

However, the debate as such is currently the strongest, if not the only, impact nanotechnology has on society and culture – perhaps the strongest it will ever have? Furthermore, current ideas of nanotechnology, including hopes and fears articulated in visions about 'societal and ethical implications', have an impact on decisions on the current and future directions of nanoscale research and development, such that the dynamics of the debate determines the future shape of nanotechnology, including its future 'societal and ethical implications'. This opens up an important opportunity for cultural and social scientists without joining the visionary debate. By studying the debate on 'societal and ethical implications' of nanotechnology with their own methods, they can make important contributions to the understanding of factors that impact the current and future 'societal and ethical implications' of nanotechnology. Whether such an understanding of the debate will have and impact on the debate is yet to be seen though.

My first contribution in this chapter is an analysis of the various meanings of 'societal and ethical implications', with focus on the U.S. (Section 2). We will see that the major groups engaged in the debate have quite different meanings. Since these groups have more or less strong interests in nanotechnology that determine their meanings, I point out these interests as well. To complement the bird's eye view, I also include my own group, that of cultural and social scientists, their specific interests, and their sophisticated meanings. Understanding the different meanings may help avoid misunderstandings, such as when, for instance, politicians ask cultural and social scientists to study 'societal and ethical implications'. Following up the semantic analysis, I describe the mutual impacts of these meanings among the interest groups of the debate, *i.e.* how one group influences the meaning of 'societal and ethical implications' of the other (Section 3). The results are used to identify the semantic mediators and the semantic leaders, *i.e.* the groups whose meanings dominate the debate, and the formation of semantic alliances. From that I finally draw some more speculative conclusions on some of the likely 'societal and ethical implications' of nanotechnology in the near future (Section 4).

2. Interest Groups and their Meanings of 'Societal and Ethical Implications of Nanotechnology'

2.1 Science Fiction Authors

Science fiction writers are the most professional group engaged in writing visions on the impacts of technology on culture and society, and many are used to making a living out of that.

Within the genre of science fiction, nano-science fiction is certainly one of the most flourishing fields nowadays. An online bibliography on Nanotechnology in Science Fiction lists 189 books, novels, and anthologies, published between the mid-1980s and November 2003 in the English language only (Napier 2004). Milburn has identified many nano-science fiction stories in the 1940s and 1950s and argues that these stories already inspired Richard Feynman's 1959 visionary speech 'There's plenty of room at the bottom', which later became the posthumous founding myth of nanotechnology (Milburn 2002). Invisibly small devices or the manipulation of the 'ultimate building blocks of nature' have been a favorite topic ever since the genre of science fiction emerged and appear throughout the works of Jules Verne and H.G. Wells. In addition, 'manipulating-nature' was the pivotal theme in all the 19^{th}-century 'mad scientist' stories, which in turn go back to medieval and early modern satires of alchemy (Schummer 2006). Thus, the vagueness of nanotechnology definitions is passed on to the vagueness of what is nano-science fiction.

Unlike the name suggests, today's science fiction stories are hardly about fictional science and rarely about research and development of fictional technologies, but mainly about the use of fictional technologies in social contexts. As any other stories, they focus on characters, their thoughts, emotions, and transformations, and their interactions and social contexts, which are more or less radically modified by fictional technologies (Landon 1997). And unlike the visionary engineers who made nanotechnology prominent by making epistemic claims about a likely future, science fiction authors explicitly declare that their works are invented narratives, such that both text types are linguistically well distinguishable and still have quite separated readerships, despite border-crossing authors who increasingly blur the boundary (Schummer 2004c).

Although the primary goal of science fiction is entertainment, the genre is frequently divided up according to different moral messages expressed by optimistic or pessimistic prospects of technology for society. A utopian branch, frequently related to Jules Verne, would celebrate the positive prospects of technology for society and a distopian branch, frequently related to H.G. Wells, would warn of the negative prospects of technology for society. While the distinction between Verne and Wells is certainly more complex, it is true that there were very optimistic science fiction stories, particularly in the early 20th century in the U.S. (Hirsch 1957-58), and that there is a distopian tradition (*e.g.* Orwell's *1984*) and a tradition of horror stories, which goes back to the 19th-century 'mad scientist' stories. However, there are also traditions of mystery, fantasy, detective, and crime thrillers that overlap with science fiction and do not fit the dichotomy.

Many of the stories that are today called nano-science fiction, including for instance Neal Stephenson's *The Diamond Age* (1995), also run under the insider labels of 'Cyberpunk' and 'Postcyberpunk', depending on whether they focus on a radically computerized society or additionally employ fictional biotechnology.[1] The nihilistic undertone and the focus on human alienation might qualify them as distopia, but this is frequently balanced by a fascination for the visionary techno-world. As Brooks Landon (2004) has argued, even if the fictional nanotechnologies threaten the current condition of humanity, the stories frequently provide prospects of transcendence "in the numinous form of Bear's noosphere and Di Filippo's URB or in the form of enhanced and expanded consciousness found in nanotechnology narratives by Goonan, McCarthy, McDon-

[1] See http://en.wikipedia.org/wiki/Cyberpunk and http://en.wikipedia.org/wiki/Postcyberpunk (29 June 2004).

ald, and Reynolds". Instead of conveying a simple moral message, it is rather up to readers to make their own positive or negative judgment on the fictional technology's impacts on society. While many readers might feel uncomfortable with such visions, Cyberpunk has, as a matter of fact, inspired many, if not all, visions of transhumanist utopia.

Few nano-science fiction stories directly prompt moral questions about technology. An example is Michael Flynn's *Nanotech Chronicles* (1991). However, Flynn (particularly in 'The Washer at the Ford'), draws his readers into a network of different moral positions and arguments, illuminates various positive and negative impacts of fictional bionanotechnology on society, such that readers learn more about the complexity of moral issues and dilemmas, rather than receiving simple answers or moral messages (Berne & Schummer 2005). There are exceptional cases, however, like Michael Crichton's *Prey* (2002) that employs Drexler's grey goo fiction. In the tradition of 19th-century mad scientist horror stories, Crichton retells the old fable of scientists (here, software engineers) who loose control over their work to the extent that they are threatened and finally controlled by their own creations.

For the majority of nano-science fiction authors, 'societal and ethical implications of nanotechnology' is an experimental field of composing social contexts with visionary technologies (mostly computer technology) that more or less radically change humans and society, from using new tools to achieving a state of transcendence. Apart from making a living and from entertaining readers, their major interest seems to be to make readers think about general social and moral issues, about the place of technology in society, and about radical change, without providing simple answers or moral messages. Many have taken visionary ideas from Eric Drexler and many have in turn inspired transhumanism.

2.2 Scientists

Research without 'societal implication' is equivalent to the much denounced research in the 'ivory tower' for which funding has drastically been cut. Since the costs of scientific research have tremendously increased during the past 50 years, due to the growing standards of instrumentation required at almost all the research frontiers, the emphasis on 'societal implications' is vital for any research project to be funded. It serves as justification to funding institutions and the public and is frequently taken as a measure of quality and importance. Because for any scientific research 'societal implications' can only be in the future, the talk of 'societal implications' of present research is necessarily of prognostic or visionary character, a promise that nobody can guarantee. Natural scientists, who by their science education have no particular expertise in societal matters, are faced with the tricky rhetorical challenge to make promises that are taken as justification and quality measure of their research, without running the risk of disappointing or being accused of fraud. As a rule, they reduce the notion of 'societal implication' to possible technological application of their research.

Before dealing with experimental scientists and engineers in detail, it is necessary to introduce a separate group that has provided a visionary framework and a challenge to experimental scientists. Indeed, software engineers have taken a lead in developing visions of 'societal implications' of nanotechnology. Since Eric Drexler published his vision of nanotechnology in 1986, nanotechnology was framed with, if not formulated in terms of, grand engineering visions of radically changing the society by 'revolutionizing' almost all the existing technologies. The visionary climate was particularly fueled by computer scientists and software engineers, like Ralph Merkle, Ray Kurzweil, Hans Moravec, and Marvin Minsky,[2] who attached to nanotechnology further transhumanist ideas and a framework of computational visions to be materialized by natural scientists and electrical and mechanical engineers. This has led to the strange situation that the current market of popular books on nanotechnology is dominated by such visionary narratives frequently authored by software engineers.[3] Writing for a general lay audience, these soft-

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[2] Minsky, Merkle, Kurzweil, and Moravec are all directly or indirectly involved in transhumanism. Minsky serves on the Board of the Extropy institute (www.extropy.org); Merkle is director of Alcor (www.alcor.org), a transhumanist organization specialized in cryonics; Kurzweil's book *The Age of Spiritual Machines: When Computers Exceed Human Intelligence* (1999) is one of the leading visions for transhumanists; and Moravec wrote the first issue of the *Journal of Transhumanism* (Vol. 1, 1998), later called *Journal of Evolution and Technology*.

[3] For a detailed analysis of current popular books on nanotechnology and the public interest in these books, see Schummer 2005.

ware engineers were not under pressure by any scientific community to substantiate their visions by scientific evidence, particularly since they wrote about subject matters beyond their own profession. As we will see in the *Policy Makers and Science Managers*, however, many of the visions were taken over by science managers and policy makers when they decided to fund nanotechnology on a large scale.

Experimental scientists and engineers are ambivalent about the visionary climate that has thus evolved. On the one hand, they feel uncomfortable with the far-reaching promises, which are not based on scientific evidence, and the resulting far-reaching expectations, which they are almost sure they cannot meet. On the other, it provides a welcome background for pointing to the required societal implication of their individual research and for promoting their specific ideas of what nanotechnology is.

Although most chemists were ignorant about nanotechnology still in the 1990s,[4] chemistry has quickly emerged as the dominating nanoscience in the U.S. by 2003 (Schummer 2004a). Despite the diversity of chemical ideas of nanotechnology (including, among others, research on nanoparticles, fullerenes, proteins, polymers, supramolecular systems, and molecular electronics), they are strictly opposed to and openly distance themselves from the ideas of nanotechnology by Drexler and his followers.[5] Nonetheless, chemists, each for their own particular research project, employ direct or indirect references to Drexler's visionary framework, though in a more modest and careful form.

For instance, George M. Whitesides (2001), a chemist who works on biomimetic chemical systems, rejects Drexler's approach while relating Drexler's broader vision to his own approach:

> Fabrication based on the assembler [*i.e.* Drexler's approach, J.S.] is not, in my opinion, a workable strategy and thus not a concern. For the foreseeable future, we have nothing to fear from grey goo. If robust self-replicating micro (or perhaps nano) structures were ultimately to emerge,

[4] For instance, an anthology on the 'Challenges and Visions' of chemistry in the 21st century published by the American Chemical Society in 1998 did not yet include a mentioning of nanotechnology (Barkan 1998).

[5] See, for instance, the Drexler-Smalley debate in *Chemical & Engineering News*, 81, No. 48 (December 1, 2003), 37-42.

> they would probably be chemical systems as complex as primitive bacteria. Any such system would be both an incredible accomplishment and a cause for careful assessment.

Two pioneers in molecular electronics, Mark A. Reed and James M. Tour (2000), pose the question:

> Will it be possible someday to create artificial 'brains' that have intellectual capabilities comparable – or even superior – to those of human beings?

which they answer in a review of their *own* research as follows:

> [...] scientists have achieved revolutionary advances that may very well radically change the future of computing. And although the road from here to intelligent machines is still rather long and might turn out to have unbridgeable gaps, the fact that there is a potential path at all is something of a triumph. The recent advances were in molecular-scale electronics [...] By pushing Moore's Law past the limits of the tremendously powerful technology we already have, these researchers will take electronics into vast, uncharted terrain. If we can get to that region, we will almost certainly find some wondrous things – maybe even the circuitry that will give rise to our intellectual successor.

Richard Smalley (1995), in the introductory part of a public speech about his very specific work on the use of carbon nanotubes for energy storage, claims:

> The list of things you could do with such a technology [nanotechnology] reads like much of the Christmas Wish List of our civilization.

The big visions circulating around the vague ideas of nanotechnology allow presenting to the public every highly specialized research project as being part, if not the central part, of one big 'revolution'. Due to the division of labor between scientists and the public relation departments of their institutions, the message can be disseminated without running the risk of undermining professional credibility. Universities in the U.S. appear to be in a competition of who is leading the 'revolution', as the following three headline examples from different media illustrate:[6]

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[6] Note that the term 'nanotechnology revolution' goes back to a book co-authored by Drexler (Drexler, Peterson & Pergamit 1991) before it was adopted in 2000 in the motto of the National Nanotechnology Initiative 'Supporting the Next Industrial Revolution'.

> Harvard looking to lead nanotechnology revolution.[7]
>
> Houston is playing leadership role in nanotechnology revolution.[8]
>
> The Physical Sciences in the UCLA College are taking a leading role in the new revolution at the nanoscale.[9]

Of course, the term 'revolution' here does not refer to a conceptual or theoretical revolution in the meaning of Thomas Kuhn. Instead, it means 'industrial revolution', which seems to be the biggest societal implication that today's nanoscientists can think of. Since, for scientists, 'societal implications' almost exclusively means technological applications, relating their research to 'industrial revolution' is the ultimate research justification and the ultimate measure of quality.

Finally, there is a small, though growing, group of natural scientist for which 'societal implications' of nanotechnology has, through their professional perspective, a different meaning. Environmental scientists and toxicologists are beginning to investigate the potential harm of nanoparticles to the health of human and other living beings and their impact on ecological systems.

In sum, among the group of scientists and engineers there are three different groups with different kinds of meanings of 'societal implications'. Software engineers associate it with grand visions of radical changes of society in which everything becomes possible by software control. The experimental scientists and engineers who are actually engaged in nanoscale research refer to such visions in more modest and indirect form, from technological application to industrial revolutions, to legitimize their own specific research projects and to promote their particular notions of nanotechnology. For toxicologists and environmental scientists it rather means risks to health and environment, the topics of their own research.

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[7] *Post Harvard: An Online Community for Hayward Alumni* (News from 19 May 2004) [https://www.aad.harvard.edu/devel/html/news_nanotechnology.html].

[8] *Houston Business Journal* (19 January 2004) [www.bizjournals.com/houston/stories/2004/01/19/focus2.html].

[9] *UCLA College Report*: 'It's a Small, Small World', Vol. 2, Spring/Summer 2004 [www.cnsi.ucla.edu/small_world.pdf].

2.3 Policy Makers and Science Managers

Once they decide to support nanotechnology research on a large scale, policy makers and science managers are in need to justify the funding to voters and other people they have to respond to. One way to do so is by making visionary promises about the revolutionary power of nanotechnology, how it will change the whole of society to the better. However, opening the visionary power box, in order to convince the skeptics, may also frighten others who are afraid of too much technological power or who oppose the suggested changes. Thus, the political talk of 'societal implications' needs to be well balanced.

In the U.S., President Clinton was the first to make nanotechnology a political matter of high priority in 2000, so that the first political statement to the broader public was the White House press release (White House 2000) that announced the National Nanotechnological Initiative (NNI).[10] It was entitled 'Leading to the Next Industrial Revolution', which the NNI later modified to its motto 'Supporting the Next Industrial Revolution'. Here we learn that nanotechnology is "likely to change the way almost everything – from vaccines to computers to automobile tires to objects not yet imagined – is designed and made."[11] NNI's foundational report, issued six months later, had an even bigger vision (NSTC 2000):

> The effect 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 this century.

The original press release also included the first public mentioning of societal and ethical implications of nanotechnology, which still puzzles interpreters today:

> Ethical, Legal, Societal Implications and Workforce Education and Training efforts will be undertaken to promote a new generation of

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[10] For a more detailed analysis of the political development, see Fogelberg & Glimell 2003, pp. 40-44, and Glimell 2004.

[11] The sentence was actually taken from a brochure issued shortly before by the National Science and Technology Council (NSTC 1999) which spelled out the vision in more detail, reminding of Eric Drexler's earlier vision.

> skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The impact nanotechnology has on society from legal, ethical, social, economic, and workforce preparation perspectives will be studied. The research will help us identify potential problems and teach us how to intervene efficiently in the future on measures that may need to be taken.

The text suggests that "societal and ethical implications efforts" is, like "Workforce Education and Training efforts", something that can be "undertaken" to "promote a new generation of skilled workers" because it can "identify potential problems and teach us how to intervene efficiently"; that it also includes the economic perspective; and that it *must* contribute to "rapid progress in nanotechnology". "Societal and ethical implications" efforts are somehow associated with education and economics and put under the imperative of progress.

Nearly four years later, when President Bush signed the 21st Century Nanotechnology Research and Development Act in December 2003, the corresponding White House press release has lost much of the grand vision tone and sounds rather like a list of various specific research projects (White House 2003):

> Nanotechnology offers the promise of breakthroughs that will revolutionize the way we detect and treat disease, monitor and protect the environment, produce and store energy, and build complex structures as small as an electronic circuit or as large as an airplane. Nanotechnology is expected to have a broad and fundamental impact on many sectors of the economy, leading to new products, new businesses, new jobs, and even new industries.

The visionary power box has largely been reduced to economic promises.[12] It would seem that politicians have returned to a balanced and pragmatist point of view that avoids stirring up fears among the American people. Interestingly, there is no more mentioning of 'societal and

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[12] In the NSF report on *Societal Implications of Nanoscience and Nanotechnology* from 2001 (Roco & Bainbridge 2001), 'societal implications' further includes the impact on industrial manufacturing, national economy, medicine, environment, space exploration, national security, and 'American leadership', as well as the needs for moving nanotechnology to the market, interdisciplinary education, and workforce preparation for future nanotechnology business.

ethical implications', although that has become a central part of the Bill,[13] so that it is worth analyzing its meaning there in some detail.

The Bill, as a novelty in the U.S. history, requires the establishment of an American Nanotechnology Preparedness Center (Sec. 9), which shall

> (1) conduct, coordinate, collect, and disseminate studies on the societal, ethical, environmental, educational, legal, and workforce implications of nanotechnology; and
> (2) identify anticipated issues related to the responsible research, development, and application of nanotechnology, as well as provide recommendations for preventing or addressing such issues.

In this unsystematic collection of 'implications' it remains quite obscure what 'societal implications' means. Some clarification is provided when the legislators require from the general National Nanotechnology Program (Sec. 2) to consider:

> ethical, legal, environmental, *and other* appropriate societal *concerns*, including the potential use of nanotechnology in enhancing human intelligence and in developing artificial intelligence which exceeds human capacity [my emphasis],

which should be addressed, among others, by the

> convening of regular and ongoing public discussions, through mechanisms such as citizens' panels, consensus conferences, and educational events, as appropriate.

The list of anticipated 'societal concerns' is further detailed in the requirement from the National Research Council (Sec. 5) to perform within three years a "study on the responsible development of nanotechnology"

> including, but not limited to:
> (1) self-replicating nanoscale machines or devices;
> (2) the release of such machines in natural environments;
> (3) encryption;
> (4) the development of defensive technologies;
> (5) the use of nanotechnology in the enhancement of human intelligence; and
> (6) the use of nanotechnology in developing artificial intelligence.

[13] http://thomas.loc.gov/cgi-bin/query/C?c108:./temp/~c108PRZXRc

It seems that, for U.S. policy makers, 'societal concerns' is the generic term and means critical concerns by members or groups of the society, which can be ethical, legal, environmental, or other 'appropriate' concerns, and which should be addressed and prevented by participatory models and education to make the American society 'prepared' for nanotechnology. The broader concept, 'societal implications', thus includes, on the one hand, the impact of ideas about future nanotechnology on such concerns, but excludes the impact of ideas in society on the development of nanotechnology.

Since the two issues that are explicitly mentioned twice – the "use of nanotechnology in the enhancement of human intelligence" and "in developing artificial intelligence which exceeds human capacity" – are explicit transhumanist visions, which are otherwise not considered nanotechnology, it is obvious that some U.S. policy makers want to prepare their society for more than nanotechnology. Thus, unlike a shift to a more balanced and pragmatist view, as the White House press release suggests, the prospected 'societal and ethical implications' of nanotechnology now include even more fantastic visions as well as possible resistance by the American people that need to be addressed by educational measures.

There are yet two other political aspects that deserve closer attention. Regardless of what it really means, nanotechnology has become a symbolic subject of international competition, much like the Cold War space program. From the first initiative to numerous speeches and the Nanotechnology Bill, "ensuring United States global leadership" (Sec. 2) is a dominant motive. Thus, every NNI/NSF report takes great pains to compare the U.S. dollar input in nanotechnology with those in Europe and Japan, thereby overlooking low salary countries like China and South Korea who are actually quite strong in research output (Schummer 2004a). Once involved in the symbolic competition, no country wants to lag behind. Since the vague definition of nanotechnology allows to call most of current research in chemistry, physics, biomedical engineering, materials science, electrical engineering, and so on nanotechnology, relabeling of research budgets, sometimes along with effective budget cuts, is a common strategy to increase the official funding of nanotechnology by orders of magnitude.[14]

In addition to the symbolic competition by means of figure cosmetics, the focus on nanotechnology provides the opportunity to rearrange the landscape and policies of research funding. In the U.S., where the physical sciences and the biomedical sciences have separately been funded by the NSF and the NIH (National Institute of Health), respectively, the NNI with its Director Mihail Roco from the NSF is the strongest effort to undermine that division. Whether, in the long run, the NNI will turn into a third independent pillar or a reinforcement, and reorientation, of the NSF, any current efforts at making nanotechnology big, from getting as many disciplines involved to making nanotechnology the center of transhumanist visions (Roco & Bainbridge 2003), will have an impact on the redistribution of responsibility and power among U.S. agencies.

In sum, for U.S. policy makers and science managers, 'societal implications' of nanotechnology has two kinds of meaning. On the on hand, it includes visions about the welcome impact on business and technology development of national concern as well as transhumanists visions of human enhancement and perfection; on the other, it includes fears of the unwelcome impacts on society, including the resistance against nanotechnological and transhumanists visions by members or groups of society. Depending on person, time, circumstances, and audience, the relative weight of the two kinds of meanings, including their various aspects, can greatly vary. In addition, policy makers and science managers also hope for an impact on symbolic leadership and the structure of governmental agencies, which both require nanotechnology being as big as possible.

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[14] To provide but one example from Germany, which has continuously been cutting down research and education budgets: A report by the federal Ministry for Research and Education (BMFT 2002a), published in January 2002, still listed the total amount of €71.8 million of federal funding for nanotechnology for the total period from 1997 to 2005; five months later, the same ministry issued a nano-report (BMFT 2002b), published in June 2002, claiming that federal funds for nanotechnology had already been €149.2 million from 1998-2001.

2.4 Business

After the dot-com boom in the late 1990s and the bubble burst of 2000, investors are keen to find new opportunities for making much money in short time. Two business groups have quickly responded. On the one hand, nanotechnology start-ups have allied to nano-business associations in various countries to represent their common interest and propagate a blooming future of nanotechnology to its current and future sponsors, *i.e.* governmental and private investors.[15] On the other hand, numerous business consultants, venture capital and investment firms are seeking a share in mediating between the manufacturing business and private investors. Until recently, their efforts to attract private investors consisted largely in providing information via NanoBusiness Internet Portals and nanobusiness reports.[16] The information usually comes as a news mixture of scientific 'breakthroughs', market events, political events, and 'analyses' about hot investor opportunities. For instance, Forbes/Wolfe, who started issuing the first newsletter with 'insider information', *Nanotech Report*, knows that "Stunning breakthroughs in Nanotechnology are about to transform the future of our economy and make EARLY INVESTORS RICH."[17]

Nanobusiness headlines follow a simple stereotype that captures the essence of the information to be hammered into the minds of potential investors. All they need to know is that nanotechnology is about small things, but will become big business. Here are some headline quotes:

> "Small Stuff, Big Business"; "The Very Small is Getting Big"; "Nanotech Promises Big Changes by Getting Small"; "Small Is Big"; "Small Is the New Big"; "Small Science Has Big Opportunities"; "Small world's

[15] For instance, USA NanoBusiness Alliance (www.nanobusiness.org), European NanoBusiness Association (www.nanoeurope.org), Canadian NanoBusiness Alliance (www.nanobusiness.ca), Israeli NanoBusiness Alliance (www.nanobusiness.org.il); in the U.S. there are at least 17 other local and state alliances (see www.nano.gov/html/funding/businessops.html).

[16] For nanobusiness Internet portals, see www.nanoinvestornews.com, www.nanoapex.com, www.nanotechnologyinvestment.com, www.nanoxchange.com, and www.nanovip.com; also www.smalltimes.com has a strong focus on business (see Section 2.5). For a list of 64 nanobusiness reports, see www.researchandmarkets.com/search.asp?q=nanotechnology.

[17] www.newsletters.forbes.com/nanotech/ (June 30, 2004).

> big achievement"; "Thinking Small, Winning Big"; "Big News in Small Tech"; "The Next Big Small Thing"; "From Small Dimensions to Big Business"; "Nano Research Could Mean Big Business"; "If It's Nano, It's BIG"; "Thinking Big about Nano"; "The Next Big Thing is Very, Very Tiny".

Recent efforts have tried to bring nanotechnology to a broader investor market. Since March 2004, First Trust, a bank that specializes in retirement plans, offers a 'nanotechnology' mutual fund called FTNATX that largely consists of stocks from well-known companies that produce such diverse goods as chemicals, pharmaceuticals, gasoline, electricity, computers, chips, and scientific instruments.[18] Three weeks later, Merrill Lynch introduced a Nanotech Stock Index at the New York Stock Exchange,[19] which includes smaller companies of a variety of fields, such that Merrill Lynch has been charged to misuse the nano label as a tactic for fraudulent stock promotion (Reisch 2004). In their accompanying 'research report' called 'Nanotechnology: Introducing the Merrill Lynch Nanotech Index' (April 8, 2004), the investment bank argues (p. 2):[20]

> We believe nanotechnology could be the next growth innovation, similar in importance to information technology over the past 50 years. [...] The National Science Foundation (NSF) sees a potential market totaling $1 trillion in the next 10-12 years.

What is puzzling here is not so much their professional optimism for their own stock index, but that one of the biggest investment banks worldwide refers to the NSF, which specializes in funding the physical sciences and engineering, as an authority in business matters.[21]

Indeed, NSF's forecasted $1 trillion market is quoted in almost any nanobusiness report – sometimes the '$1 trillion market' appears only as 'expert estimates'. The reason for NSF's authority becomes obvious when Lux Capital, a venture capital firm that focuses on nanobusiness,

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18 www.ftportfolios.com/Common/dp/portfoliosummary-print.asp?fundid=3761&Trust=nate1 (last visited, 30 June 2004). Major stocks include Dow Chemicals, Dupont, Exxon, General Electric, Hewlett-Packard, IBM, Intel, Motorola, Varian, and Veeco Instruments.

19 www.ml.com/about/press_release/04012004-1_nanotech_index_pr.htm (June 30, 2004).

20 www.ml.com/about/press_release/pdf/04012004_nano_index.pdf (June 30, 2004).

21 The reference seems to be Roco & Bainbridge 2001, p. 3 (Section 2: 'Nanotechnology Goals').

praises their own expertise along with their 250-page *The Nanotech Report 2003*, because they would have been "the first to recommend following government funding."[22] It does not matter if NSF's forecast is right or wrong, as long as the number meets business hopes. If governmental science funding agencies believe in nanobusiness, business advisors follow their lead, copy their visions, and sell them – in the form of quite expensive 'reports' – to investors eagerly awaiting the next boom, thus creating a self-fulfilling prophecy bubble.

2.5 Transhumanists

Transhumanism is a quasi-religious movement that originated in California in the 1980s with adherents in many different countries nowadays. Transhumanists believe in futuristic technological change of human nature for the achievement of certain goals, such as freedom from suffering and from bodily and material constraints, immortality, and 'super-intelligence'.[23] It is quasi-religious in its members' earning for Salvation,[24] and it is futuristic in the adoption of various technological visions, such as visions of nanotechnology; the stepwise transformation of human bodies into robots; the 'atom-by-atom copying of the brain'; the electronic 'uploading, copying and augmentation of minds' to be connected in cyber-societies; cryonics; and space colonization to cope with over-population. Since transhumanists believe that classical humanism would rest on a

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[22] http://www.luxcapital.com/nanotech_report_b.htm (June 30, 2004).

[23] See the information on the website of the World Transhumanist Association (www.transhumanism.org); particularly informative are 'The Transhumanist Declaration' (December 2002) and 'The Transhumanist FAQ: A General Introduction' written by philosopher Nick Bostrom (Bostrom 2003). The WTA has two publication media, Transhumanism (www.transhumanism.com) a board for articles and news, and the *Journal of Evolution and Technology* (www.jetpress.org). For an early and partly distanced view, see also Regis 1990.

[24] The religious character is a matter of degree and varies from individual to individual. All transhumanists subscribe to the distinction between being human (the state of striving for Salvation) and being posthuman (the state of Salvation), but they may differ in two regards. First, transhumanist may differ in whether the only existential purpose of being human is striving for Salvation (transcendence) or whether there are other purposes of equal importance. Second, they may consider the transformation from the human state to the posthuman state, which reflects the theological distinction between immanence and transcendence, discontinuous or continuous.

static notion of human nature, they call themselves 'transhumanist' to point out their teleological attitude towards radical change. Their ultimate goal is to overcome the present human condition and become 'posthuman'; and many are awaiting the 'singularity', a short phase of accelerated technology development that shall make all this happen.

Transhumanists have particularly great expectations for nanotechnology as envisioned by Eric Drexler. Indeed, it is the key technology vision on which most of transhumanism rests nowadays. First, they foresee the development of Drexler's 'assemblers' (Drexler 1986) that should manufacture abundant materials and products of any kind to be made available for everybody, so that material needs will disappear. Second, they expect 'assemblers' to become programmable tool-making machines that build robots at the nanoscale for various other transhumanist aspirations – a vision that has essentially fuelled the idea of 'singularity'. Thus, they thirdly hope for nano-robots that can be injected into the human body to cure diseases and to stop (or reverse) aging, thereby achieving disease-free longevity or even immortality. Forth on their nanotechnology wish list are nano-robots that can step by step redesign the human body according to their ideas of 'posthuman' perfection. Other nano-robots shall, fifth, make 'atom-by-atom copies of the brain', sixth, implement brain-computer-interfaces for 'mind uploading', seventh, build ultra-small and ultra-fast computers for 'mind-perfection' and 'superintelligence', and, eighth, revive today's cryonics patients to let them participate in the bright future.

Besides an individualist branch, which comes with a particular libertarian attitude under the label of 'Extropianism' and which is organized in the Extropy Institute (www.extropy.org), there is a strong moralist approach that derives from classical utilitarianism. Assuming that all people share their goals and that the technological visions are feasible, transhumanists consistently argue that all technological efforts ought to be made to achieve their goals and that any omission to do so and any attempt to prevent this are morally wrong. However, they also acknowledge possible dangers of the envisioned technologies and argue for a rational debate in which objective risks need to be compared with the benefits.

Transhumanists have an *existential* interest in nanotechnology, as a means for the ends of personal and/or societal Salvation, and thus differ from other people who do not share transhumanist goals and for whom technologies are but means for ordinary goals. It is this difference in interest that makes transhumanists a special interest group about 'societal and ethical implication of nanotechnology'. On the one hand, they have very specific ideas about what the personal and social implications will be, *i.e.* that nanotechnology will enable the 'posthuman' condition. Thus, transhumanists are pushing the discussion on 'societal and ethical implication of nanotechnology', like William S. Bainbridge, director of various programs at the U.S. National Science Foundation since 1992 (Roco & Bainbridge 2001, 2003), and Mike Treder, Director of the Center for Responsible Nanotechnology founded in 2002 (www.crnano.org). On the other hand, their existential end let them consider the means, *i.e.* the development of nanotechnology à la Drexler, much more likely and much more important than other people, which has direct implications on risk/benefit assessments.

Transhumanists generally argue for replacing subjective risks perception of a technophobic society by objective risks assessment. At the same time, however, they keep their own subjective assessment of the potential benefits, *i.e.* individual and/or societal Salvation, as the objective standard. Thus, in any risk/benefit analysis of nanotechnology, transhumanists are much more ready to assume risks because they personally see much greater benefits, and they see these benefits much more likely, even certain, to come. Moreover, if salvation through nanotechnology is taken as the largest possible benefit that is certain to arrive soon, the benefit of nanotechnology always outweighs whatsoever likely risk. At this point, any risk/benefit analysis becomes obsolete because the outcome is always predetermined.

Against this background, some transhumanists, including leading figures, express quite disturbing but consequent views. Max More, philosopher and Chairman of the Extropy Institute, argues for replacing the precautionary principle in legislation with what he calls the "proactionary principle" (More 2004): "People's freedom to innovate technologically is valuable to humanity. The burden of proof therefore belongs to those who propose restrictive measures." Hence, if, for instance, certain nanoparticles are only likely to cause cancer on workers of a nanotechnology firm, because some workers have actually cancer and the nanoparticles are carcinogenic on test animals, More's principle would prohibit any restriction on the nanoparticle development as long as it is not proved that these nanoparticles actually cause cancer on humans, which would require cancer experiments with humans.

Nick Bostrom, philosopher and Chairman of the World Transhumanist Association, has even more frightening views. In his discussion of the risks of technologies, he distinguishes between "endurable risks", such as nuclear reactor meltdowns and carcinogenic pollutants, and "existential risks", *i.e.* "events that would cause the extinction of intelligent life" (Bostrom 2003, question 3.3). While "endurable" risks are "recoverable", because "they do not destroy the long-term prospects of humanity as a whole", existential risks are not, so that transhumanist "recognize a moral duty to promote efforts to reduce existential risks". In that mixture of radical utilitarianism and apocalyptic admonition, risks are perceived only for humanity as a whole, are either recoverable for humanity or existential for humanity, and only the existential ones really count. The risks of individuals, to their health and lives, are less important because their risks can be outweighed by steps towards transhumanist salvation of humanity. It is not so much the imaginations of the 'posthuman' condition, which are mostly taken from science fiction stories, but the relative disregard for individual human dignity in risk assessments, *i.e.* the willingness to sacrifice individuals for the sake of global salvation, that makes transhumanism so inhumane.

Following Drexler's *Engines of Creation* (1986), transhumanists combine utopian visions with distopian visions of nanotechnology to derive normative claims. Such as nanotechnology offers salvation, such does it include the potential of 'existential risks'. Theologically speaking, nanotechnology bears both the highest good (*summum bonum*) and the highest evil (*summum malum*), making it the most important thing one can imagine. Because nanotechnology is so powerful, 'rogue states' or terrorists could abuse the power to destroy all intelligent life on earth. Since for transhumanists the technological development as such is unavoidable (technological determinism), responsible people must have command over the most advanced nanotechnology to protect humanity against evil use. Hence, advancing nanotechnology is not only required for Salvation, but also a moral obligation to avoid Armageddon. Personal motives thus perfectly harmonize with moral duties, which might be one of the reasons why transhumanism is so appealing for many.

In sum, for transhumanists the 'societal and ethical implications' of nanotechnology are personal and/or societal Salvation as well as the threat of Armageddon, from both of which they derive normative claims to advance research and development of nanotechnology as fast as possible.

2.6 The Media and the Public

The most important mediators between science and society are the media. Since investigative science journalism in newspapers and magazines has rapidly decreased, the journalist's task largely consists in selecting news from a growing supply by news service companies that mostly originate from press releases. However, whether they do their own investigations or select and modify news provided by news services companies, most journalists try to apply the perspectives and interest foci on science which they think their readers have. Thus, within the scope of available news, the media coverage of topics corresponds to a large degree to the interests and concerns of the public, to what the public understands by 'societal implications' of nanotechnology.

To get a rough quantitative idea of how the media reports on nanotechnology, I have analyzed all the 160 news articles published between December 5, 2003 and June 30, 2004 that are archived by the news portal Topix.net under the category 'nanotechnology'.[25] Topix.net covers mainly U.S. media that are available online, including local and national newspapers and general magazine as well as many topical magazines and online media. Although the coverage is not really representative of all media, because only those available online and free are included, it is sufficiently diverse to provide a semi-quantitative picture.

Of all these articles on nanotechnology, 32.4% appeared in general newspapers and magazines, 30.0% in business magazines, 18.8% in sci-

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[25] www.topix.net/tech/nanotech.

ence & technology magazines, and another 18.8% in *smalltimes*, a magazine that combines nano-business with nanotechnology news. Although the distinction between business and science & technology magazines is still discernible in their mission statements, particularly in older ones, the boundary is increasingly blurred, so that *smalltimes*' publishing concept of combining both might be forward-looking. The convergence of business magazines and science & technology magazines suggests that people interested in business are also increasingly interested in science & technology and vice versa. If we divide up the coverage of *smalltimes*, we may say that about 40% of all nanotechnology media coverage appears in business magazines.

Table 1. Topics of nanotechnology media coverage

	All Media (%)	General Media (%)
Business	50.6	55.8
Politics	7.5	7.7
SciTech/Grants	13.8	13.5
SciTech/Research	11.9	5.8
SciTech/Education	3.1	1.9
SciTech/Visions	5.6	1.9
Concerns (ELS)	5.0	9.6
Others	2.5	3.8

What do these various media report on nanotechnology? Table 1 presents the results of the article content analysis of various topics of the nanotechnology media coverage, both for all media types together and for the class of general newspapers and magazines. The dominating topic is business, which consists of market news on new companies, changes or new cooperations or alliances of former companies, investment opportunities, and general market trends in the local, national, or global nanotechnology business. Politics includes the opinions and decisions on nanotechnology by policy makers, which, as a rule, are about funding nanotechnology, from county council decisions to 'Bush's Signs $3.7 Billion Nanotechnology Bill'. Most reports on science are not about research but about grants for new research projects or new nanocenters, with headlines, like 'University XY gets $3 Million Nanotech Grant'. If we add up these three categories, it turns out that 71.9% of all articles about nanotechnology are about money and only about money. In the general media, as much as 77.0% are about money, because nanotechnology is mostly covered in the business section of newspapers. Actual research is covered only in 11.9% of all articles, although 18.8% of all articles appear in science & technology magazines. In the general media, reports on actual research (5.8%) or education (1.9%) are almost negligible. Surprisingly, also nanotech visions play a minor role and are mainly published in science & technology magazines including *smalltimes*.

The category of Ethical, Legal, and Societal Concerns (ELS) has been filled only on the occasion of three specific events during the period of investigation: a U.S. study on the potential toxicity of buckyballs on fishes; a British study on the possible transfer of nanoparticles from a pregnant rat to the fetus; and a Swiss report by the insurance company Swiss Re on how to insure nanotech firms. These concerns are mostly covered by general media and are, apart from money, the only topic worth mentioning here (9.6%). Since the American media responded to almost all such studies during the period, including foreign studies that are usually not much considered, it is likely that more such studies can considerably increase the media coverage of Ethical, Legal, and Societal Concerns.

Assuming that the media coverage roughly corresponds to the average American public interests in nanotechnology, we may conclude that currently 3/4 of the interests are about money and 1/10 about health and safety concerns, which might rise on special occasions. That is what, in this order, matters to people, what the average American public is supposed to understand by 'societal and ethical implications' of nanotechnology.[26]

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[26] The average public interest greatly differs from people with a strong interest in nanotechnology, excluding researchers and experts in nanotechnology. Here, the visionary literature, including transhumanist visions and nano-investor guides, is the dominant interest focus (see Schummer 2005).

2.7 Cultural and Social Scientists

Cultural and social scientists, including philosophers, have a much more sophisticated meaning of 'societal and ethical implications' of nanotechnology than any of the groups discussed before, which is therefore impossible to review in the few following remarks, the more as this group comprises many different disciplines.[27] As researchers they are first of all interested in analyzing and understanding the *mutual* impact between nanotechnology and society. Rather than taking technology as a given mysteriously autonomous force with one-way impacts on society, they consider scientists and engineers who actively work in nanotechnological research and development as members of society. On the one hand, they are interested in how cognitive and instrumental traditions, cultural values and belief systems, and societal needs and interests groups contribute to the generation and shape of nanotechnology. (Thus, this chapter tries to identify interests groups and their different meanings of 'societal and ethical implication'.) On the other, they investigate how *ideas* about nanotechnology, from research papers to political statements and journalist reports to visionary promises, move into society and could impact on or are in conflict with ethical theories, cultural values, belief systems, and societal needs. And since they consider science and technology as part of society, they are also interested in how the emergence and developments of nanotechnology change the disciplinary landscape and the general relationship between science and engineering.

The interest of cultural and social scientists in 'societal and ethical implications' of technology is first of all a professional interest in understanding, and in this regard it is fair to say that they are, among all groups mentioned in this chapter, the definite experts in these matters. Their specific interest in nanotechnology may differ, however. Because there are many different theories around on the mutual impact between technology and society, nanotechnology might serve as a particular case study for supporting one of the various theories, or for by promoting one or the other notion of post-xy, from post-modernism to post-normal science. In addition, the nano-hype, with its abundant talk of 'societal and

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[27] For a bibliography, see Schummer 2004d.

ethical implications' and the increasing budgets for related efforts, provides new opportunities for cultural and social scientists, from orientating research towards more current issues and engaging in partnership models with scientists and engineers to securing research funds or career opportunities.

Apart from research, politicians increasingly expect from cultural and social scientists to 'educate' the public beyond their professional duties of academic education. Thus, the already quoted White House press release announced to "undertake" "ethical, legal, societal implications [...] efforts [...] to promote a new generation of skilled workers". And the U.S. Nanotechnology Act requires "mechanisms such as citizens' panels, consensus conferences, and educational events" to shape the public opinion. Whether or not cultural and social scientists as individuals are willing to engage in such promotional events, it is questionable if they are the real experts here, rather than politicians, talk show masters, or media monopolists. I suspect that a techno-scientistic misconception of the cultural and social sciences underlies all those political expectation: such as natural scientists can continuously be moved from 'pure' research to applied research and engineering, such can cultural and social scientists be moved from cultural and sociological research towards cultural and social engineering. While scientists and engineers have actually control over their experimental systems and can manipulate them for either the study of behavior or the optimization of performance, cultural and social scientists never have any such control over social systems, not even in sociological experiments. Thus, the political expectations seem to rest on wrong advices about the methodology of the cultural and social sciences.

How can they cope with such ill-advised political expectations? One option would plainly be to deny the expected expertise, at the risk of loosing funding for important *research* in 'societal and ethical implications'. Another option would be to assume the expertise, based on the authority of knowledge and academic independence. However, once they engage in the promotion of political goals, whether they personally subscribe to these goals or not, cultural and social scientists lose just the academic independence on which their expertise is supposed to rest. The only viable option seems to be assuming the role of neutral mediators between different interest and opinion groups. Here, the expertise rests not so much on talk show master qualities than on the professional capacities to analyze different positions and their underlying assumption, to identify misunderstandings, common grounds and insurmountable differences, to define conditions of fair disputes, and to know something about the dynamics of social conflicts and cultural history.

In sum, for cultural and social scientists 'societal and ethical implications' of nanotechnology means the mutual impact between nanotechnology and society from many different perspectives. Their main interest is a research interest in understanding the particular situation or in defending a general theory. While such research might bring up models for better mediating between society and nanotechnology, it is neither their expertise nor their primary interest to meet political expectations of shaping the public opinion.

3. The Mutual Impact of Meanings: Semantic Dynamics

In the previous section we have identified the meanings of 'societal and ethical implications' of nanotechnology by various groups and their particular interests. These groups relate to major societal subsystems (literature, natural science and engineering, politics, business, religion, media, cultural and social science) by being those parts of the subsystems that are actively engaged in the current debate on 'societal and ethical implications' of nanotechnology in the U.S.. Having used the analytical classification of societal subsystems as a heuristic tool for identifying the groups and their meanings, we can now go one step further and analyze the mutual semantic impact between these groups to study the dynamics of the debate. Unlike analytical subsystems, the groups and their members overlap and exchange meaning. Somebody can, for instance, be a transhumanist and an engineer at the same time, or move from science to business, or transfer meaning from business to politics. There may even be alliances between two or more groups or a broader movement in which one group takes a lead.

In this section, rather than providing a complete analysis of the semantic dynamics of the debate, I perform only a preliminary study to identify the dominating groups and their meaning(s) of 'societal and ethical implications' of nanotechnology. Based on the material from Section 2, I collect evidence about the mutual impact of the groups' meanings and try to distinguish between influential and less influential groups and between original and mediated meanings. It is understood that 'impact' here does not mean political impact but exclusively semantic impact, *i.e.* the impact of group A's meaning of 'societal and ethical implications' on group B's meaning.

The impact of *science fiction authors* is perhaps most difficult to estimate. The rapid growth of the nano-science fiction book market suggest that their meaning has a growing impact on the public, although that is not yet discernable in the brief media analysis of Section 2.6, so that the impact might still be limited to specific groups, like the community of science fiction readers. We have evidence, however, for a strong impact on both transhumanists and visionary engineers, since most of their visions appeared in science fiction stories before, as well as for some impact on scientists, including the posthumous founding figure Richard Feynman. All these impacts are indirect, however, because the actual meaning of 'societal and ethical implication' changes when ideas are transferred from fiction to forecasting or to normative systems. As professional fiction authors, the originality of their nanotechnology vision has been very high, although they recently began to borrow from visionary software engineers.

Thus, *visionary software engineers* have an increasing impact on recent science fiction authors, as well as strong impacts on transhumanists, business people, and to some extent on politicians, because they feed theses groups with visions and are frequently engaged themselves in business or transhumanism. By providing a rhetorical framework to nanoscientists for publicly justifying actual research, they also influence the meaning of this group. Their meaning of 'societal and ethical implication' of nanotechnology is semantically original because, even if they borrow ideas from science fiction authors, they transform them into forecasts by claiming that these will be the actual 'societal and ethical implications'.

Nanoscientists are less influential because of their underdeveloped notion of 'societal and ethical implications', which is taken over from other groups in a moderated form and thus not very original. However, to some degree they have a discernable impact on the media/public, as reflected in media coverage, and on politicians, as the recent political turn towards more specific research projects as opposed to Drexler-like ideas of nanotechnology illustrates.

Toxicologists and environmental scientists seem to have a strong impact on the media/public, although they are hardly involved in the current debate yet. Representing the science-based side of concerns, their meanings are not only original but also to some degree taken over by politicians, as the Nanotechnology Bill suggests, and by cultural and social scientists.

Politicians have a discernable impact on the media/public and, through funding agencies, a strong impact on nanoscientists. As we have seen, they also impact the investment business that follows governmental funding. Contrary to their strong impact is the low degree of originality of their meaning of 'societal and ethical implications' that, apart from national connotations such as symbolic leadership and military application, combines various other meanings, though with particular accentuation. The combination of strong semantic impact and strong but selective semantic susceptibility, along with low semantic originality, makes them the most important and powerful mediators in the debate.

Business is very influential on the media, as the coverage illustrates, and on politicians, who particularly emphasize the economical prospects of nanotechnology. Because both several nanoscientists and visionary engineers run their own nano-business, such that a move towards entrepreneurship seems to be an appealing option for members of both groups, it is assumed that the business meaning also impacts these groups to some degree. Although the idea that nanotechnology will be the next 'big thing' on the investment market sounds less original, it is nonetheless the original semantic contribution from business to the meaning of 'societal and ethical implications' of nanotechnology – provided that governmental agencies like NSF did not raise the business idea earlier.

The impact of *transhumanists* is again difficult to estimate. Since we find transhumanists particularly among visionary engineers, such that both groups strongly overlap, and also among science fiction authors and in governmental agencies, it is reasonable to assume that they impact the meaning of these groups accordingly. In addition, the explicit mentioning of transhumanist vision in the U.S. Nanotechnology Act suggests that the impact on policy makers is not insignificant. Since transhumanists have taken over most, if not all, ideas about nanotechnology from visionary engineers and science fiction authors, they might seem to be less original. However, similar to the transformation from fiction to forecasting, they transform these ideas into a normative religious system, such that the meaning of 'societal and ethical implications' of nanotechnology considerably changes, which is an original semantic contribution.

For the *media/public* in a democracy we may, despite the current lack of evidence, assume that they have a strong impact on politicians. The strong focus of current nanotechnology news on business, particularly on investment opportunities, suggests also some impact on business. Furthermore, as we have seen in Section 2.2, nanoscientists, or their institutions, increasingly address the public through press releases, and thereby adjust their meaning to media standards. The media is clearly the least original group and, not surprisingly, an important mediator with both some semantic impact and a strong semantic susceptibility.

Finally, the sophisticated meaning of 'societal and ethical implications' of *cultural and social scientists*, though being highly original, has no discernable impact on any of the other groups up to now. The only indirect impact seems to be on transhumanists, because the leading and most eloquent transhumanists not only have a PhD in philosophy, but also developed their views against the background and in opposition to classical humanist ideas.

Tables 2 and 3 summarize the results of the mutual impacts and the originality of meanings among the groups. It is understood that the analysis is thus far only preliminary and that further research can provide more evidence of impacts and a more sophisticated fine-tuning. Within these limitations, however, we may try to analyze the role of the various groups and their meanings in the debate on 'societal and ethical implications' of nanotechnology.

Due to their low overall impact, both nano-scientists and cultural and social scientists play only a marginal role in the debate, despite the fact that the originality degrees of their meanings greatly differ. Two other groups, politicians and the media, are largely mediators of meaning, because of their low originality degrees along with both considerable impacts and susceptibilities. That does not mean that politicians and the media play no important role in the debate, however, since they can highlight one meaning at the expense of others. Among the remaining five groups with medium to high impacts and original meanings, toxicological and environmental scientists stand out because they have thus far no discernable direct impact on either of the four other groups, such that their impact is limited to mediation through the media or politicians. Hence, the semantic core of the debate on 'societal and ethical implications' of nanotechnology consists of the meanings of four groups, which I call the *semantic leaders*: science fiction authors, visionary engineers, transhumanists, and business people.

Table 2. The mutual impact of the meanings of 'societal and ethical implications of nanotechnology' among interest groups.

	SciFi	VisEng	Nano Sci	T&E Sci	Polit	Business	Trans-hum	Media	C&S Sci
SciFi		++					++	+	
VisEng	++		+		+	++	++		
NanoSci					+			+	
T&E Sci					+			++	+
Polit			++			++		+	
Business		+	+		++			++	
Transhum	+	++			++				
Media			+		++	+			
C&S Sci							+		

The semantic leaders of the debate form a strongly connected cluster with regard to the mutual impact of their meanings of 'societal and ethical implications' of nanotechnology (Figure 1). That is no coincidence because their meanings, unlike those of all the other groups, refer to highly visionary ideas. Indeed, the same visions can easily be, and have actually been, exchanged between science fictions authors, visionary engineers, and transhumanists. What science fiction authors invent in an experimental manner as fictional 'societal and ethical implications' of nanotechnology can become seriously meant forecasts by visionary engineers and a pathway towards Salvation with normative claims by transhumanists, and vice versa. Business differs from these groups by focusing only on those visionary forecasts that can be translated into business and investment opportunities. The semantic leaders thus form a visionary alliance that is rather robust against the less visionary meanings by other groups. Only business is indirectly susceptible to corrections if, for instance, major concerns from toxicological and environmental scientists are mediated via politicians and the media/public. In particular, the alliance is not very susceptible to both the more realistic views of the prospects of nanotechnology by experimental scientists and the more sophisticated meanings of 'social and ethical implications of nanotechnology' by cultural and social scientists. Even if politicians were not fostering the visionary climate as they do, they would have no discernable impact on science fiction authors, visionary engineers, and transhumanists.

Table 3. Characterization of the meanings of 'societal and ethical implications of nanotechnology' by interest groups.

	Impact	Susceptibility	Originality
SciFi	medium	low	high
VisEng	high	medium	high
NanoSci	low	medium	low
T&E Sci	medium	low	high
Polit	medium	high	low
Business	high	medium	high
Transhum	medium	medium	high
Media / Public	medium	high	low
C&S Sci	low	low	high

4. Conclusion: An Outlook into the Near Future

Provided that the analysis of the semantic dynamics of the debate on 'societal and ethical implications' of nanotechnology is, despite its simplifications and preliminary state, correct enough to identify the semantic leaders and the visionary alliance, we may try to guess some possible developments. And since most about nanotechnology is about the future, I will conclude with a brief speculative outlook into the near future that is based on the analysis, some common sense psychology, and lessons from the history of science.

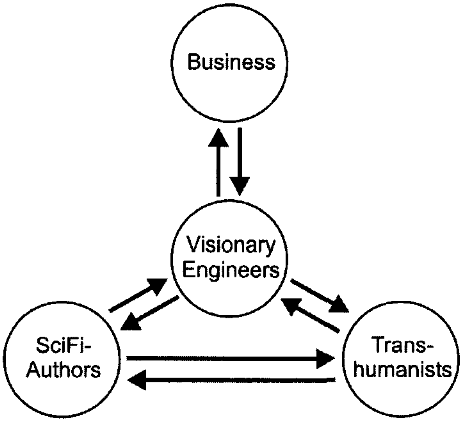

Figure 1. The visionary alliance in the debate on 'societal and ethical implications of nanotechnology'. Arrows indicate the impact of meaning as described in the text.

Due to the lack of checks and balances, the visionary alliance will certainly drive the visionary climate further through feedback loops and will disseminate their visions more into the broader public via the susceptible media. Since visions, rather than transferring information, induce hopes and fears, emotions are likely to determine the 'societal and ethical implications of nanotechnology' more than anything else.

In economics, which is strongly driven by hopes and fears, the few existing internal efforts to prevent the next bubble on the investor market seem to be much too weak compared to the expectations set free by the visions. The increasing number of investment firms or gurus who explicitly warn of the next bubble do everything to make exactly this happen, because their simple message to investors is that one should invest now and get out before the bubble bursts. Hence, the dotcom phenomenon seems to be likely to repeat on the nanotech market, the more as a bubble is the most profitable period for many investors and investment mediators. If the bubble burst is not an inherent part of that development, a series of serious news about the toxicity of some nanoparticles might be able to cause the unstable system to collapse.

There are more serious events likely to come than the ups and downs of the stock market. The visionary message of unlimited power to create new things and to shape the entire world anew atom-by-atom will likely split people who are to some degree interested in science into three groups: those with strong hopes, those with strong fears, and those who feel nauseated by dubious visions. Because the hopes will, of course, be frustrated, the likely net result of the visionary messages is strong hostility towards science from all three groups. If science managers and politicians are successful in getting most of the science and engineering disciplines on the nano-bandwagon, the resulting hostility is not one from single societal groups against a single discipline, but from the majority against all of science and engineering, *i.e.* a broad anti-scientific movement.

The societal impacts of nanotech visions essentially differ from the impacts of software visions, because the former is about the manipulation of matter whereas the latter is only about writing commands for machines. Visions about artificial intelligence (AI), which were circulated since the 1950s, slowly died in the face of technical problems and misconceptions of human intelligence, without preventing people from, say, using computers. It seems to be no coincidence that software engineers have transferred AI visions to nanotechnology to establish a new visionary terrain. However, the new terrain is actually an old visionary terrain that has a long historical legacy of cultural fears and frustrated hopes and that is imbued with sensitive notions of which the semantic leaders seem to be rather ignorant.

Visions about unlimited wealth and immortality by manipulating the ultimate building blocks of nature have fascinated Europe from the 13^{th} to the 18^{th} century. Hopes made people blind and susceptible to numerous frauds; kings, like Philip IV of France and Edward III and Henry VI of England, used the swindle on a large scale to finance their wars; many researchers, after years of unsuccessful laboratory attempts, dropped their interest in experimental science altogether, considered it worthless and harmful to knowledge, and retreated into contemplation or mystics; priests and theologians, if they were not personally involved, condemned any manipulation of matter as tampering with Nature or God, as the sin of hubris (Ogrinc 1980, Obrist 1986, Schummer 2003). In the 19^{th} century, when modern chemistry had replaced the alchemical visions and emerged as the model of the experimental laboratory sciences, chemists made new promises of experimentally analyzing the true ultimate building blocks of nature and manipulating them for the benefit of society, upon which writers started an unprecedented metaphysical and quasi-moral campaign that not only created the powerful rhetorical weapon of the 'mad scientist', but also established the ongoing split between the so-called 'two cultures' (Schummer 2006). In the 20th century, similar stories repeated several times. From the chemical industry, who promised a perfect world made of new materials or unlimited food from crops that are immune against pest either by pesticides or genetic modification, to nuclear engineers, who promised unlimited energy by atomic fission or fusion – each time the visionary propaganda downplayed any possible problems or risks, denounced critical voices, caused fears and hostility, and frustrated all those who were naive enough to believe in the recurring visions. Due to the visionary alliance, nanotechnology has every prospect of becoming the next big thing, even bigger though.

Acknowledgments

Support for this work was provided by the Deutsche Forschungsgemeinschaft through a Heisenberg Fellowship. I would like to thank Arie Rip and two referees for their useful comments.

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ACKNOWLEDGMENTS

The chapters of this volume are reproduced with permission from the journals *Hyle: International Journal for Philosophy of Chemistry* and *Techné: Research in Philosophy and Technology*. They first appeared as:

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