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Science Technology Human Values 2007; 32; 196
DOI: 10.1177/0162243906296918

Science, Technology, & Human Values
Volume 32 Number 2
March 2007 196-220

10.1177/0162243906296918
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Expectations and the Emergence of Nanotechnology

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Although nanotechnology is often defined as operations on the 10^{-9} meters, the lack of charisma in the scale-bound definitions has been fortified by remarkable dreams and alluring promises that spark excitement for nanotechnology. The story of the rhetorical development of nanotechnology reveals how speculative claims are powerful constructions that create legitimacy in this emerging technological domain. From its inception, nanotechnology has been more of a dream than reality, more fiction than fact. In recent years, however, the term *nanotechnology* has been actively drawn toward the present to begin to deliver on the fantastic expectations. This debate over time and timing is loaded with paradox. This work examines how future claims work to define what counts as nanotechnology and reveals dilemmas that accompany temporal disjunctures. Science and politics converge in debates about the future of technology as expectations serve to create and enforce power and legitimacy in the emerging area.

Keywords: *expectations; nanotechnology; time; innovation; emergence*

The boundary is permeable between tool and myth, instrument and concept, historical systems of social relations, and historical anatomies of possible bodies, including objects of knowledge. Indeed, tool and myth mutually constitute each other.

—Haraway (1991, 164)

Like all discourses, "the future" is constituted through an unstable field of language, practice and materiality in which various disciplines, capacities and actors compete for the right to represent near and far term developments.

—Brown, Rappert, and Webster (2000, 5)

Nanotechnology: Poltergeist or Zeitgeist?

Images of crazed nanomachines wreaking havoc on innocence compete with promises of obedient molecular machinery killing cancer cells and enabling zero-emission industrial production. As a technological fashion, new buzzword, and funding magnet, the dangerous yet sexy appeal of nanotechnology is revamping old products and services. Expectations of nanotechnology are abundant yet contrary, proliferated yet contested. They spark curious hopes and fears. Such speculative claims clamor to set the scene for what counts as nanotechnology.

But why is nanotechnology so alluring and demonic? Since when did chemistry and engineering become the work of prophets and magicians? This article explores battles between so-called visionaries and scientists contesting what nanotechnology is and should be, and considers the way that different actors use future claims to assert their politics.[1] As we shall see, the emergence of a new technological domain is fortressed and legitimated through debates over the future.

The case of nanotechnology reveals the ways different actors colonize the future and introduces questions of legitimization, competing methods for establishing truth, and the trouble with temporally based assertions. Who are the carriers of legitimate vision? By what measures are futures authorized? How far into the future is too far? Who creates legitimacy with what kind of appeal to methods is a critical question that plagues the relationships between science and politics, between the present and the future.

This work explores how expectations of nanotechnology operate to establish the new technological domain and with what dilemmas. The development of a technological domain is attributed to many different factors, which are too large and looming to address in one article, including the convergences of disciplines, the expansion of institutions and research facilities, grant organizations and other funding instruments, as well as the relevant aspects of political, economic, social, and cultural life and media. All elements of such an actor network affect how the field is constituted and reconstituted, as well as how the field is bound in terms of possibilities and expectations.

The expectations of nanotechnology move among the actors and are granted meaning through continual interactions and negotiations. Joint meanings are created from visions and form a platform for innovation. As a temporal abstraction, the future of nanotechnology is constructed and managed. It is useful to investigate by whom and under what conditions nanotechnology emerges, and with what consequences. In search of the "dialectics of promises," the circuits of expectations are made transparent (van Lente 1993).

The case of nanotechnology unfolds around an early thought pioneer in the field, Eric Drexler, who has come to represent the far future visions of molecular manufacturing. Drexler often stands in tension with others in the scientific community, yet most actors in the nanotechnology space engage in talk of future potential and debate the structure of the field vis-à-vis the future. Evidence of this sort of volatility is found in a recent article by Drexler that recants early nanotechnology scenarios (Drexler and Phoenix 2004).[2] As different voices clamor to set the scene for what counts as nanotechnology, actors and positions evolve, morph, and collapse.

The Dynamics of Expectations

Future rhetoric always involves statements about what is to come situated in a larger world of an imagined future. The concept of expectation is akin to motive and intention, yet maintains an explicit conceptual link to time and an implicit link to tacitly-held knowledges. Characterizations of nanotechnology have long occupied the space of the future, as in future benefits, future uses, and future scientific discoveries that might lead to a new world order.

Expectations have been little studied in relation to technology since Nathan Rosenberg wrote that "expectations concerning the future course of technological innovation are a significant and neglected component . . . inasmuch as they are an important determinant of entrepreneurial decisions" (Rosenberg 1976, 523). Notably, the work of Harro van Lente (1993) analyzes the meaning, politics, and function of images of the future for the ongoing development of science and technology, and is an important contribution. Another work, *Contested Futures* (Brown, Rappert, and Webster 2000), explores the ways in which technology is rhetorically shaped through future discourse. The collection's departure is:

> social actors, at individual, institutional or wider cosmopolitan levels construct future expectations which may run in parallel with and contest each other, occupying different time-frames and carrying different interests. Therefore, we need to ask how and why futures are contested, and how future scripts are stabilized around a specific set of expectations and practices. (Brown, Rappert, and Webster 2000, 5)

This work follows in the rally of *Contested Futures* and builds on existing work in the science, technology, and society (STS) tradition by dealing with the travels and travails of nanotechnology expectations.[3]

Theoretical Departures

Although actor network theory (ANT) and the work of Latour have sophisticated throughout the years, early Latourian ANT offers a particularly nuanced perspective on technology that aids the reading of the circuitry of nanotechnology expectations. ANT indicates that, like all technologies, the significance of the concept of nanotechnology is bound not simply to a quality of scale (or of function or discipline) but also to the social characterization that accompanies the technology, infuses it with meaning, legislates its existence, and authorizes its materiality. Technologies are not merely tools that are used or applications of science that are discovered, but rather are made through claims and counterclaims and constructed in one way rather than another, which is stabilized in social and material structures (Jasanoff et al. 1995; Bijker and Law 1992; Latour and Woolgar 1979). Technology is, therefore, the culmination of competing material and linguistic resources in which the technological artifacts (including their representations) have a role in mutually constituting strategies and in aligning interests and visions of the future.

Actors are engaged in a process of *inscribing* visions onto the field of nanotechnology.[4] Although *vision inscriptions* (or scripts) can circulate in local settings, for instance, when a photonic switching designer builds in multiple switching on the expectation that carriers will prefer malleability in their lines, we can also see other inscriptions occurring on a field level, as in nanotechnology at large. Scripts can be circulated widely in magazine articles and other news media, or specifically in a firm's mission statement or in a scientist's expectation for his or her research group. The script is a kind of anticipatory knowledge or knowledge claim that lays out a particular *program of action* to be followed, resisted, or modified (Akrich and Latour 1992).

When looking to describe technologies and the implications of their emergence, a multitude of factors derived from heterogeneous actors need to be considered (Latour 1987; Hassard and Law 1999). The actor network is made from many textual, material, and human elements, such as legislature, financial instruments, universities, government laboratories, entrepreneurs, venture capitalists, strategic plans, public media, and, last but not least, scientists and engineers and their artifacts. In this work, one element within actor-network transactions takes priority—representations of the future of nanotechnology. Drawing on representations of nanotechnology derived from personal interviews, newspapers, journal articles, assorted Web sites, white papers, and conference participation, nanotechnology is studied entangled with human and other kinds of material actors.[5]

Nanotechnology: Facts and Fictions

Nano, derived from the Greek word for *dwarf*, is combined with *technology* to signify operations occurring on the scale of 10^{-9} meters. A nanometer is a billionth of a meter, that is, about 1/80,000 of the diameter of a human hair, or ten times the diameter of a hydrogen atom. The scale of nanotechnology is an obvious first and important delineator of what kinds of activities, artifacts, tools, knowledges, and structures comprise the technological domain.[6] Scale-based definitions offer an encompassing, conservative view in which nanotechnology involves the further miniaturization of existing techniques and processes. Such definitions also lead many companies that have been making a business out of minute processes, such as catalyst production, to translate their activities into nanotechnology, thus making nanotechnology a more ubiquitous technology than originally conceived.

Intriguingly, much of what is labeled nanotechnology is not on the nanoscale but rather is focused on the micron level. Even stranger still, the term *nanotechnology* has come to symbolize "smaller" rather than scale, as evidenced by the cooperation between the National and Aeronautics and Space Administration (NASA) and the U.S. Department of Defense to develop and launch three 10 kg spacecraft—so-called nanosatellites—to investigate satellite coordination (Martin et al. 1999). There is more to nanotechnology than a simple delineation of nanometers.

It sheds little light on the complexity of nanotechnologies' development to say that it is technology on the scale of a nanometer or to give a simple description of what is currently counting as nanotechnology. Rather, one must also tend to the human, institutional, and economic actors and their situations, knowledge representations, and agendas. As a modest beginning of this larger process, a brief history of the concept is here pursued, leading to the popular scripts evident in nanotechnology.

A Star Is Born

Self-replicating, programmable, manufacturing architectures were known by John von Neumann in the 1940s but did not come into everyday technoculture vernacular until recently. Richard Feynman, a well-regarded Nobel Prize–winning physicist, spoke early of manipulating matter on the atomic level. In a speech given in 1959 entitled, "There's Plenty of Room at the Bottom," he claimed that "the principles of physics, so far as I can see, do not speak against the possibility of maneuvering things atom by atom," and, indeed, felt it "a development which . . . cannot be avoided" and proceeded to challenge scientists to store the *Encyclopedia Britannica* on the head of a straight pin (Feynman 1960). Although the trend toward miniaturization has been proceeding for decades, the precise control over atomic structure that Feynman explained was considered novel. The name *nanotechnology* has obscure origins with Taniguchi's (1974) work on ultraprecise machining.

Science Fictions

Yet Feynman's ideas and Taniguchi's term lay dormant until Dr. K. Eric Drexler's book, *Engines of Creation: The Coming Era of Nanotechnology* (1986), sparked new imaginings of the possibilities and risks of technologies on the nanoscale.[7] His book marks the origins of the heightened awareness of the term and the formulation of what is said to be a new industrial revolution. As an MIT undergraduate, Drexler saw the connections among molecular machinery, molecular biology, and the systems engineering aspects of complicated projects pursued in the aerospace field. Drexler referred to nanotechnology as "an anticipated technology giving thorough control of the structure of matter at the molecular level. This involves molecular manufacturing, in which materials and products are fabricated by the precise positioning of molecules in accord with explicit engineering design" (Drexler 1992, 1). In *Engines of Creation*, Drexler envisioned molecular machines programmed by built-in nanocomputers to accomplish specific tasks. Nanotechnology is imagined to enable the creation of molecular machines capable of manipulating individual atoms that can be reconfigured to formulate precisely engineered, seamless artifacts.

These devices are not merely synthetic machines but rather are composed of organic material—carbon, oxygen, nitrogen, and hydrogen—and would ideally use a diamonoid structure as the framework on which to construct objects. Functionally working on the atomic level, these machines would choreograph the movement of atoms into precisely organized and useful configurations. Depending on the mission programmed into the computer, the organism might break chemical bonds that glue atoms and molecules together or position atoms in particular arrangements to construct new forms. These are smart machines, not only because of the mission programmed within but also due to the sensing components that allow new decisions to be made.

Drexler outlined three main components of nanotechnology—nanoassemblers, nanoreplicators, and nanocomputers. The nanoassemblers would be the mechanics responsible for gathering and positioning molecules in desired constructions. He now calls his vision *molecular manufacturing* to refer to "a process of construction based on atom-by-atom control of product structures which may use assemblers to guide a sequence of chemical reactions" (Drexler 2003, 25). For our purposes, *nanobots* signifies Drexler's vision of nanotechnology.[8]

These nanobots, according to Drexler in *Engines of Creation*, are the solution to pollution, scarce food resources, and economic inequality. They will enable humans to travel and live in space, thus counteracting some of the side effects of the life extension also made possible by the nanobots' propensity for cellular repair. Nanotechnology will be responsible for "launching the human race into a new world" in which labor, capital, raw materials, energy, and land cost nothing and abundance rules, thus refiguring the capitalist production system as we know it (Drexler 1986, 98).

Drexler has been deemed an "avatar of nanotechnology" and a "guru of the nanoists" (Stix 1996). He became a spokesperson mustering political support, an advocate (setting up the Foresight Institute), and a "messiah" with the long-term vision of nanobots. He held, with the scenario group Global Business Network and the Computer Science Department at Stanford University, the first international conference on nanotechnology in 1989. In addition to *Engines of Creation* (Drexler 1986), he also coauthored *Unbounding the Future* (Drexler and Peterson 1991), which presents different scenarios on the future of nanotechnology. Drexler taught the first course in nanotechnology at Stanford University in the late 1980s and authored the first textbook on nanotechnology, *Nanosystems: Molecular Machinery, Manufacturing and Computation* (1992). In 1991, Drexler formed the Institute for Molecular Manufacturing (IMM), which raises funds and channels them to researchers working toward nanobots.

In many ways, Drexler has been a key figure for this new technological paradigm and has dominated representations of nanotechnology from the late 1980s through the 1990s. His steps may have begun to establish a new discipline or, rather, a new interdisciplinary study.

To be clear, this dominant story of nanobots has developed alongside actual material developments also called *nanotechnology*. The multifaceted history of nanotechnology includes spectacular work toward miniaturization that has arguably been advancing for decades. Fueled by successes in the semiconductor industry and spawned from the microelectromechanical systems (MEMS) community, nanotechnology has been enabled by instrumentation like the scanning tunneling microscope. Discoveries such as

Buckyballs and, later, carbon nanotubes have provided the material foundation to fashion the dreams of nanotechnology.

Highlighting Drexler's role in the rhetorical development of nanotechnology should not obscure the material developments that have built the field. Neither the story of material development nor that of rhetorical development alone captures the meaning and significance of nanotechnology. Nonetheless, given this article's focus on the rhetorical development of the field, the story now moves from history to the present time to elucidate the ongoing dilemmas with Drexler's vision and the emergence of nanotechnology.

Science Factions

Today, most scientists do not give credence to Drexler's representation of nanotechnology and instead focus on Feynman as the genius behind the origins of the field. Drexler is often downright ignored, as evidenced by the recent UK Royal Society/Royal Academy of Engineering study of the social, ethical, and environmental dimensions of nanotechnology. Despite its otherwise exhaustively comprehensive, 150-page coverage, Drexler is only discussed as a minor figure in the appendix (Royal Society 2004).

In a personal interview, the head of NASA's nanotechnology project referred to Drexler as spinning science fiction. He said that the impetus for nanotechnology came from Feynman's famous lecture and "that is what all serious people follow. I want to distance myself from anything Drexler talks about . . . most people who work in the laboratory do not subscribe to anything Drexler says. In many cases, it is like science fiction. Who knows if it will turn out?" (Meyya Meyyapan, director of NASA's nanotechnology program, personal telephone interview, February 22, 2002). "Real scientists" doing "real work in the laboratory" do not have time or patience for the longer term vision of Drexler's nanobots.

One such "real scientist," Richard Smalley, a Rice University chemist who won the Nobel Prize, was a critic of Drexler and had throughout the years made a small enterprise out of rebuking Drexler's claims. Smalley regularly criticized Drexler's premises for the development of nanobots. Smalley was not alone. There are many other critiques of Drexler, often made publicly at conferences, in the popular media, and in other debates on the new technological domain. For instance, in a *Nature* magazine article, Drexler's vision is taken up in the introductory paragraph of an article about nanotechnology. Drexler is, however, implicated in the "unwanted baggage" that burdens researchers (Macilwain 2000, 730). Again, the "serious" scientists are hampered by the visions of Drexler.

Nanobots: Violent or Virtuous?

Yet, despite the scientific communities' rejection of Drexler's vision, nanobots still remain a figure of popular debate, as evidenced by the article, "Why the Future Doesn't Need Us," in *Wired* (2000) by Bill Joy, the prominent Sun Microsystems scientist who wrote about the "grey goo" problem with nanobots in this article. The grey goo problem refers to the unchecked proliferation of self-replicating assemblers wrecking havoc. Joy called for a halt of nanotechnology research on the grounds of its potential to induce human extinction (Joy 2000).

Shortly thereafter, Ray Kurzweil, "techno-guru" author of *The Age of Spiritual Machines* (a book arguing for artificial intelligence and a dismissal of the dilemmas around downloading human consciousness; Kurzweil 1999), came to redeem nanotechnology in his article, "Promise and the Peril" (Kurzweil 2000). In this article, Kurzweil rallied against the relinquishment of nanotechnology research, arguing that it would instead go "underground where development would continue unimpeded by ethics and regulation" causing terrorists to reap the rewards. He urged scientists to be ethical in the research threads so that humanity can advance their values through technology. Richard Smalley best summed up the scientific debate about the grey goo problem. *Science* quoted Richard Smalley as saying that Drexler's proposed assemblers are "impossible" and continuing, "[M]y advice is, don't worry about self-replicating nanobots. It's not real now and will never be in the future" (quoted in Service 2000, 1526).

In 2001, *Scientific American* ran an entire issue on nanotechnology. Drexler was featured not as a technologist but as a futurist, and his article was followed by one that condemns the tools he proposed. George Whitesides, a Harvard chemist, wrote, "Fabrication based on the assembler is not, in my opinion, a workable strategy and thus not a concern" (Whitesides 2001, 84). Smalley returned with further critique, plainly stating, "Self-replicating, mechanical nanobots are simply not possible in our world," citing what in the nanoworld are known as the "fat fingers" and sticky fingers problem (Smalley 2001, 77). Rebuttal papers appeared on the Foresight Institute Web page (Drexler et al. 2001).

The last Smalley and Drexler debate took place in *Chemical and Engineering News* and demonstrated the way the two scientists talk past each other (Baum 2003). Although the first round focused on the problem of "sticky fingers"[9] and the presupposed limits of chemistry, the second round deteriorated as Drexler retreated into mechanico-engineering language, leaving Smalley in the land of chemistry. Drexler summoned a highly technical debate drawing on the theoretic possibility of molecular manufacturing, whereas Smalley largely ignored Drexler's technical argument and instead concluded with a social responsibility line that accused Drexler of scaring the children.

As we can see in these debates, despite Drexler's efforts to rebuke claims with a greater number of, and more detailed technical reports and scientific articles along with his stout assertion that no one has ever been able to prove that basic science wrong, he has been displaced as the key professional spokesman of the field (see, e.g., Drexler 1992, 1994, 1995, 1999). For instance, according to the well-known Institute of Nanotechnology Web site in the United Kingdom, the pioneers of nanotechnology do not include Drexler at all, and instead call on Nobel Prize winners and inventors of magnification devices (Institute of Nanotechnology 2002).[10]

This issue of *Scientific American* included Drexler as a "fringe element futurist," berated his presentation of future tools, and situated his views as the greatest risk to nanotechnology. As one contributor said,

> If the nano concept holds together, it could, in fact, lay the groundwork for a new industrial revolution. But to succeed, it will need to discard not only fluff about nanorobots that bring cadavers back from a deep freeze, but also the overheated rhetoric that can derail any big new funding effort. Distinguishing between what's real and what's not in nano throughout this period of extended exploration will remain no small task. (Stix 2001, 83)

The debate over the dangers of nanobots has extended beyond scientific journals and into popular culture with Michael Crichton's *Prey* (2002). His thriller describes the horrific consequences of out-of-control nanobots that escape from the laboratory. *Prey* caught popular imagination effectively and spurred even more concern about the regulation of nanotechnology.

The dangers and risks of nanobots further spilled over into U.S. congressional hearings and the more authorized circles of the U.S. federal government. For example, a 2004 report, "Nanoscience and Nanotechnology: Opportunities and Challenges for California" (California Council on Science and Technology 2004), discussed nanotechnology with references to nanobots, albeit in an unpleasant light. Christine Peterson of the Foresight Institute responded, "[T]he concept of molecular machines appears only in the form of 'plagues of self-replicating nanobots' as in . . . *Prey*. The envisioned benefits of molecular manufacturing may be needlessly delayed by this confusion" (Foresight Press Advisory 2004). Once again, nanotechnology's future frames the debate.

Pluralization of the Field

The avalanche of all things nano has been incredible throughout the past decade. The English Institute of Physics launched a new magazine called *Nanotechnology* in 1991 that has been followed by dozens more. In 1992, the Institute for Scientific Information found that the prefix *nano* was one of the most popular among new journals (Crandall 1996, 30). Corporate research and development departments began using the term *nanotechnology* beginning with IBM's investment announcement in 1991, when nanotechnology was represented as "central to the next epoch of the information age" (Crandall 1996, 26). Josh Wolfe, cofounder and managing partner of Lux Capital, speculated that IBM is now devoting about 50 percent of its long-term research and development spending to nanotechnology (Kary 2002).

Countless new institutes at universities have been inaugurated, especially in 2000-2001, which is roughly correlated to the start of the National Nanotechnology Initiative (NNI) in the United States. The NNI takes a more grounded, scientific approach to nanotechnology yet with enough inspired rhetoric to stimulate other nations to take their nanotechnology research development seriously in a kind of waterfall effect.[11] Similar efforts have been launched in Germany, England, and Japan. In late 2003, U.S. President George W. Bush allotted a whopping US$3.7 billion for nanotechnology research (Lawson 2003).

The conference calendar is too booked to manage, yet notably has recently become populated with conferences on "Investing in Nanotechnology" or "NanoInvesting." Venture capital firms have announced their dedication to the promise of nanotechnology and act as big proponents of the nanotechnology boom. They are active on the conference network yet attempt to balance the generation of hype with their demand for short-term gains. Such gains are surprisingly limited given the extreme magnetism nanotechnology has for funding.

Conclusions: The Battles Continues

As new actors, such as national governments, academic centers, corporate research and development departments, and venture capital funders, entered the scene, the meaning of nanotechnology has been transformed and fractured from Drexler's original meaning of molecular manufacturing to an ubiquitous, yet nonetheless ambiguous, technology—nearly a zeitgeist.

"What's real and what's not" in the space of nanotechnology has always been confused and debated. The ambiguity about the future of nanotechnology is latent in the concept itself. With Drexler's induction of the term, the future promises took center stage and have remained key characters in setting the stage for what is nanotechnology. The prominence of the promises have become downplayed, however, and the focus shifted to more immediate, achievable goals. A more conservative meaning, one that is bound either to commercial developments with a shorter term horizon or to a more stringent disciplinary perspective, has usurped the nanotechnology envisioned by Drexler.

The Future in the Making

The purpose of this story is not simply to show how different agendas aspire to the forefront due to their spokespersons' positioning. We should expect that the visions are indebted to local circumstances, interests in innovation and commercialization process, institutional affiliations and disciplinary background, and so on. Although the Drexlerian script is essential in the story of nanotechnology told from the perspective of promises and dreams, visions, and expectations, it is not the characteristics of the individual claim makers that are at stake—this is not merely a story about Eric Drexler.

It is not individual actors who are making the field, despite the fact that this article follows individual scientists and engineers. Such a presentation should not obscure the fact that the making of a new technological domain is complex and emergent, and is mutually constituted by networked actors who are members of different enclaves in the domain. What matters here is what lies between them and what circulates among them—*the discourses of the future*.

Analyzing Expectations

Because our task is to trace the representations of the future of nanotechnology and to determine the role of such expectations and the power they wield, we need some analytic tools to begin to unravel the story and make sense of what has happened to the meaning of nanotechnology's future. This story of nanotechnology and the debate between the Drexlerian vision and others in the scientific community can be usefully analyzed through the ANT tradition as *translations*.

Actors align interests by advancing them into the network through processes of *enrollment* and *translation*. *Translation* in ANT refers to the process by which actors are defined and constituted by each other, or how actors *enroll* other actors into positions that suit their purposes (Callon 1999). A translation presupposes a medium or a "material into which it is inscribed," so that translations are "embodied in texts, machines, bodily skills [which] become their support, their more or less faithful executive" (Callon 1991, 143). The inscription includes *programs of action* for the users. *Enrollment* is, then, a measure of the success of the translation, or whether the receiving actor took up the interest or program.

So, then, the question becomes how actants enroll other actors into positions (conceptual or material) that suit their interest or agenda. Once others take up a particular representation of the future, *translation* has occurred (Latour 1987). What is also interesting in the case of nanotechnology is a translation that is unsuccessful—a representation of the future that was circulated but then overridden by another. What this directs our attention to is the mutability of contestations, and the ways in which heterogeneous actors define and redefine their technological frameworks.

Fighting Wor(l)ds

A closer look at the translation process reveals how expectations move, and with what consequences. In his book *Science in Action*, Latour (1987) analyzed fact building as an argumentative process aimed to establish legitimacy. Latour referred to processes of translations as original interpretations given in hopes of attracting the interests of others. A successful translation involves enrolling other people to your interests. He outlined several strategies for translating interests:

1. Create interests.
2. Shift own interests (taking up the interests of those to be translated).
3. Take a detour (a shortcut) from one's path toward others' interests.
4. Reshuffle interests and goals (displace goals, invent new goals, and invent new groups). (Latour 1987, 108-9)

Translation has two main meanings, the normal linguistic meaning (like translating from one language to another), and the geometric meaning (referring to mobilization). In this sense, Latour noted, "[T]ranslating interests means at once offering new interpretations of these interests and channeling people in different directions" (Latour 1987, 117). The point is that if the claim circulates and becomes a part of others' resources in professing new knowledges, the claim begins to stick, actors are enrolled, and translation occurs.

These other resources, which Latour called *allies*, not only include figures and equations but also refer to other associations that draw social authority to a claim. The reputation of a researcher or institute, inclusion in curricula, citations in scientific or technical articles, or success with fundraising could all serve to support a claim. In this sense, the scientific and technical are always social, bound up to issues of legitimacy and what counts as building credibility in different communities. It is important to note that such credibility is not, then, relatively or arbitrarily earned, or simply a matter of drawing enough resources toward your argument. The resources are lodged in particular traditions and discernable systems of social relations, which grant them authority.

For example, one of the blows to Drexler's reputation is a 1996 *Scientific American* article (which attacked his personality, his conception of nanotechnology, and his followers) that drew from the authority of scientists in the field who disagreed with his vision (Stix 1996). In response to the *Scientific American* attack, Drexler (and researchers funded by the Institute for Molecular Manufacturing (IMM)) rallied technical literature supporting their visions, issued a rebuttal on the Web, and awaited a response. By using the Web, they had bypassed the standard letter to the editor procedure, for which they were criticized and threatened. In the aftermath, Drexler commented, "[D]espite all their critical-sounding words, they have nothing to say against the scientific underpinnings of nanotechnology, and can't point to anyone credible who does" (quoted in Phelps 1996, 1).[12]

As in most scientific controversies, Drexler typically responded to his critics with the initiation of new experimental studies, computer simulations, graphical representations, and a growing host of technical articles conceptually supporting his claims. The Drexlerians busily made arguments for *theoretic possibility* and in time mustered together many research papers and studies to use as weaponry in the debate over the truth of the future of nanotechnology. When other scientists use existing literature to refute the possibility of molecular machines, notably the problems of quantum effects and some key uncertainties about the behavior of molecules on the nanoscale, the Drexlerians come back with even more claims and evidence.

Translating and Negotiating Meaning

As we see with Drexler and his vision, it is simply not enough to supply the arguments. One cannot just fortify a testament with enough resources (even technical and scientific texts) to establish credibility. The strength of a claim is bound to how many people take up the claim, use the claim, and are convinced by the claim. We need to ask more questions that move us beyond simply presenting the claim and the supporting argumentation. Were real concerns addressed, or were the debaters arguing ineffectually by appealing to different methods? Who was (and was not) convinced, and why?

Whether an expectation is shared serves as an indicator of the success and strength of the claim. Some expectations have power, and others are more superficial, lacking an impact on material, social, or institutional actions. According to Harro van Lente (1993), the degree of sharedness can vary along a continuum ranging from an individual's idiosyncrasies that no one bothers with to self-evident expectations that actors take for granted. Van Lente maintained that the vigor of expectations can be considered in light of the "degree to which they are shared and articulated, by the effort that is needed to get them accepted as an argument or resource" (1993, 38). How shared an expectation is—the degree of consensus among the actors—depends on how completely others are enrolled into the specific *programs of action* (Akrich and Latour 1992) inscribed in the visionary scripts.

If we take Drexler's vision and look on what happened as a process of fact building, we ask: How was his representation of nanotechnology taken up by others? Why were his representations of the future of nanotechnology embraced or disparaged, and through what mechanisms? To have a claim accepted, one must convince others to take it up and be sure that once they do, the claim is not transformed into a different one.

The term nanotechnology traveled far and wide, but the consequence of nanobots revolutionizing every aspect of life was obscured. In Drexler's case, the scientific community took up his term by engaging his vision in articles, in journals, and at conferences. *Scientific American*, *Science*, and *Nature* all made the effort to criticize him. In this way, others took part in constructing his claim by applying the term *nanotechnology* to their scientific and technological practices, seeking funding under the auspices of nanotechnology and engaging in debates about what really counts as nanotechnology. These mobilizations of the claim occurred and eventually led to new nanotechnology research laboratories, large government spending, and international research networks dedicated to nanotechnology.

We can see that Drexler's term was taken up, but the second battle of maintaining the meaning was lost or at least misplaced. Part of this defeat deals with the space left open for others to own the term. Negotiation occurred with different actors applying the term as it suited their needs, and the meaning of nanotechnology in terms of its potential became the subject of worldwide debate. Yet, in this process of negotiation, the original meaning of nanotechnology as little robots that will reform political, economic, and industrial life was dropped. This transformation of meaning is the cost of leaving open the "margin of negotiation" that allows the term to become something for everyone (Latour 1987).

Drexler's vision was not fully translated, and was instead adopted and renegotiated. Exploring this negotiation process offers some clues to the workings of expectations and the way in which translation occurs, and, in effect, how a future discourse travels. As Latour maintained, "In such a venture, the statement will be accommodated, incorporated, negotiated, adopted and adapted by everyone and this will entail several consequences" (Latour 1987, 208). One consequence is that the concept does not have one author but many. Whether the adoption of the expectation becomes linked to the development of a new tool, such as the dual-tip scanning tunneling microscope, the institutionalization of a nanotechnology research agenda, or a meeting of science fiction aficionados about nanotechnology, each actor/author writes his or her meaning of nanotechnology.

Another consequence of the dynamics of spreading an expectation is that the term may be co-opted by a more authorized source so as to add to the credibility of the claim. This kind of adaptability is demonstrated in the way that the scientific community resurrected a speech by Richard Feynman to adopt him as the father of nanotechnology. It is regularly said that it was Feynman who presented the early challenges that fueled the development of what is now known as nanotechnology—not Drexler.

Author(owner)ship takes an interesting twist within nanotechnology. Who the father of nanotechnology is depends on the progeny. If you are more tightly aligned with scientific communities, your father is Feynman, but if you are affiliated with popular science journals, industry, or the cultural realm, you are more likely to refer to Drexler as the father of nanotechnology. In 2003, however, Drexler published a paper that explicitly attempts to realign himself with the Feynman vision by explaining when and how the fracturing misinterpretation was made (Drexler 2003). Drexler contended that the problem lies in a misreading of Feynman. In his paper, he positioned nanobots as an extension of and not a deviation from Feynman's vision. The battle to own nanotechnology continues to unravel.

Temporality and Expectations

The transformation of the meaning of the term *nanotechnology* can be read as a problem of temporality and of the discrepancies between time horizons, or, in other words, as a tension between quantitatively different expectations. The recourse to time built into an expectation can be short term or longer term, yet is rarely made explicit. This invisible temporal marking is part of the reason for controversies over the future of nanotechnology. As we have seen, Drexler's vision was longer term, such that his expectations were not easily taken up by his colleagues yet were embraced by the public.

The expected benefits in his future were appealing to those beneficiaries but threatening to those who would be held accountable to them—the scientists and technologists. The scientists pulled in the reigns of time to be able to deliver on results that could still count as nanotechnology. Revising the concept of nanotechnology to the nearer term sets the stage for accomplishment and more manageable targets.

There are still, however, risks laden in the term. Bringing the term *nanotechnology* into the National Nanotechnology Initiative (NNI) had some unexpected consequences signaling that Drexler's vision had not been forgotten. Rather, it has etched itself in public memory, returning to haunt those who translated the term to define their own research. In a personal interview, a representative of the Foresight Institute explained,

> The poor scientists adopted the term *nanotechnology*, along with its old meaning with huge expectations, as a long-term, exotic, extreme technology. The term got picked up by the government as the NNI. The term got pulled onto a conservative, fairly boring national program with boring scientists . . . then [when confronted with the big expectations] the boring scientists were forced to say, "No, you are confused about nanotechnology." They got burdened with the sexy term that they don't want. . . . They want to talk about what they are doing today. It makes them furious [when the media interview them for revolutionary research]. (Christine Peterson, director of Foresight Institute, personal interview, Los Altos, CA, January 29, 2002)

The "real scientists" working in their laboratories could not meet the advances proposed by Drexler, especially given the time horizons set by funding agencies. His vision was long term, could not offer deliverables, and aggravated the divide between Drexler and his peers. Due to public enthusiasm about "the next big thing," the scientists were confronted with media and public groups seeking the return on the promises that the researchers unwittingly took up when they coded their scientific agendas *nanotechnology*.

The story of the NNI adoption of Drexler's term highlights another of the problems with temporal inscriptions—the potential for unmet expectations. The media and investors interested in new technologies were looking for Drexler's nanotechnology, but were confronted instead with premature (i.e., not commercially viable) processes. The public began to expect robots in their bloodstream curing whatever ails them, but when confronted with an ultra-fine dust heralded as the next advance in nanotechnology, their excitement became jaded.[13]

The field has been "de-boted" to an extent through processes negotiating the meaning of nanotechnology. Nanotechnology has been actively drawn into the present by scientists and has come to symbolize the state of the art of small technology in many discrete disciplines. This could be called the *scientification* of the nanotechnology vision. The revolutionary character proposed by Drexler is misplaced, and nanotechnology becomes instead a widely dispersed, nearly unidentifiable domain that lurks everywhere at once—a poltergeist. The effort is clear to move nanotechnology away from robots to a wider definition that encompasses different research paradigms.

Actor Worlds and Legitimization

Many contend that the meaning of nanotechnology broadens to the point that it has no meaning, and, as Drexler is fond of saying, *nano* is a marketing and financing term. Despite little resonance with scientific discussions and practices, add the prefix to your service or product and you will receive the desired support. Scientists use the visions of nanotechnology in some arenas, such as investment or political circles, yet shun them when with their own peers. This selective use of the visions of nanotechnology signifies the way in which temporality defines the parameters of the field. It is a ubiquitous concept but can still be called on to usher in excitement about the new promises of technoscience. Scientists use the distant future and its promises to gain funding and legitimacy with the politicians, but continue to reject the vision when seeking legitimacy within their own communities of practice (Brown and Duguid 1991) or actor worlds (Callon 1986).

Different enclaves use the term selectively and transform the meaning to their advantage. A politician will have a different explanation of nanotechnology than a computer scientist or potential investor, because they are part of distinct but interacting enclaves, or actor worlds. These actor worlds are unified by a specific way of acting and performing in a particular context. For example, a scientist does not become a scientist or act like a scientist without a particular method, a disciplinary background, a research institute, and supporting structures, which serve to grant authority. The concept of actor world also introduces the dilemma of insiders and outsiders, which is important because part of the debates portrayed about the future of nanotechnology deals with who is considered an expert and who is considered a problem.

Drexler attempted to align himself within the actor world of engineers as opposed to that of scientists. This distinction affords him the luxury of speaking to theoretic possibility, although he notes that more authority is granted to scientists (Eric Drexler, personal e-mail communication, May 23, 2003). Drexler's theoretic possibility, however, does not easily translate into scientific legitimacy. The validity or credibility of an expectation claim cannot be tested by traditional measures—like verifying a fact. Potentiality thus poses a problem for the methods of science and, as we have seen, is not easily reconciled through the argumentative style of Drexler and his peers.

Talk of potentiality is thus avoided in many of the research communities devoted to nanotechnology. Drexler's vision was longer term; it frustrated the scientists to no end, for their tools for creating authenticity cannot enter the contemptuous terrain of the future. When speaking with each other, the far future is avoided in favor of more immediate concerns and deliverables. The future, despite the productive uses that it maintains, is illegal territory for most scientists most of the time.[14] Drexler's ruin can be read as a cautionary tale about those scientists and engineers who trespass into the future. It is a paradox that in light of this conflict of methods, scientists fear aligning and engaging with Drexler while simultaneously using the term when it benefits their research.

Drexler's distant future representations failed to convince the scientists as scientists. Although the translation of his claims may have been incomplete, traces of the original concept remain active and useful for seducing funders. The sexy visions then, however, vengefully cause residual irritations to those scientists who succeed in recolonizing the future of nanotechnology in light of their scientific agenda.

The Politics of the Future

This study began with the aim to interrogate the promises of nanotechnology to expose the functioning of technological expectations. As such, the unit of analysis became "the future"—a metaphoric space in which stories are formulated, worlds are (and continue to be) constructed and anticipated, expectations circulate, and rationalizations are made. It has been demonstrated that the future is an active arena, one both pregnant and populated with agendas, interests, and contestations.

Like historical claims, claims about the future serve also to solidify meanings and muster support for defining reality. Speculative claims, as ordinary claims, are powerful constructions that create legitimacy in a technological domain. Like the legitimization processes that occur during fact building, expectations serve a very real, very palatable role in the development of nanotechnology. The point is that building facts and building promises both operate similarly and become interesting when translated into action.

That is, the future is a rhetorical and symbolic space to work out "what is nanotechnology," but it also serves a productive role that underlies everyday decision making, alliance building, and resource allocation. Potentiality is shifted and revised based on the agendas, interests, and needs of those engaged in the space. Both as a rhetorical and blatant theoretical chartering of nanotechnology, potentiality is used and manipulated by various actors to gain and lose allies, muster authority, and legitimate projects. The future is a legitimating discourse but with crippling side effects as it becomes too loaded.

We have seen that representations of nanotechnology have changed, and we should expect them to continue to change as new actors enter the scene and the scene shifts in turn. There is even the possibility that the term *nanotechnology* will break down as a useful descriptor as burgeoning fields develop their own distinctive discursive, institutional, and social framings. In the meantime, Drexler's vision is alive, well, and annoying to those who choose to ignore it in a studied fashion, and it is inspirational to others. Due to his landmark position, he provided others opportunities to position themselves as more sophisticated and realistic. He provided a reference point for "serious" nanotechnologists. The inspired are the entrepreneurs, the young scientists who are moving into the new field, and those who are looking to be attached to the next technological boom. So although one discourse dominates, that of a ubiquitous nanotechnology, the nanobot vision remains to motivate, haunt, secure, and exasperate different audiences.

The power and legitimacy exercised by the scripts render promises and expectations as actors in the constitution of a new domain. There is little innocence in such imaginings—instead, they are forces to be reckoned with. This battle for power over the future, the ability to set the stage for what counts of nanotechnology, is complex and intertwined with social authority, legitimacy, and what kind of power is wielded. The meaning, the function, the power of any representation is resonated through the network as a successful enrollment of other actors. Science and politics fold in on each other in these fascinations about what is to come.

Notes

1. I use the reified categories of *scientists* and *visionary* for explanatory ease, but it is well-known that the categories are muddled and rarely so plainly distinct.

2. When this article was submitted for publication (2004), Drexler and Phoenix (2004) released a short article in which they reconsidered the notion of self-replication in nanotechnology-based fabrication, arguing that it may be more efficient to use nonbiologic systems. This dismissal of self-replication is to quell fears of runaway replication (also known as *grey goo*) and redirect popular debate on the risks and promises of nanotechnology.

3. STS literature has seen a revitalization of expectations research in the past few years and has covered various technological paradigms, for example, genomic and biotech (Fortun 2001; Fleising 2001), pharmacogenetics (Hedgecoe and Martin 2003), telemedicine (Rappert and Brown 2000), information technology (Geels and Smit 2000; Wyatt 2000), and membrane technology (van Lente and Rip 1998).

4. Madeleine Akrich (1992) called the end product of this vision inscription a "script" that is similar to the meaning of representations of the future, visions, and expectations that is used here.

5. The fieldwork informing this piece consists of documentary and popular data supplemented by nineteen in-depth interviews and, in addition, correspondence with key actors, including Drexler. The main documentary data were congressional reports, white papers, Internet publications, trade articles, and the like. Ongoing monitoring includes participation in newsgroups and electronic bulletins focused on nanotechnology. Popular media outlets devoted to nanotechnology have also been monitored for an excess of the research period.

The series of semistructured, in-depth interviews was conducted with those engaged in the nanotechnology space, of which topics bordering on the meaning and history of nanotechnology are presented here. Interviewees were furnished with a prepared interview scheme containing areas of relevance and an overview of the research. All interviews were recorded and later transcribed. Interviewees were selected based on the nature of their relationship to nanotechnology—given that the study is concerned with the rhetoric of the future of nanotechnology, marketing gurus, futurists, foresight practitioners, and technology advocates are also included in the investigation, thus rounding out the interviews with scientists, engineers, and research managers.

6. *Nanotechnology* is regularly defined in respect to scale; for instance, the U.S. Nanotechnology Initiative said that "nanoscale science, engineering, and technology [comprise] the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new properties and functions" (Rocco 2002). Or, following NASA, "Nanotechnology is the creation of functional materials, devices and systems through control of matter on the nanometer length scale (1-100 nanometers), and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale" (NASA 2002).

7. The book was preceded by a paper, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation" (Drexler 1981), and an article in *Smithsonian* magazine entitled, "When Molecules Will Do the Work" (Drexler 1982).

8. Drexler has, however, made a strong objection to this characterization in a personal e-mail correspondence with the author (dated September 14, 2004), stating that "nanobots is not my term, and plays directly to the distortions propagated by my all-too-political enemies. . . . [T]his use of the term poisons understanding of the actual concepts and future prospects." I note this objection but stick to the phrasing for stylistic reasons and to highlight the contentious nature of the debate.

9. *Sticky fingers*, also called *fat fingers*, refers to the adhesion of atoms to each other, which is presumed to make difficult the precise maneuvering of atoms necessary in molecular manufacturing.

10. The list includes Feynman, James Gemzewski (who worked with scanning tunneling microscopy, now at the University of California, Los Angeles), Sir Harry Kroto (1996 Nobel Prize winner for chemistry for the discovery of fullerenes), Ralph Merkle, Richard Smalley (1996 Nobel Prize winner for chemistry), George Whitesides (for his work in biochemistry, materials science, catalysis, and physical organic chemistry), and Gerd Binning and Heinrich Rohrer (for inventing the scanning tunneling microscope in 1981).

11. The amount of investment, US$422 million in 2001 (US$604 million in 2002), is widely evoked as a rationale for taking nanotechnology seriously. The National Science

Foundation has forecast that the market for nanotechnology products and services will reach $1 trillion by 2015 (National Science Foundation 2001). The U.S. government has invested about $1 billion in nanotech in 2001 and 2002, and Venture Capitol (VC) contributions were expected to reach that level in 2002, according to research by Lux Capital, a VC company devoted to nanotechnology (Kary 2002).

12. He continued,

> The article obscured this in a cloud of opinions on other questions, and dragged in some pure name-calling. But now, cornered by a direct challenge to back up their position, they have responded with more dancing and dodging—not making arguments, not citing arguments, not even saying what an argument on their side could possibly look like, or who could deliver it, but, instead, saying that arguments of some sort could be made, by someone, somewhere, someday. That is awfully close to a declaration of intellectual bankruptcy. (Quoted in Phelps 1996, 1)

13. Given the large federal (i.e., taxpayer) investments in nanotechnology, serious disapproval could threaten funding streams and political balances.

14. Gilbert and Mulkay (1984) noticed a similar phenomenon and argued that scientists have different repertoires that they use in different contexts. They noted, "Formal accounts are couched in terms of an empiricist representation of scientific action . . . this empiricist repertoire exists alongside an alternative interpretative resource . . . [that] tends to be excluded from the realm of formal discourse" (Gilbert and Mulkay 1984, 40).

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