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

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'Nanotechnology' is still in its infancy. Nevertheless, and despite ongoing disagreements about how 'nanotechnology' ought to be defined, narratives emerging from a diversity of sources share the notion that the societal impacts of nanotechnology could be transformational, perhaps radically so, in social realms as diverse as privacy, workforce, security, health, and human cognition. One consequence of this shared belief is a nascent effort to understand, anticipate, and perhaps manage the implications and dynamics of the societal impacts of nanotechnology.

A rapidly expanding menu of conferences and reports, sponsored by governmental and non-governmental bodies in the US and Western Europe, attest to a growing concern about the societal effects of nanotechnology (e.g. Roco and Bainbridge, 2001; ETC, 2003; Meridian Institute, 2005; Wilsdon and Willis, 2004; Royal Society/Royal Academy of Engineering, 2004). In the US, a federal initiative to fund nanoscale science and engineering (NSE) research was accompanied at its inception in 2000 by a commitment to support a parallel, if substantially smaller, research effort on societal implications. Three years later, the US Congress actually passed legislation to mandate the expansion of this effort.

In this paper we ask: what roles are the social sciences playing in the emerging co-evolution of nanotechnology and society, and, crucially, how do those roles come to be defined? To probe this question, we look to the US experience in constructing three brief narratives of our own to illustrate the 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 and technology studies ('science studies' hereafter) and science and technology policy scholars seem to have engaged with the challenges of nanotechnology only when stimulated by the

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appearance of federal research funding starting in about 2001. Thus, they did not materially participate in the framing of public discourses about nanotechnology, or in the design of research programmes to study the social implications of nanotechnology. In their absence—perhaps due to their absence—a policy programme 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 origins and early development of nanotechnology have yet to be critically investigated by historians and science studies scholars, but the canonical story (also see McCray, 2005) 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, p. 7).

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 tunnelling 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 the buckyball the 'molecule of the year' in 1991. Kroto, Smalley, and Curl shared the 1996 Nobel Prize in physics (Nobelprize.org, 1996).

Government and private investment in nanoscale science and engineering (NSE) continued to expand. In the US, the National Science Foundation (NSF) began its first programme devoted exclusively to NSE in 1991, funded at about six million dollars (World Technology Evaluation Center, 1998). In 1998, the US government organized the Interagency Working Group on Nanotechnology, 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, p. 5).

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 relabelling existing research activities to take advantage of the latest funding fad, but the trend also signalled 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 1,677 (Figure 1), and 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, *Nanotechnology*, was launched in 1990; two more journals, *Nanostructured Materials* and the *Journal of Nanoparticle Research*, were started later in the decade, and an additional four were launched between 2001 and 2003: *Fullerenes, Nanotubes, and Carbon Nanostructures*, *International Journal of Nanoscience*, *Nanoletters*, and *Nanobiotechnology*.

The political processes that led to the selection of NSE as a priority focus within US research agencies, the role of commercial incentives in determining research trajectories, the processes by which diverse research activities in numerous, disparate scientific fields congregated beneath the nanotechnology umbrella, and other aspects of the internal dynamics of our admittedly linear and descriptive story, await additional study. For our purposes, however, the lack of nuance in this story is precisely the point. Rapid increases in government attention, public funds, and scientific activity occurred without significant scrutiny or critique; to date, the NSE story has mostly been told by those who have promoted or otherwise been involved in this version of the story.

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

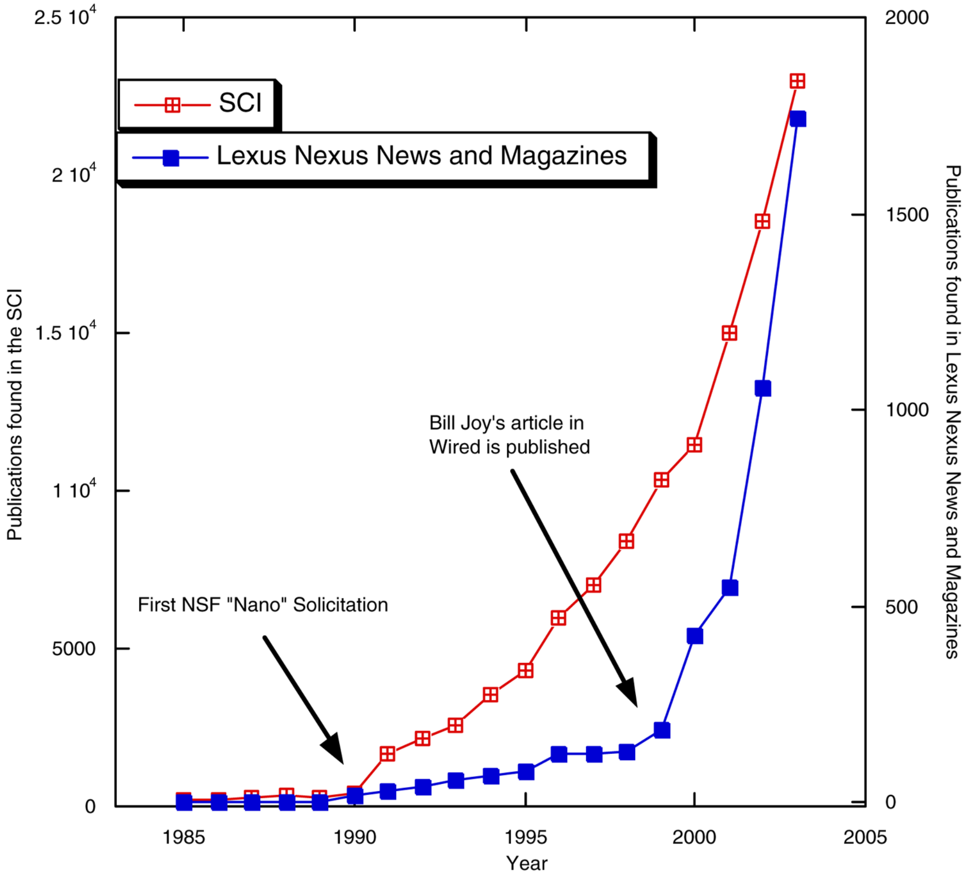

Figure 1. Nanotechnology in science literature and popular press

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, p. 10).

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 (p. 12).

As an MIT-trained engineer, and claiming to stand 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 scepticism 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 (based on searching the amazon.com website). Examples include: Kevin Anderson and Doug Beason's 1993, *Assemblers of Infinity*; Michael Flynn's 1991, *The Nanotech Chronicals*; and Ian McDonald's 1994, *Terminal Café*. 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 imagining what could be done with it' (p. 31).

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 1,750 (Figure 1). Michael Crichton's nanotech-catastrophe book *Prey* (2002) became a national bestseller. Amazon.com lists 21 hardcover books (non-fiction 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 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 and 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 (p. 7).

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.

Joy's solution was to argue for 'relinquishment: to limit development of the technologies that are too dangerous, by limiting our pursuit of certain kinds of knowledge' (p. 8). 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* (Garreau, 2000) and *New York Times* (Markoff, 2000). 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 1991 the popular journal *The Futurist* published a series of letters 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* (e.g. Braun *et al.*, 1997) and *Research Policy* (e.g. Meyer, 2000) began to track scientific and technical trends. As late as 2000, however, nanotechnology was not visible 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 *et al.* (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]' (p. 9).

While some scholars may have flagged nanotechnology as an area in need of scrutiny prior to 2000, we find little evidence of this. For example, there is no mention of nanotechnology in scholarly works that confronted the broad challenges of governing societally transforming technologies. The comprehensive *Handbook of Science and Technology Studies* (Jasanoff *et al*., 1995), 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) do not deal with nanotechnology even in passing. The *Science and Technology Policy Yearbook*, which includes proceedings from an annual forum sponsored by the American Association for the Advancement of Science, included no articles about nanotechnology until the 2001 edition (Teich *et al*., 2001). The National Science Foundation did not fund research on the societal impacts of nanotechnology until the early 2000s.

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 1990s 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?). 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 apparently not participating in the gradually unfolding societal discourse about nanotechnology. Notably, however, in 2001 two academic papers were published that analysed 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 US 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, and 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 programme of the Human Genome Project, as well as the Human Dimensions of Climate Change initiative of the US 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 co-author Sarewitz), 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 later in that chapter the authors state 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. 14, 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).

Following this conference, in its request for proposals (RFPs) for 2001 and 2002, the NSF included a call for social science inquiry into nanoscale science and engineering under the Social, Behavioral, and Economic Sciences Directorate (SBE). There were no projects funded under SBE in either of those two years, in part because, as the 2002 National Research Council (NRC) report 'Small Wonders' suggested, '... no funding was allocated directly to the Directorate of Social and Behavioral and Economic Sciences, the most capable and logical directorate to lead these efforts' (NRC, 2002, p. 34). All of the NSE proposals for 2001 and 2002 would be competing with each other, pitting social science projects not only against each other but against science and engineering projects as well. The 2002 NRC report outlined a series of concerns, from funding to intellectual commitment, about social implications of NSE research and concluded 'that the NSET (Nanoscale Science, Engineering and Technology Subcommittee) develop a new funding strategy to ensure that the societal implications of nanoscale science and technology become an integral and vital component of the NNI' (NRC, 2002, p. 48).

Although the language in the RFP for FY 2003 was identical to 2001 and 2002, a stronger funding commitment by NSF led to support for two major projects at roughly $1.5 million each over five years. One of these projects was the development of NanoBank, a web-based database, covering all published aspects of NSE; the other project focused on outreach and research activities to examine concepts of understanding and control necessary to achieve effective democratic deliberation about NSE. In succeeding years a small number of modest (10s to 100s of thousand dollar) projects were granted to academic scholars working 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 programme 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 US 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 about 5% of total project expenditures, which amounted to $162 million for the period 1991–2003 (Ow, 2005).

Through 2004, NSF funding for research on the social implications on nanotechnology was disbursed in a non-strategic manner to diverse universities. The situation is now partly changing. In 2004, the US Congress passed the '21st Century Nanotechnology Research and Development Act', whose main purpose was to assert 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, 2003, emphasis added). Prior to the passage of this legislation, the US 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, Ernest Hollings.

The US 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 (Kurzweil, 2003); Christine Peterson, who was President of the Foresight Institute, which Drexler had founded and which bases its advocacy of nanotechnology on Drexler's notion of molecular manufacturing; and the science studies scholar Langdon Winner, a long-time advocate of increased democratic participation in technological decision making. Notably, among the questions each witness was asked to address was: '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, p. 2).

The issues raised in the Science Committee hearing are explicitly addressed in the 21st Century Nanotechnology Research and Development Act, which includes clauses that single 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 . . . (p. 3).

In response to the passage of the legislation, NSF in August 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. The programme solicitation included 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, p. 9).

Four years after NSF began to provide support for social science and humanities research on the societal implications of nanotechnology, and in the early stages 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 fails to reveal 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 recent empirical work (e.g. Mody, 2004; Berne, 2005), but the key point here is that this area of research has been created by a federal funding commitment; it did not arise directly in response to the societal challenges presented by the emergence of nanotechnology.

Alliance of Common Sense and Science Studies

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 endeavour? 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 US 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 programme 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, p. 71); 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 programme from the outset was that it conducted research on the implications of science emerging from the HGP, but did not address deeper questions about 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, particularly the provision of research grants for academic social scientists and humanists, was not likely to prove policy-relevant. Cook-Deegan further describes how 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 programme. 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 (2006) 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 centres are required to 'include activities that address societal, ethical, and environmental concerns', and such centres must, 'insofar as possible, [integrate] research on societal, ethical, and environmental concerns with nanotechnology research and development' (PL-108-153, 2003, p. 3).

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 (by which we mean the broadly disseminated processes in which decisions about nanotechnology are made) a part of the knowledge creation process itself (Guston and Sarewitz, 2002), pushing it 'upstream', as it were, into the earlier stages of the innovation process (Wilsdon and Willis, 2004), where scientists and engineers are making choices about the types of problems they address, the approaches they use, and 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 (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 Schaffer, 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; Funtowicz and Ravetz, 1992; Sarewitz *et al*., 2004). That is, science and society 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 reflection on the social implications of nanotechnology *as part of the nanotechnology research process itself?* Such reflection would expand awareness of the breadth and potential implications of alternative choices available to nanotechnology researchers and other stakeholders. 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. Moreover, it appears that the 2000 NSF-sponsored conference on the societal implications of nanotechnology, which marked the agency's first explicit recognition of the importance of this issue, was instigated primarily by NSF's Mihail Roco, chair of the government Interagency Working Group on Nanoscience, Engineering and Technology. This top-down process, with science studies scholars nowhere to be seen, bares an eerie similarity to the origins of the HGP ELSI programme, which was the idea of HGP Director James Watson (Cook-Deegan, 1994). 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 programmes 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 US Senate and House of Representatives 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 did not have to worry about the academic barriers to interdisciplinary research that so often obstruct effective integration—they could simply decree cross-disciplinary integration as a condition of receiving federal support.

Early House and Senate approaches to the legislation diverged on the question of whether social implications work should be an integral part of all NSF-funded NSE research, or whether a major centre 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, Senator Hollings, was from South Carolina, pushed for the funding of a centre, 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 centre. 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 US 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 favours accommodation of minority views, because any one disgruntled elected 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 of key importance because it makes clear that Congress viewed the social implications nanotechnology in terms that went beyond the traditional technocratic risk-based formulations to include explicitly normative 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, and so on.

We do not mean to be overly optimistic. As Fisher and Mahajan have noted, most of the 21st Century Nanotechnology Research and Development Act is devoted to accelerating the pace of NSE advance. On the one hand, as a result of the new law, the National Science Foundation has recently decided to support a five-year, multi-university experiment in reflexive governance of nanotechnology, as sketched above (for more information, see http://cns.asu.edu/). On the other, the scale of this effort is miniscule relative to the billion-dollar federal NSE endeavour. It is difficult to imagine that a single attempt to prototype and study new institutional arrangements for the governance of nanotechnology would lead to a scaling-up of effort sufficient to have a significant impact on choices and innovation paths at the US national level in the near-term. Yet it may also well be the case that serious efforts to understand and potentially manage the societal effects of nanotechnology are farther along, at an earlier stage in the evolution of the technology, than has been the case for previous episodes of emergent transformational technologies (Woodhouse, 2005). This may be modest progress.

Conclusion

We have asked: what roles are the social sciences playing in the emerging co-evolution of nanotechnology and society, and, crucially, how do those roles come to be defined? Our brief narratives illustrate that the first several decades of nanotechnology were unencumbered by formal input from the social sciences, even though the world-transforming potential of nanotechnology was proclaimed by Richard Feynman in 1959, and imaginatively expanded by techno-visionaries and science fiction writers starting in the early 1980s. Science studies scholars were largely absent from the processes by which the social meanings and implications of nanotechnology became part of public discourse. They were also, at best, marginal players in the US while bureaucrats and lawmakers began to set an agenda for discussion about, and research into, the societal implications of nanotechnology. As a result, nanotechnology got a 15-year head start on serious thinking about how society ought to govern its emerging capability in molecular manipulation, and the science studies community—much like society at large—finds itself in a position of reaction and dependence relative to nanotechnology.

This is not to say that science studies has nothing to offer here. Indeed, the deeply textured understanding of the social embeddedness of science and technology constructed by science studies over the past few decades cries out for application to the design of regimes for more reflexive governance of potent emerging technologies (Guston and Sarewitz, 2002). Yet, as our stories suggest, it is perhaps no more than fortuitous that the 'common sense' of legislative aides led to a formal mandate for the application of such insights to the nanotechnology research enterprise itself. Moreover, the fiscal commitment that underwrites this mandate is probably too small to have a broad impact on technological governance, at least in the near-term.

What would it take for the science studies community to play a more assertive and effective role in framing discourses, setting research priorities (its own, as well as those of technoscientists), and designing governance structures for future technoscience 'revolutions'? As a first step, a greater commitment to and capacity for serious surveillance of embryonic areas of scientific and technological endeavour, coupled with a greater commitment to policy engagement, would seem to be in order. Fulfilling such a commitment would initially require cross-disciplinary alliances with researchers from related fields who deploy tools such as foresight and forecasting, research evaluation, innovation indicators, and policy analysis. Our nanotechnology story suggests that, in the absence of a strategically proactive approach to setting their own agendas, science studies scholars are likely to remain no more than intellectual pilot fish hitching a ride on the technoscience leviathan.

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