Small, but Determined: Technological Determinism in Nanoscience

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Abstract: 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 paper explores nano's non-presentism and suggests ways to further explore nano-determinism.

Keywords: *nanotechnology*, *non-presentism*, *futurism*, *social construction*.

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

HYLE – International Journal for Philosophy of Chemistry, Vol. 10 (2004), No. 2, 101-130.

between 1985 and 1995, there briefly flourished a cottage industry devoted to splicing apart the various threads of technological determinism, 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 of 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 flexible interpretability 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 article, 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, 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 inevitable 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 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 article draws most heavily on the social construction of technology (or 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 one discipline 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 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', like 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 sciences, 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 sciences.[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 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 conceived 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 the field, 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 envisions) 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 paper, 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 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]icro-electronics 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, bearing, 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 the trope 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 one centimeter – represented by a familiar animal such as a bee or a cat) to the 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 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 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. [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*, rather than social groups, 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 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 imposition 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 post-war 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 about 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 encourage 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 lighthearted 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.

Notes

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

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

[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.

[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.

[9] See Schummer 2004.

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

[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.

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

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

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

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

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

[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.

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

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