Nanotechnology:

From Feynman to the Grand Challenge of Molecular Manufacturing

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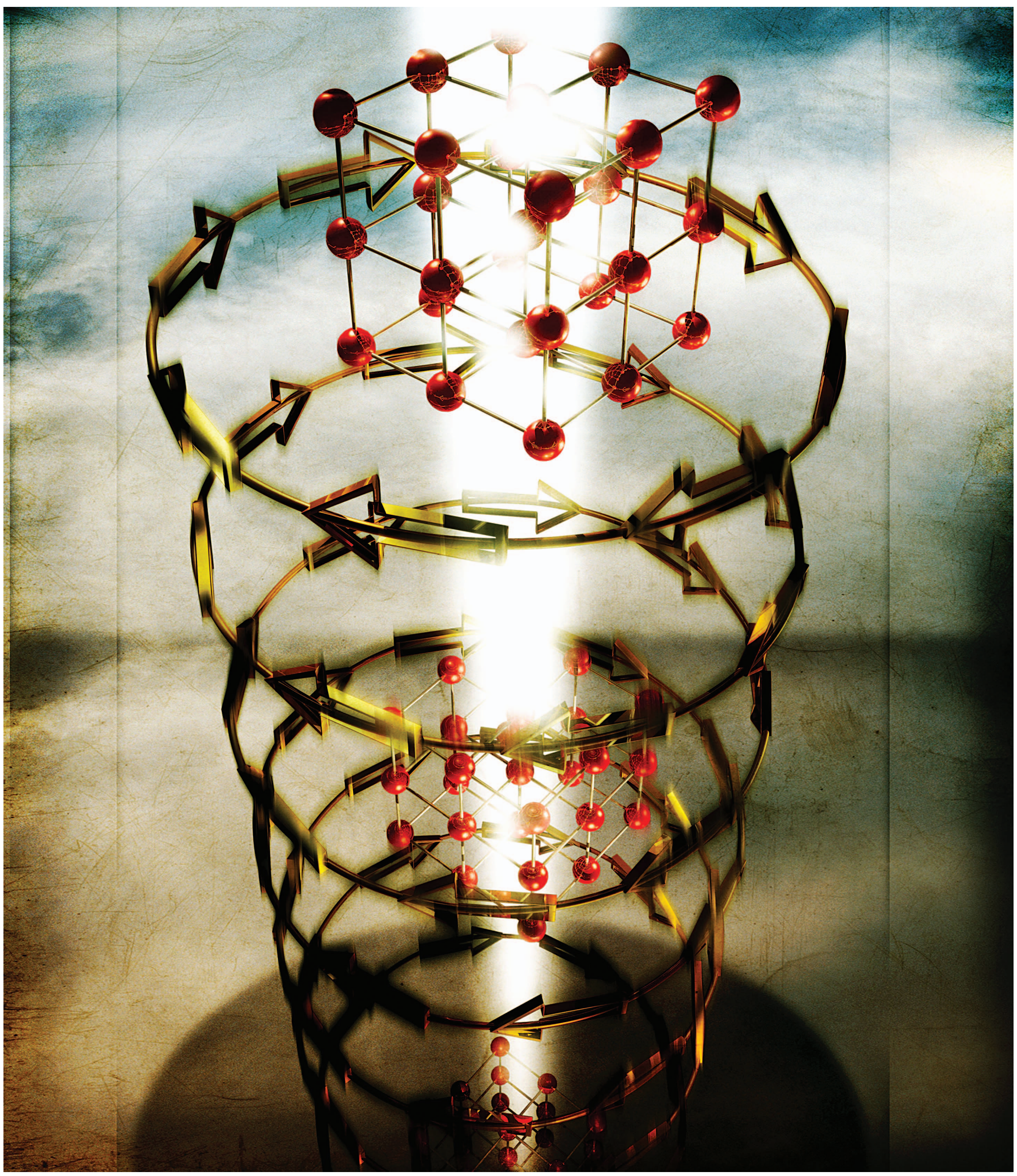

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The term nanotechnology has come to have two primary meanings: 1) new science and technology that takes advantage of properties operating at the nanoscale, and 2) building with atomic precision through the use of molecular machine systems. The first meaning refers to developments occurring today; the second to an ambitious technological goal at least a decade off. These radically different meanings are making coherent discussion of public investment policy and societal implications very difficult.

Matter can be perceived as something to be manipulated more precisely, building large products from the "bottom-up."

I will distinguish them by referring to the first as near-term nanotechnology and the second as molecular machine systems, or molecular nanotechnology (MNT), also termed molecular manufacturing. This paper will attempt to sketch the history of the field overall, the confusion that has arisen between the various types of nanotechnology, the politics of U.S. funding, and prospects for broadening future R&D to put greater emphasis on the goal of building with atomic precision. Although I strive for accuracy and fairness, in appraising my argument the reader should know that the Foresight Institute, of which I am an officer, is one of the main partisans in the controversy under discussion.

The Feynman Goal

Perhaps surprisingly, it was the second, futuristic meaning that was introduced first. The basic concept was outlined by Nobel Prize-winning physicist Richard Feynman in 1959, when he said "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big" [1]. He described building with atomic precision, and even sketched out a pathway involving a series of increasingly smaller machines. He explained, "if we go down far enough, all of our devices can be mass produced so that they are absolutely perfect copies of one another." These assertions were sufficiently new to his audience of physicists that some in the audience laughed, under the impression that he was joking [2], [3].

Although he did not use the term, it is clear that Feynman was pointing toward what is today termed molecular manufacturing, a goal of using systems of molecular machines to build with precision at the atomic level subsequently explored by K. Eric Drexler in journal articles beginning in 1981 [4], [5] and in the textbook *Nanosystems* in 1992 [6]. Thinking in terms of molecular machines leads to a fundamental change of viewpoint: Rather than taking physical matter as a given, with an uncontrolled bonding structure having to be carved away into smaller pieces of approximately the correct composition and shape (the "top-down" method of product construction), matter can be perceived as something to be manipulated far more precisely, building large products from the "bottom-up" [9]. If this could be actualized, it potentially would affect every physical object from computers to the human body, leading an early observer to comment that it "could bring more change than all that had come about since near-medieval times" [10].

To envision this proposed technology, picture a conveyor belt and assembly line such as one would find in a factory today — but at the nanoscale. Molecular manufacturing would combine the chemical action of reactive molecules with the atomically precise three-dimensional positioning seen in contemporary scanning probes. Building macroscale products with this technology of course would require massive parallelism. Manufacturing performed in this manner would maintain control over all materials being utilized, leaving little excuse for dumping excess molecules into the air or water — and thereby substantially reducing chemical pollution [11]. One can also envision nanoscale robotic systems for medical applications. Assuming that the manufacturing processes could be performed cheaply and in a decentralized manner, the implications for alleviating poverty are inescapable. [12], [13]. Space transportation and development likewise would benefit, perhaps enormously [8].

On the other hand, the history of technology reveals that any powerful new technology can be used for harmful as well as beneficial purposes, and MNT advocates began early on to explore potential military uses and accident scenarios [8], [12], [13]. A non-profit organization, Foresight Institute, was formed in 1986 to educate the technical community and general public on these and other issues, with the intention of "preparing for nanotechnology."

Inspired in part by the mid-1970s' Asilomar guidelines developed by biotechnologists seeking to conduct their early work in ways both safe and publicly acceptable, Foresight in 1999 published draft guidelines for safe development of MNT, including specific recommendations for environmental protection such as requiring artificial rather than natural fuel sources [16], [17]. (See Table I.)

Researchers from many fields began to re-label and adapt their work as "nanotechnology," partly to make clear the interconnections, and partly to jump on what was coming to be a funding bandwagon. They were of course aware that the word had a radical-sounding connotation; as one of the planners of the NNI, Hewlett-Packard researcher Stan Williams, stated, he "didn't like the word nanotechnology" [18]. Nevertheless, the term had the advantage of capitalizing on a decade's publicity regarding potential medical and other benefits, enhancing the likelihood of administration support and U.S. congressional funding.

At U.S. congressional hearings held in June 1999 to discuss establishing a major new nanotechnology R&D program, supporters of molecular manufacturing were represented by computational nanotechnologist Ralph Merkle, who described potential MNT benefits and argued "the benefits will be pervasive across companies and the economy; few if any companies will have the resources to pursue this alone; and development will take many years…. We know it's possible. We know it's valuable. We should do it" [19]. It seems unlikely that MNT advocate Merkle would have been given such a central role (as one of four invited to testify) if the new program's proponents had not intended to send Congress the message that MNT research would be included in the expanded initiative [20]. A 1999 NNI promotional brochure likewise described and seemingly endorsed "Feynman's vision of total nanoscale control," terming it "the original nanotechnology vision" [21]. Another NNI document explained, "the essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization" [22].

In January 2000, President Clinton went to the California Institute of Technology to announce the new U.S. National Nanotechnology Initiative (NNI), initially to be funded at a level of $500 million. Although MNT was not explicitly funded, Clinton's comments —presumably drafted by someone close to the program — seemed to indicate that the Administration's attitude toward federally funded pursuit of the Feynman vision was favorable. MNT advocates of course would have preferred a targeted program, but we assumed that the nearer-term nanoscale research would gradually build infrastructure useful for molecular machine systems.

TABLE I
Foresight Guidelines on Molecular Nanotechnology (Excerpts):

"MNT products should… incorporate systems for minimizing negative ecological and public health impact."
"Regulators should have specific and clear mandates, providing efficient and fair methods for identifying different classes of hazards and for carrying out inspection and enforcement."
"The safe development and use of MNT depends, in part, on the good judgment of the researchers…in avoiding and actively preventing unsafe uses of MNT and in insuring that commercial systems have built-in safeguards."
"The developing MNT R&D community and industry should adopt appropriate self-imposed controls, formulated in light of current knowledge and the evolving state of the art. The possibility of the necessity for additional controls remains an open question, and its resolution may depend to some extent on the success of voluntary controls."
"Accidental or willful misuse of MNT must be constrained by legal liability and, where appropriate, subject to criminal prosecution."
"A substantial R&D program is needed to clarify the nature, magnitude and likelihood of the potential risks, as well as the options available for dealing with them effectively."

Controversy Arises

In April 2000, however, a serious public relations problem arose when respected technologist-entrepreneur Bill Joy published a long essay in Wired magazine reviewing potential downsides of various technologies, including MNT (referred to as "nanotechnology"), and called for "relinquishment" of pathways he considered too dangerous [23]. As then-Chief Scientist of Sun Microsystems, Joy's ideas provoked widespread discussion. Although his proposal for relinquishment was not immediately taken up by any major activist groups, the original NNI program designers nevertheless became concerned that discussion of MNT risks could possibly impact federal funding for all nanotechnology [24].

Two responses were possible: 1) acknowledge the power of the technology and openly discuss ways to avoid potential problems, or 2) deny that the potential problem exists. While Foresight had long advocated the first path, NNI leadership opted for the second. Richard Smalley, who in 1993 "to explain to people what I thought the future was…had given the board of governors here at Rice…copies of some of Eric's books" [2], published a critique of MNT in *Scientific American* in September 2001. Now partially disagreeing with Feynman, he said, "There's plenty of room at the bottom. But there's not *that* much room…To put every atom in its place — the vision articulated by some nanotechnologists — would require magic fingers." He suggested that steric issues ("fat fingers") and molecular adherence problems ("sticky fingers") would render the

MNT goal impossible [25]. Chemist George Whitesides, writing in the same issue of *Scientific American*, raised technical objections to MNT ranging from friction, to power, to information storage and processing. Responding to the assertions, Drexler and colleagues pointed to experiments contradicting some of the alleged constraints, suggested that MNT theory had been partly misinterpreted, and argued that some of the Smalley-Whiteside problems were not fundamental ones but more like design constraints to be overcome by appropriate engineering [26], [27].

From the viewpoint of the Foresight Institute – admittedly a partisan one – the debate from that time on lacked the character one would hope to find in serious intellectual disputes with substantial public consequences. The critics of MNT did not tackle the points of disagreement systematically, using whatever logic and evidence would have been appropriate. Instead, the disagreement was conducted in terms closer to what one often finds in political campaigns. For example, at a joint EU/NSF workshop in early 2002, rather than responding to technical and policy concerns expressed about potential problems with nanomachinery, NNI director Mihail Roco attempted to shut down inquiry by decreeing that "None of this exists… this is only science fiction…these aspects stay outside the development of nanotechnology as we intend it" [29],[30]. At a subsequent industry conference, the NNI director projected that what he termed fourth-generation nanotechnology, "molecular nanosystems," would probably arrive by about 2020; but he made no mention of that term's long association with molecular manufacturing [31]. "People following the NNI (in 2002) knew where it was headed and that it tried to avoid MNT-related topics" [32].

Foresight and the Institute for Molecular Manufacturing sought to counteract this trend in various ways, including, at the invitation from the White House Office of Science and Technology Policy, proposing recommendations for "Balancing the National Nanotechnology Initiative's R&D Portfolio" [33]. The situation grew more interesting yet, however, when well-known author Michael Crichton published the nanotech thriller-horror novel *Prey* in November, 2002 [28]. Ethics scholars began to weigh in, as did the ETC Group, both calling for new processes for public participation, and the latter calling as well for a moratorium on some types of nanotechnology commercialization.

One can envision nanoscale robotic systems for medical applications.

Both public participation advocates and MNT advocates were well represented at hearings of the House Science Committee in early 2003 [34], [35], when the NNI was being converted to a more permanent program, and the committee's draft legislation effectively addressed both goals. The public participation provision was weakened prior to passage, however, and MNT opponents successfully lobbied for a last-minute wording change, replacing the requirement for a MNT feasibility study with the generic term "molecular self-assembly," which may prove vague enough to distract the study away from substantive issues [36].

At about the same time (December 2003), at least some of the attendees at a meeting of the National Science Foundation on societal implications of nanotechnology reported that they tacitly understood that discussion of MNT was verboten for anyone who wanted to retain credibility there [38], [39]. That same month, the cover of the leading chemistry weekly, *Chemical & Engineering News*, featured a vivid illustration of molecular manufacturing [40], and the issue included a debate between Smalley and Drexler. The former no longer asserted that MNT would require "magic fingers," but adduced other technical and metaphorical arguments, which Drexler of course attempted to rebut (successfully, in my opinion). Most readers probably found that the exchange ended rather unsatisfactorily, but it did have the virtue of making the controversy more visible [41], [42]. Policy journals have begun to cover nanotechnology politics and policy, including the present publication and the *Bulletin of Science, Technology & Society* [43].

Deliberately Moving Toward MNT, or Not?

We are now at a crossroads with regard to MNT technology. A certain fraction of researchers in the physical sciences and engineering assume that, since molecular machine systems exist (and are powerful) in nature, the proposal that artificial ones could someday be built, and be even more powerful, is rather obvious. Many of them assume that the NNI is working toward this goal, a perception that, while mistaken, is understandable because, as this is written, an internet search on the term "nanotechnology" indicates that the MNT view of nanotechnology still dominates the top ten sites, despite billions of dollars of NNI spending on nearer-term work. Even the harshest critics of MNT admit that the concepts "even in the scientific arena… tend to dominate discourse around the possibilities of nanotechnology" [44].

Given the current controversy, most of those potentially receiving government funding avoid expressing a definite opinion; when put on the spot, however, few are willing to say that MNT is impossible [45], [46]. Stanford physicist Stephen Chu has estimated fifty years for the more difficult applications [47], not an implausible estimate if one assumes no coherent effort. Given the military and economic advantages expected to accrue to the country reaching real MNT capabilities first, however, such a long delay seems unlikely. Ray Kurzweil has estimated thirty years [35], Ralph Merkle says "probably not many decades" [48], and the Center for Responsible Nanotechnology offers the low estimate — "less than twenty years from now — possibly less than ten" [49].

Despite the lack of a focused program, a significant amount of research now in progress is contributing to MNT infrastructure in fields ranging from molecular self-assembly, scanning probes, and organic synthesis, to the atomically precise areas of nanoparticle and nanofiber work. (See [43] for a partial summary.) Some of this was covered at the first Symposium on Molecular Machines in October, 2004 [64].

Eventually, I anticipate that the U.S. will adopt as its nanotechnology Grand Challenge the goal foreshadowed by Feynman in 1959 and described by nanotech venture capitalist Steve Jurvetson: "Whether conceptualized as a universal assembler, a nanoforge, or a matter compiler, I think the "moon-shot" goal for 2025 should be the realization of the digital control of matter, and all of the ancillary industries, capabilities, and learning that would engender" [50]. A July 2004 report on nanotechnology from the U.K.'s Royal Society and Royal Academy of Engineering, while focused primarily on near-term nanoparticle safety, included favorable coverage of the potential for "bottom-up" massively parallel nano-manufacturing using directed assembly to build products with — in the longer term — zero waste [59]. And in the strongest pro-MNT statement by a political leader to date, the President of India recently cited both Feynman and Drexler in a call for his nation to develop molecular machines with abilities including DNA repair [60].

Whatever the prospects for a civilian program, a military one seems close to inevitable. Warfare has already moved into the nanoscale in the sense that bioweapons are systems of molecular machines that attack other biological systems. For defense, one would like to have tougher, stronger, more flexible molecular machine systems, and this is what MNT should be able to provide. Given this need, it seems only a matter of time before a one or more governments launch military R&D MNT programs.

Such an effort will not necessarily start first in the United States, of course. Another technologically ambitious country, or perhaps even a large multinational, could begin first. A prime candidate is China, which has a large focus on nanotechnology and a large number of educated and inexpensive researchers. Another candidate is Israel, with its strong military orientation, which has announced a determination to be a leader in nanotechnology.

My hope is that inquiry, deliberation, and policy attention soon can move beyond the relatively unproductive controversy between near-term and longer-term nanotechnology. We need to be looking at 1) how to manage the intellectual property resulting from publicly-funded MNT research to maximize public benefit, and 2) how to deliver the economic and environmental advantages of molecular manufacturing without also distributing the ability to construct powerful new weapons. Though their ranks need to be expanded greatly, a number of scholars and public intellectuals in fact are analyzing such issues. Among these are Glenn H. Reynolds, author of the first law review article on nanotechnology, who continues to develop policy recommendations [51]-[53]. Lawrence Lessig, a law professor at Stanford, is carrying his groundbreaking intellectual property work called "Creative Commons" into the science arena, with plans to apply it to nanotechnology [54]. And Chris Phoenix at the Center for Responsible Nanotechnology is working to outline gaps in our knowledge of molecular manufacturing and what studies are needed to attempt to fill them [55].

One of the most pressing questions actually may recently have been settled – the question of whether continuing down the MNT track would necessarily mean creating risks of autonomous self-replicating nanomachines (as depicted, or caricatured) in *Prey*. It now seems clear that there is no need for a nanomachine able to duplicate itself as biological systems do, because MNT machinery can be made on an assembly line just as ordinary "macro" machines are. Self-replication would be a very difficult feature to implement, in any case, with no obvious economic advantage, and with several types of perceived and actual risks. Hence, many MNT advocates now believe that "the construction of anything resembling a dangerous self-replicating nanomachine can and should be prohibited" [58].

Another bugaboo that should be politely dismissed is the notion that MNT advocates believe their technology will be able to solve all human problems. Given that some of these, such as the desire to take others' goods and dominate one's neighbors, seem to be deeply embedded in a fraction of human personalities, on reflection no one could take seriously the notion of a general technological fix for social problems. However, by developing public policies in advance, we should be able to substantially reduce the drawbacks of MNT technology, increase benefits – especially for the world's have-nots, and limit MNT use in coercion. We can start now by working toward intellectual property reform, including more inexpensive, collaborative "open source" technologies, and weapons proliferation-reduction systems featuring increased openness [63].

MNT Unstoppable

In sum, MNT advocates believe that the technology 1) is coming, 2) has large potential benefits to medicine, the environment, transportation, energy, and virtually every area of physical technology, 3) has large potential abuses including by militaries, and 4) cannot be stopped. MNT critics disagree. Humanity will not know for some time which side proves correct, yet must decide now how to respond to the controversy. One way to put the choice that partly sidesteps the disagreement between MNT advocates and critics is this: Would an intelligent civilization rather risk wasting effort in preparing to cope wisely with MNT (and then find out the technology is impossible)? Or would the civilization be better off hoping that MNT is impossible (and then being caught unprepared if it actually emerges)? The international technical community, including professional societies such as IEEE with its social and ethical emphasis, can play an important role in helping the world to make this choice.

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