Too Little, Too Late?: Research Policies on the Societal Implications of Nanotechnology in the United States

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Despite the fact that "nanotechnology" is still in its infancy—is even, arguably, still prenatal—indeed, despite ongoing disagreements about how "nanotechnology" ought to be defined, knowledgeable people have converged around the notion that, whatever nanotechnology is, and whatever it will become, its implications for society are going to be transformational, perhaps radically so, in social realms as diverse as privacy, workforce, security, health, and human cognition. One apparent consequence of this convergence is the commitment by the U.S. federal government to fund not just nanoscale science and engineering (NSE) research, but also research on the societal implications of NSE.

In this paper we present three brief narratives to illustrate the surprisingly independent evolution of 1) NSE research, 2) speculations and concerns about the implications of nanotechnology, and 3) government commitment to supporting research on the societal implications of nanotechnology. Conspicuously absent from these stories is the influence of several decades of scholarship on the interactions of science, technology, and society. The community of science studies and science policy scholars seem to have engaged with the challenges of nanotechnology only when stimulated by the appearance of federal research funding starting in about 2001. Thus, they did not materially participate in the framing of public discourse about nanotechnology, or in the design of research programs to study the social implications of nanotechnology. In their absence—perhaps due to their absence—a policy experiment was implemented that may permit this same community to play a newly effective role in the governance of science and technology.

Three Nano Narratives

1. Science: How Nanotechnology Began to Get Big

The canonical story of the origins of nanotechnology (which we will not dispute) goes something like this:

In 1959, Richard Feynman gave a speech at the annual meeting of the American Physical Society called "There's Plenty of Room at the Bottom," in which he predicted that physicists would eventually be able to manipulate matter at the molecular or even atomic scale, and would thus usher in a new technological revolution. "It doesn't cost anything for materials, you see. So I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, stamping parts, and so on. As we go down in size, there are a number of interesting problems that arise. . . . But I am not afraid to consider the final question as to whether, ultimately—in the great future—we can arrange the atoms the way we want; the very atoms, all the way down!" (Feynman, 1960)

The tools to begin to pursue Feynman's playful predictions started to come on line in the coming decades. In 1980, IBM scientists used a scanning tunneling microscope to directly image individual atoms for the first time. The development of the atomic force microscope in the mid 1980s further advanced imaging capabilities, and in 1990, again at IBM, scientists actually manipulated individual Xenon atoms to write their company logo (NSTC, 1999; 2000). A giant step had been taken toward confirming Feynman's assertion that it should be possible to print the entire *Encyclopedia Britannica* on the head of a pin.

Meanwhile, physicists Harold Kroto, Richard Smalley, and Robert Curl discovered in 1985 that carbon exposed to high temperatures could form spherical molecules, later dubbed "buckyballs," which rapidly led to the discovery of numerous, similar carbon-based molecules characterized by both great chemical stability, and great physical strength. *Science* magazine named buckyballs the "molecule of the year" in 1991. Kroto, Smalley, and Curl shared the 1996 Nobel Prize in physics. (e.g., Nobelprize.org, 1996).

Government and private investment in nanoscale science and engineering (NSE) continued to expand. In the U.S., the National Science Foundation (NSF) began it's first program devoted exclusively to NSE in 1991, funded at about six million dollars (World Technology Evaluation Center, 1998). In 1998, the U.S. government organized the Interagency Working Group on Nanotechnology (IWGN), whose work led, two years later, to the initiation of the multi-agency National Nanotechnology Initiative (NNI), funded at $270 million; by 2004 the investment had increased to $961 million (Roco 2004). NSF's 2004 solicitation for NSE research proposals provides an update on Feynman's original vision; still prospective in terms of actual outcomes, it is nonetheless inaugural in pronouncing that the revolution has arrived: "The nanometer (one billionths of a meter) is a magical point on the dimensional scale. Nanostructures are at the confluence of the smallest human-made devices and the largest molecules of living systems . . . A revolution has begun in science, engineering and technology, based on the ability to organize, characterize, and manipulate matter systematically at the nanoscale. Far-reaching outcomes for the 21st century are envisioned in both scientific knowledge and a wide range of technologies in most industries, healthcare, conservation of materials and energy, biology, environment, and education." (NSF, 2004)

Scientific productivity grew apace. Starting in the early 1990s, the prefix "nano" began increasingly to appear in the titles of scientific journal articles and scientific grant proposals. To some extent this trend almost certainly reflects the opportunism of scientists relabeling existing research activities to take advantage of the latest funding fad. But the trend also signaled the effects of technological and conceptual advances that increasingly allowed new types of research on materials and processes at the nanoscale, and the synergies of such new opportunities with increased availability of research funds, especially from the government.

From 1985 to 1990, the annual number of publications in the Science Citation Index (SCI) that included the prefix “nano” in the title hovered between 200 and 400. Between 1990 and 1991, the number jumped from 378 to 1677, most likely reflecting a response to the growing programmatic focus of federal funders (Figure 1). What appears to be exponential growth in publications continues: in 2003, SCI lists 23,015 papers with the “nano” prefix in the title. In parallel, the number of NSF grants with the prefix “nano” in the title increased from the low 10s in the late 1980s and early 1990s, to almost 600 in 2003. The first journal devoted exclusively to nanoscale science and engineering was launched in 1990; two more journals were started later in the decades, and an additional four were launched between 2001 and 2003.

Insert Figure 1 here

2. Science Fiction: From Weird to Wired

The word “nanotechnology” appears to have been coined by a Japanese engineer in 1974 (Klaes, 2004), although it entered the public lexicon through Eric K. Drexler’s 1986 book *Engines of Creation*. Drexler’s vision for the future of nanotechnology was largely an extrapolation of Feynman’s original idea, taken to its logical extreme: “Molecules will be assembled like the components of an erector set, and well-bonded parts will stay put. Just as ordinary tools can build ordinary machines from parts, so molecular tools will bond molecules together to make tiny gears, motors, levers, and casings, and assemble them to make complex machines.” (Drexler, 1986, ch. 1) The crucial attribute of nanotechnology, in Drexler’s vision, was the capacity for self-assembly, in order to create necessary efficiencies of time, energy, and scale. Self-assembly “will let us build almost anything that the laws of nature allow to exist. In particular, they will let us build almost anything we can design - including more assemblers. . . . Assemblers will open a world of new technologies. Advances in the technologies of medicine, space, computation, and production - and warfare - all depend on our ability to arrange atoms. With assemblers, we will be able to remake our world or destroy it. So at this point it seems wise to step back and look at the prospect as clearly as we can, so we can be sure that assemblers and nanotechnology are not a mere futurological mirage.” (ch. 1)

As an MIT-trained engineer, and standing on Feynman’s shoulders, Drexler possessed technical legitimacy, one consequence of which was a brief review of *Engines of Creation* in the *New York Times* (Monmaney, 1986), which noted Drexler’s “unembarrassed faith in progress through technology,” and voiced general skepticism about his vision of “molecular manufacturing.” Reviewing *Engines* in *Technology Review*, the noted robotics engineer Hans Moravec (1986) mostly poked fun at Drexler’s “absurdly anthropocentric” nano-utopia, yet also asserted “atomic scale construction is not just possible but inevitable in the foreseeable future.”

It would be nearly 15 years before Drexler began to get broad attention, but science fiction writers were meanwhile spinning out visions of what molecular manipulation and self-replication might imply. Moravec’s 1986 review of *Engines* included the idea that “medical nanobes [might] rebuild you from the inside out in their own image.” Yet a year earlier, Greg Bear’s novel *Blood Music* (1985) had spun out precisely this scenario, where a discredited scientist injects himself with self-replicating “nanites” that take over and “improve” his body, then escape and do the same to the rest of humanity. In the same year, Paul Preuss’s novel *Human Error* (1985) speculates about self-replicating hybrid bio-nano machines that can enhance the performance of their human hosts (at least the ones that don’t die in the process).

Between 1985 and 2000, at least 37 science fiction novels were published that spun out a variety of nano-enhanced futures. Many of these were concerned with exploring not just the technological implications of nanotechnology, but also the social dilemmas and consequences that might ensue. As Neal Stephenson imagines in *The Diamond Age* (1995): “Now nanotechnology had made nearly anything possible, and so the cultural role in deciding what should be done with it had become far more important than imaging what could be done with it.”

Despite this activity outside the formal boundaries of technoscience, public interest in nanotechnology appears to have been modest throughout the 1990s. Mentions of the word “nanotechnology” in popular print media included in the Lexis-Nexis database rose very gradually and arithmetically, from 10s per year to a total of 183 in 1999. Most of these mentions were magazine and newspaper coverage of the latest scientific breakthroughs and technological possibilities. Nanotechnology was still the stuff of techno-nerds.

Then something changed. Media mentions of “nanotechnology” more than doubled in 2000, to 423, and by 2003 had exceeded 1750 (Figure 1). Michael Crichton’s nanotech-catastrophe book *Prey* (2002) became a national bestseller. Amazon.com lists 21 hardcover books (nonfiction and fiction) with the word “nanotechnology” in the title published before 2000, and 84 published between 2000 and 2004. *Scientific American*, a magazine about science but for general audiences, ran seven articles with the prefix “nano” in the title between 1993 and 2000; the number jumped to 54 between 2001 and 2004. Similarly, *Technology Review* published 44 articles that included the keyword “nanotechnology” between 1997 and 2000; over the next four years the number more than quadrupled, to 183.

Why did nanotechnology so suddenly become a mote in the public eye, a buzzword that epitomized the rapid advance of science and innovation? Certainly the rapid growth of research interest and productivity in the NSE field made it ripe for media interest, and the launching of the NNI in 2000, which was widely covered in major print media, correlates with the rapid expansion of media coverage. Much of this coverage continued to focus on the latest breakthroughs at specific laboratories. We speculate that, among other factors, as universities strove for a piece of the expanding NSE budgetary largesse, they promoted their own NSE research activities more aggressively to the media.

Yet a stimuli of perhaps equal importance was the now-famous article in *Wired* magazine by Bill Joy, chief scientist at Sun Microsystems, entitled “Why the Future Doesn’t Need

Us," (Joy 2000) prognosticating doom for the human species as a result of the emergent power of three converging technologies: nanotechnology, genetic technology, and robotics. Expanding on scenarios already published by Drexler, as well as the ideas of the inventor technological visionary Ray Kurzweil (1998), Joy wrote: "robotics, genetic engineering, and nanotechnology . . . pose a different threat than the technologies that have come before. Specifically, robots, engineered organisms, and nanobots share a dangerous amplifying factor: They can self-replicate. A bomb is blown up only once - but one bot can become many, and quickly get out of control." While Drexler had devoted a chapter to the possible dangers of self-replication, he had also considered it to be a manageable problem. Joy saw it as intrinsically uncontrollable.

His solution?: "relinquishment: to limit development of the technologies that are too dangerous, by limiting our pursuit of certain kinds of knowledge." Joy's position as one of the chief architects of the world's high technology information infrastructure meant that he could not be dismissed as a fringe voice or Luddite, The contrast between the "gee whiz" utopian breathlessness of the scientific promoters of nanotechnology, and the "oh my god" catastrophism of Joy's vision, created a tension ideally suited for journalistic treatment. His article received broad coverage, and thus legitimation, in the mainstream media, including the *Washington Post* and *New York Times*. Nanotechnology was on the radar screen.

Interlude: Mud in Joyville

Rapid increases in the public investment in NSE starting in 2000 had to be explained and justified. The inauguration of the NNI was accompanied by a promotional brochure aimed at non-technical audiences, entitled "Nanotechnology: Shaping the World Atom by Atom" (NSTC, 1999), which proclaimed nanotechnology as "a likely launch pad to a new technological era because it focuses on perhaps the final engineering scales people have yet to master." (p. 4) "If present trends in nanoscience and nanotechnology continue, most aspects of everyday life are subject to change." (p. 8) "The total societal impact of nanotechnology is expected to be much greater than that of the silicon integrated circuit because it is applicable in many more fields than just electronics." (p. 8) And the ultimate goal of the nanotechnology revolution?: "unprecedented control over the material world." (p. 1)

Such language, which displays an historically oblivious optimism that borders on the quaint, testifies either to a conspicuous isolation of those involved in planning and promoting the NNI from anyone who might have been thinking about the societal complexities of scientific and technological change, or a conscious decision to ignore any such thinking. The publication of "Why the Future Doesn't Need Us" only months after the NNI's unveiling must therefore have been particularly galling to those involved in promoting the initiative.

Indeed, Joy's proposal to "relinquish" certain potentially fruitful lines of scientific research is not just unacceptable but literally incomprehensible to most scientists. Advocates of the benefits of nanotechnology thus sought from the outset to discredit the plausibility of Joy's ideas on either the scientific grounds that self-replicating "nanobots," as originally described by Drexler, were impossible (e.g., Armstrong, 2001; also see discussion in Sarewitz and Woodhouse, 2003), so there was nothing to worry about, or on the grounds that stopping the advance of NSE knowledge was impossible, so we would just have to figure out how to deal with it (e.g., Peterson, 2004). NSF's Mikhail Roco, the director of the NNI, and Nobel prize-winner Richard Smalley, the co-discoverer of buckyballs, in particular were known to be highly antagonistic to Drexler's ideas (e.g., Baum, 2003; Peterson, 2004; Berube and Shipman, 2004). After the initial flurry of attention devoted to Joy's article, scientific criticism of the Drexler-Joy scenario has been sufficiently effective to keep it out of most mainstream published discussions and accounts of possible social implications of nanotechnology.

Although one can only speculate, it seems to us that the high level and persistent energy of scientific critique of Joy and Drexler cannot be rooted in the technical objections to the scenario, but in the unavoidability of Joy's logic: if uncontrollable self-replication of autonomous nanobots is possible, then a strong case can be made that relinquishment of certain lines of investigation is not only rational but sensible. Because relinquishment is unthinkable, self-replication must be deemed impossible.

3. Science Studies: Nowhere to be Seen

As early as 1990 the popular journal *The Futurist* published an article entitled "Nanotechnology and Human Values" (Wrubleski, 1991); during the 1990s business magazines such as *Forbes* and *Futures* also featured occasional coverage of the implications of nanotechnology, and academic journals such as *Scientometrics* and *Research Policy* began to track scientific and technical trends. As late as 2000, however, nanotechnology was nowhere on the agenda of scholars who study the societal implications of science and technology. Searches on terms such as "nanotechnology" and "nano*" in the Social Sciences and Arts and Humanities Citation indices show little if any academic interest in nanotechnology during the 1990s. Mnyusiwalla and others (2003) writing in the technical journal *Nanotechnology*, noted: "Despite the potential impact of [nanotechnology], and the abundance of funds, our research revealed that there is a paucity of serious, published research into the ethical, legal, and social implications of [nanotechnology].

Conversely, scholarly works that directly confronted the challenges of governing societally transforming technologies took little note of nanotechnology. For example, Richard Sclove's *Democracy and Technology* (1995), an edited volume entitled *Technology and Values* (Shrader-Frechette and Westra, 1997), and the book *Frontiers of Illusion: Science, Technology, and the Politics of Progress* (Sarewitz, 1996) include no mentions of nanotechnology.

Apart from Bill Joy, one other voice urging caution about nanotechnology was the ETC Group (previously known as the Rural Advancement Foundation International, or RAFI), an activist organization that during the 1980s and 90s played a central role in opposition to genetically modified foods, especially to Monsanto's "terminator" technologies. A

1999 article by RAFI director Pat Roy Mooney, entitled "The ETC Century: Erosion, Technological Transformation and Corporate Concentration in the 21st Century," (Mooney, 1999) included a 10 page summary of the state of nanotechnology research. Unlike Joy's diagnosis, the ETC perspective focused on a combination of equity issues (who would benefit socially and economically from nanotechnology?) and a more traditional risk framework (what are the environmental and health risks associated with nanotechnology?) But overall, the point is that on the eve of the NNI, the community of scholars devoted to understanding the social embeddedness and implications of science and technology were playing no part in the gradually unfolding societal discourse about nanotechnology. Notably, however, in 2001 two academic papers were published that analyzed the role of nanotechnology in science fiction (Johnston, 2001; Miksanek, 2001).

It is not without irony, then, that from its beginnings the NNI, and the U.S. National Science Foundation in particular, proclaimed themselves committed not just to research on nanoscale science and engineering, but to simultaneous research on the "Ethical, Legal, Societal Implications" (ELSI) of nanotechnology to "help us identify potential problems and teach us how to intervene efficiently in the future on measures that may need to be taken" (NSTC, 2000, p. 13). This commitment, of course, was no invention of the NNI, but rather echoed the decade-old ELSI program of the Human Genome Project, as well as the Human Dimensions of Climate Change initiative of the U.S. Global Change Research Program, and the 1999 recommendations of the President's Information Technology Advisory Committee (co-chaired by Bill Joy) to include research on "socioeconomic impacts" in the nation's portfolio of information technology research (PITAC, 1999). This was a top-down commitment.

In September 2000, NSF sponsored a two-day workshop on "Societal Implications of Nanoscience and Nanotechnology," a wide-ranging and ill-focused event (attended by the junior author), which led to a published volume of the same title (Roco and Bainbridge, 2001). The introduction to the volume sets out the rationale for research on the societal implications of nanotechnology: to "boost the NNI's success and help us take advantage of this new technology sooner, better, and with greater confidence." (p. 2) But a later chapter says that "the knowledge gained [from social implications research] will help policymakers and the public understand how nanoscience and nanotechnology are advancing, how those advances are being diffused, and *how to make necessary course corrections*." (p. 17; emphasis added) While most of the participants at the workshop and contributors to the volume were concerned primarily with the problem of how to effectively advance nanotechnology and its benefits, several authors did raise questions about the complex outcomes of technologically induced societal transformation (Suchman, 2001; Tenner, 2001; Crow and Sarewitz, 2001).

Over the four years following this conference, NSF funded a small number of grants to academic scholars, ranging in size from about $30,000 to $1.7 million, on the societal implications of nanotechnology, in such diverse areas as the history of the scanning probe microscope, analysis of emerging ethical and risk issues, development of various participatory techniques to enhance public dialogue, and the construction of web-based NSE databases. NSF's total commitment to a broadly construed social implications research agenda during the first four years of the program appears to have been about $10 million; total NSF expenditures on all nanotechnology research during this period were about $750 million; total, multi-agency NNI expenditures by the U.S. Government were about $2.7 billion. Social implications research amounted to less than 0.4 % of the total federal investment in NSE research. By comparison, the ELSI component of the Human Genome Project by law was funded at five percent of total project expenditures (Cook-Deegan, 1994).

Through 2004, NSF funding for research on the social implications on nanotechnology was disbursed in a non-strategic manner to diverse universities. The situation may now be changing. In 2004, the U.S. Congress passed the "21st Century Nanotechnology Research and Development Act," which mostly asserted Congressional authority over the funding and coordination of the NNI, but did include specific provisions to ensure "that ethical, legal, environmental, and other appropriate societal concerns" were considered "*during* the development of nanotechnology." (PL 108-153; emphasis added) Prior to the passage of this legislation, the U.S. Senate Committee on Commerce, Science, and Transportation held a hearing on the subject of nanotechnology which included one witness testifying about the need for social implications research—a professor from the University of South Carolina, the state represented by the Committee's senior Democratic senator. The U.S. House of Representatives Committee on Science, in contrast, convened a hearing specifically entitled "Societal Implications of Nanotechnology." Their witnesses included Ray Kurzweil, the technologist whose optimistic visions of how nanotechnology might evolve nonetheless accepted some of the technical assumptions advanced by Eric Drexler and adopted by Bill Joy (e.g., Kurzweil, 2003); Christine Peterson, who was President of Eric Drexler's Foresight Institute; and the science studies scholar Langdon Winner, a long-time advocate of increased democratic participation in technological decision making. Notably, among the questions that each witness was asked to address was this: "How can research and debate on societal and ethical concerns be integrated into the research and development process, especially into projects funded by the government." (House Committee on Science, 2003)

As a consequence of this hearing, language was included in the 21st Century Nanotechnology Research and Development Act that singles out "the potential use of nanotechnology in enhancing human intelligence and in developing artificial intelligence which exceeds human capacity," and includes the requirement for "public input and outreach to be integrated into the [National Nanotechnology] Program by the convening of regular and ongoing public discussions, through mechanisms such as citizens' panels, consensus conferences, and educational events, as appropriate . . ."

In response to the passage of the legislation, NSF in August of 2004 initiated a competition for a "Center for Nanotechnology in Society," to be located at a university or consortium of universities, and funded at a level of about $2.6 million per year for five years, with a possible five year extension. This competition is currently underway. The program solicitation includes a much broader range of potential research foci than stipulated in the legislation, such as research to "improve our understanding, e.g., economic implications of innovation; barriers to adoption of nanotechnology in commerce, healthcare, or environmental protection; educational and workforce needs;" but also lists "ethical issues in the selection of research priorities and applications and in the potential to enhance human intelligence and develop artificial intelligence; . . . and public participation and involvement in scientific and technological development and use." (NSF, 2004)

Four years after NSF began to provide support for social science and humanities research on the societal implications of nanotechnology, and on the eve of a new infusion of public funds into this area of study as a result of the new law, a scholarly literature is perhaps beginning to emerge. For example, the February 2004 issue of the *Bulletin of Science, Technology, and Society* was devoted to social implications of nanotechnology. Notably, a survey of the citations in the six articles contained in this volume confirms the absence of a significant prior literature on this issue. This situation will certainly begin to be reversed over the next several years, as researchers begin to report on the results of their federally funded work. But the key point here is that this area of research has been created by a federal funding commitment; it did not arise in response to the societal challenges presented by the emergence of nanotechnology.

How Science Studies Converged With Common Sense

The December 2004 NNI Strategic Plan (NSTC, 2004) states: "Recognizing that technological innovations can bring both benefits and risks to society, the NNI has made research on and deliberation of [the societal implications of nanotechnology] a priority." (p. 10) What are the mechanisms by which research on the social implications of an area of science and technology are supposed to improve human choices about, and social outcomes related to, that area of endeavor? Who are the constituencies who might use such research, and how might those constituencies act to address what is learned? If, for example, one considers the defunct Office of Technology Assessment (OTA) of the U.S. Congress, the idea, of course, was that specific studies of particular areas of research and innovation would help illuminate the implications of various decision options facing elected representatives. The complexity of Congressional politics meant that the capacity for OTA studies to influence decisions was both highly diluted and highly buffered, but at least the model by which OTA might contribute to decision making was easily understood.

If one considers the ELSI program of the Human Genome Project (HGP), the formula becomes less clear. ELSI research was supposed to "anticipate the social consequences of the projects' research and to develop policies to guide the use of the knowledge it produces." (Juengst, 1991) But ELSI research, conducted primarily by academic social scientists and humanists, is functionally and administratively separate from the genomics work that constitutes the core of the HGP. Nor are the results of its research directed at or responding to any decision-making constituency. Moreover, a key tenet of the HGP ELSI program from the outset was that it conducted research on the implications of science emerging from the HGP, but did not address the deeper question of how the HGP science agenda was actually set, or what science actually ought to be done. Nor were there formal mechanisms by which ELSI research could feed back into the science policy making process. Neither the genomics community supported by the HGP, nor the bioethics community who benefited from ELSI funding, sought to change this situation, which in fact protected the autonomy of both.

According to Robert Cook-Deegan's (1994) account of the origins of ELSI, several influential Members of Congress voiced concern that the structure of ELSI—basically, to provide research grants for academic social scientists and humanists—was not likely to prove policy-relevant. As Cook-Deegan explains, efforts by the National Institutes of Health to sponsor a separate policy analysis function that might link ELSI research to policy decision processes were not successful.

The 21st Century Nanotechnology Research and Development Act rediscovers this fundamental defect in the HGP ELSI program. There are no mechanisms to connect policy questions to social implications research agendas, and the processes by which research results are to enhance decision making are not stipulated. However, as Fisher and Mahajan (in review) recognized in their careful analysis of the law, it does demand something new, different, and important: integration of NSE research and social implications research. All NSE research centers are required to "include activities that address societal, ethical, and environmental concerns," and such centers must, "insofar as possible, [integrate] research on societal, ethical, and environmental concerns with nanotechnology research and development."

When combined with the further requirement that participatory decision mechanisms be included in social implications research activities, this integration of natural and social sciences raises the possibility that nanotechnology research institutions could be structured to build social learning and reflexiveness into the research process, and thereby offer internal guidance for the production of NSE knowledge. This integration, in other words, could make nanotechnology governance a part of the knowledge creation process itself (Guston and Sarewitz, 2002), pushing it "upstream," as it were, into the scientific laboratory (Wilsdon and Willis, 2004), where scientists and engineers are making choices about the types of problems they address, the approaches they use, the outcomes that they seek to pursue.

The theoretical and empirical basis for suggesting that such an approach to knowledge production might be societally beneficial builds on the last half-century of social science research into the character of scientific and technological advance. Starting in the 1950s, economists studying the relationship between technological innovation and economic growth began to build a picture of scientific research (including basic science) as embedded in a complex social network. Innovation emerged from the continual interactions of a variety of actors in a variety of institutions, including academic scientists, industrial scientists, research administrators, regulators and policy makers, corporate executives, and consumers (e.g., Mowery and Rosenberg, 1991; von Hippel, 1988).

A second branch of scholarship over the past several decades has revealed the texture of the social embeddedness of research, as elaborated in historical (e.g., Shapin and Schaefer, 1985;

Leslie, 1993), sociological (e.g., Epstein, 1996), cultural (e.g., Schwarz and Thompson, 1990), and political (e.g., Ezrahi 1990; Guston 2000) approaches. Broader, grounded theory and policy analytic treatments now recognize that any analytical framework for understanding knowledge production systems must be founded on an elucidation of social contexts within which knowledge production is occurring (e.g., Gibbons et al., 1994; Functowicz and Ravetz, 1992; Sarewitz et al, in press). Science and society, that is, are "co-produced;" they are mutually constituted through a network of actors and institutions in which decisions about science and technology are made (e.g., Latour, 1988; Jasanoff, 1996, 2004).

Is it feasible to operationalize this enormously powerful and well-supported insight in the design of knowledge-producing institutions by making co-production explicit in the knowledge creation process? In particular, through engaging scientists and various publics in discourse about the contexts, meanings and values surrounding nanotechnology (real and imagined), could institutions build a greater capacity for reflexiveness—that is, social learning that can expand the range of conscious choice—in knowledge production—as knowledge is being produced? If one takes seriously the language of the 21st Century Nanotechnology Research and Development Act, it could be interpreted as supporting institutional experimentation to probe the hypothesis that expanding awareness of context and choices in NSE research institutions can be the basis for steering knowledge and knowledge-based innovation toward socially desirable outcomes, and away from undesirable ones.

Yet, as our narratives above are meant to illustrate, social scientists and humanists had little if any engagement with nanotechnology during the 1980s and 1990s, leaving the consideration of societal implications to technologists like Drexler, Kurzweil, and Joy, to activists like Pat Roy Mooney, and to science fiction authors. Nor is there any evidence (although, admittedly, it is difficult to know where such evidence might lie) that science studies and science policy scholars were discontented with the manner in which NSF supported research on the societal implications of nanotechnology, given that such support was disbursed through standard peer-review mechanisms via programs with which scholars were already familiar, and which gave them maximal autonomy.

What, then, are the origins of the policy innovation at the core of the 21st Century Nanotechnology Research and Development Act? Our conversations with the legislative staffers who drafted the bill indicate that they well understood that the integration of social implications and NSE research could allow more informed decision making about the science itself in light of both societal goals and concerns. The staffers also recognized that one of the major failings of HGP ELSI was the lack of such integration. "It's common sense," said one staffer, who also noted that Congress was "divorced from academic politics," meaning that the legislative drafters didn't have to worry about the academic barriers to interdisciplinary research that so often obstruct effective integration—they could simply decree integration as a condition of receiving federal support.

House and Senate approaches diverged on the question of whether social implications work should be an integral part of all NSF-funded NSE research, or whether a major center should be funded as a flagship for such integrated activities. In particular, staff from the Senate Committee on Commerce, Science, and Transportation, whose ranking member was from South Carolina, pushed for the funding of a Center, because they felt that the University of South Carolina, which had already received a major NSF grant for social implications of nanotechnology, would be well positioned to compete successfully for the national center. Local politics was thus a key driver of the institutional innovation at the heart of the Act.

Political necessity was also a key to other important provisions. Science legislation is of a generally low priority in the U.S. Congress, and thus for the most part is only brought to a vote under conditions of unanimous consent (that is, without any debate or formal vote). This favors accommodation of minority views, because any one disgruntled Member can thus, in theory, block passage of a bill. So it was that majority (Republican) staff, as well as the Administration of President George W. Bush, opposed the inclusion of language mandating the use of participatory processes such as consensus conferences, but a Democratic representative worked to have this provision added in exchange for her support of the bill. This language adds considerable richness to the options that might be available for adding a significant reflexive capacity to NSE research institutions. Similarly, the language mandating the investigation of nanotechnology's implications for artificial intelligence reflected the concerns of a single representative. This language is important because it makes clear that social implications go beyond traditional risk-based formulations to broader considerations of desirability.

More generally, the social implications language in the 21st Century Nanotechnology Research and Development Act represents a response to the public debate that germinated around nanotechnology starting about the time when Bill Joy published his famous article. In some very real sense, Congress was acknowledging and seeking to address the nascent conflict and anxiety, in a way that perhaps reflected some learning from the bruising experiences of disputes over nuclear power generation, nuclear waste disposal, genetically modified foods, genomics, cloning . . . .

Or perhaps not. We do not mean to be overly optimistic. As Fisher and Mahajan (in review) have noted, most of the 21st Century Nanotechnology Research and Development Act is devoted to accelerating the pace of NSE advance. The fact that the new law would allow—and perhaps even encourages—institutional innovation for democratic governance of nanotechnology does not suggest that such innovation will occur. In particular, it will be interesting to see if the current NSF competition for a Center for Nanotechnology in Society will lead to the testing of truly novel institutional arrangements, or if it will end up settling on a more conventional organization, perhaps with a more traditional risk-communication or public-understanding-of-science focus.

Whatever happens, it is abundantly clear that the community of scholars who have, over the past several decades, built up a deeply textured understanding of the social embeddedness of science and technology, were largely absent from the processes by which the social implications of nanotechnology became the increasing focus of federal attention and largesse. One cannot help but wonder if this lack of engagedness might have been a good thing, in that it allowed the "common sense" of Congressional staff to manifest in legislation that offers the potential for a truly innovative organization of social implications inquiry that potentially threatens the autonomy of NSE scientists and science studies scholars alike.

Yet, as perversely satisfying as such speculation may be, it is perhaps closer to the mark to recognize this lack of engagedness as one of the reasons why nanotechnology got a 15 year head start on serious thinking about how society ought to govern its emerging capability in molecular manipulation. With Bill Joy's relinquishment on one side, and the NNI's full-steam-ahead approach on the other, there is plenty of room for creative experiments in scientific and technological governance rooted in theory and observation of scholars working in the fields of science studies and science policy (e.g., see Sarewitz and Woodhouse 2003; Wilsdon and Willis, 2004). Two key questions remain: Are such scholars sufficiently willing to get their hands dirty? And is the momentum of nanotechnology still amenable to anticipatory governance? A "yes" to both may be necessary if we are to move beyond the brittle, reactive, regulatory governance modes that have characterized responses to technologies from nuclear power to genetically modified foods.

References Cited

Armstrong, J.A. (2001) 'Technological Implications of Nanotechnology: Why the Future Needs Us' in M. Roco, et al. (eds). **Societal implications of nanoscience and nanotechnology**. Boston: Kluwer Academic Publishers.

Baum, R. (2003) 'Nanotechnology: Point/Counter Point', **Chemical and Engineering News**, 81**(**48), 37-42.

Bear, G. ((1985) **Blood Music**, New York: William Morrow.

Berube, D. & Shipman, J.D. (2004) 'Denialism: Drexler vs. Roco' **IEEE Technology and Society Magazine**, 23:

Cook-Deegan, R. (1994) **The Gene Wars: Science, Politics and the Human Genome**, New York: W.W. Norton & Company.

Crichton M. (2002) **Prey**. New York: HarperCollins

Crow, M., and Sarewitz, D. (2001). 'Nanotechnology and Societal Transformation,' in Roco, M.C. & Bainbridge, W. (eds.), **Societal implications of nanoscience and nanotechnology**. Boston: Kluwer Academic Publishers.

Drexler, K.E. (1986). **Engines of Creation: the coming era of nanotechnology**, New York: Anchor Press/Doubleday. Available online at: http://www.foresight.org/EOC/EOC.html)

Epstein, S. (1996). **Impure Science: AIDS, Activism, and the Politics of Knowledge**. (p. 201). Berkeley: University of California Press.

Ezrahi, Y. (1990). **The Descent of Icarus: Science and the Transformation of Contemporary Culture**. Cambridge: Harvard University Press.

Feynman, R. (1960). 'There is Plenty of Room at the Bottom, **Engineering and Science** Pasadena, CA: California Institute of Technology.

Fisher, E. & Mahajan R.L. (in review) Growing Pains: U.S. Federal Nanotechnology Legislation's Requirement to Factor Societal Considerations in to R&D

Funtowicz, S.O. & Ravetz, J.R. (1992). 'Three Types of Risk Assessment and the Emergence of Post-Normal Science'. In S. Krimsky & D. Golding (Eds.), **Social Theories of Risk** (pp. 251-273). Westport, CT: Praeger.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M. (1994). **The new production of knowledge**. London: Sage Publications.

Guston, D. (2000). **Between Politics and Science: Assuring the Integrity and Productivity of Research**. (p. 213). New York: Cambridge University Press.

Guston, D.H. & Sarewitz, D. (2002). 'Real-Time Technology Assessment'. **Technology in Culture**, 24, 93-109.

House Committee on Science (2003) Hearing Charter, **Societal Implications of Nanotechnology**, http://www.house.gov/science/hearings/full03/apr09/charter.htm

Jasanoff, S. (1996). 'Beyond Espistemology: Relativism and Engagement in the Politics of Science'. **Social Studies of Science**, 26(2), 393-418.

Jasanoff, S. (Ed.) (2004). **States of Knowledge: The Co-Production of Science and Social Order**. New York: Routledge.

Johnston, J. (2001). 'Distributed Information: Complexity Theory in the Novels of Neal Stephenson and Linda Nagata', **Science-Fiction Studies** 28: 223-245.

Joy, B. (2000). 'Why the future doesn't need us', **Wired**, 8.04.

Juengst, E.T. (1991) 'The Human Genome Project and Bioethics', **The Kennedy Institute of Ethics Journal**, 1(1): 71-74.

Klaes, Larry (2004) What is Nanotechnology? Well, It's Very, Very, Very Small. The Ithaca Journal, April 8, http://www.theithacajournal.com/news/stories/20041008/duffieldhall/1380292.html

Kurzweil, R. (1998). **The Age of Spiritual Machines: When Computers Exceed Human Intelligence.** New York: Viking.

Kurzweil, R. (2003). 'Promise and Peril'. In A. Lightman et al. (Eds.), **Living With the Genie: Essays on Technology and the Quest for Human Mastery** (pp. 35-62). Washington D.C.: Island Press.

Latour, B. (1988). **The Pasteurization of France**. Cambridge: Harvard University Press.

Leslie, S.W. (1993). **The Cold War and American Science**. New York: Columbia University Press.

Miksanek, T. (2001). 'Microscopic Doctors and Molecular Black Bags: Science Fictions' Prescription for Nanotechnology and Medicine', **Literature and Medicine** 20(1): 55-70.

Monmaney, T. (1986). 'Nanomachines to the Rescue,' **New York Times**, August 10, Section 7, p. 8.

Mooney P. (1999) 'The ETC Century: Erosion, Technological Transformation and Corporate Concentration in the 21st Century', **Development Dialogue**, 1-2.

Moravec, H. (1986), 'Engines of Creation' (book review), **Technology Review**, 8(Oct), 76.

Mowery, D.C. & Rosenberg, N. (1991). **Technology and the Pursuit of Economic Growth**. New York: Cambridge University Press.

Mnyusiwalla, A., Daar, A., and Singer, P. (2003). '"Mind the Gap": Science and Ethics in Nanotechnology', **Nanotechnology** 14: R9-R13.

National Science and Technology Council (NSTC) Interagency Working Group on Nanscience, Engineering and Technology (IWGN) (1999) **Nanotechnology: Shaping the World Atom by Atom**. Washington DC: NSTC
National Science and Technology Council (NSTC) Interagency Working Group on Nanscience, Engineering and Technology (IWGN) (2001**) National Nanotechnology Initiative: Leading to the Next Industrial Revolution**. Washington DC: NSTC
National Science and Technology Council (NSTC), Nanoscale Science, Engineering, and Technology Subcommittee (2004). **The National Nanotechnology Initiative Strategic Plan**. Washington, DC: NSTC.
Nobleprize.org (1996) http://nobelprize.org/chemistry/laureates/1996/press.html
NSF (2004) Nanscale Science and Engineering Program Solicitation FY 2005 Washington D.C. NSF
Peterson, C.L. (2004) 'From Feynman to the Grand Challenges of Molecular Manufacturing', **IEEE Technology and Society Magazine**, 23:
Presidents Information Technology Advisory Committee (PITAC) (1999) **Information Technology Research: Investing in Our Future**, Washington D.C.: PITAC
Preuss, P. (1985). **Human Error**, New York: Tor Books.
Roco, M.C. (2004). 'The US National Nanotechnology Initiative after 3 Years (2001-2003)', **Journal of Nanoparticle Research**, 6**,** 1-10.
Roco, M.C. & Bainbridge, W. (Eds.). (2001). **Societal implications of nanoscience and nanotechnology**. Boston: Kluwer Academic Publishers.
Sarewitz, D. (1996). **Frontiers of Illusion: Science, Technology, and the Politics of Progress**. Philadelphia: Temple University Press.
Sarewitz, D., Foladori, G., Invernizzi, N., & Garfinkel M. (in press). 'Science Policy in its Social Context', **Philosophy Today**.
Sarewitz, D. & Woodhouse, N. (2003). Small is Powerful. In A. Lightman, et al. (Eds.), **Living With the Genie: Essays on Technology and the Quest for Human Mastery** (pp. 63-84). Washington D.C.: Island Press.
Schwarz & Thompson. (1990). **Divided We Stand**. Philadelphia: University of Pennsylvania Press.
Shapin, S., Schaffer, S. et al. (1985). **Leviathan and the air-pump: Hobbes, Boyle, and the experimental life**. Princeton, N.J.: Princeton University Press.
Sclove, R. E. (1995) **Democracy and Technology.** New York: The Guilford Press.
Shrader-Frechette, K. & Westra, L. (1997) **Technology and Values**. New York: Rowman & Littlefield Publishers.
Stephenson, N. (1995). **The Diamond Age**. New York: Bantam Books.
Suchman, M. (2001). 'Envisioning Life on the Nano-Frontier," in Roco, M.C. & Bainbridge, W. (eds.), **Societal implications of nanoscience and nanotechnology**. Boston: Kluwer Academic Publishers.
Tenner, E. (2001). 'Nanotechnology and Unintended Consequences," Roco, M.C. & Bainbridge, W. (eds.), **Societal implications of nanoscience and nanotechnology**. Boston: Kluwer Academic Publishers.
von Hippel, E. (1988). **The Sources of Innovation**. New York: Oxford University Press.
Wilsdon, J. & Willis, R. (2004). **See-Through Science: Why Public Engagement Needs to Move Upstream**. London: Demos.

World Technology Evaluation Center (1998) R&D Status and Trends in Nanoparticles, Nanostructured Materials and Nanodevices in the United States, Washington D.C.: World Technology Evaluation Center