Nanotechnology: From Feynman to Funding

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The revolutionary Feynman vision of a powerful and general nanotechnology, based on nanomachines that build with atom-by-atom control, promises great opportunities and, if abused, great dangers. This vision made nanotechnology a buzzword and launched the global nanotechnology race. Along the way, however, the meaning of the word has shifted. A vastly broadened definition of nanotechnology (including any technology with nanoscale features) enabled specialists from diverse fields to infuse unrelated research with the Feynman mystique. The resulting nanoscale-technology funding coalition has obscured the Feynman vision by misunderstanding its basis, distrusting its promise, and fearing that public concern regarding its dangers might interfere with research funding. In response, leaders of a funding coalition have attempted to narrow nanotechnology to exclude one area of nanoscale technology—the Feynman vision itself. Their misdirected arguments against the Feynman vision have needlessly confused public discussion of the objectives and consequences of nanotechnology research.

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Debate regarding nanotechnology and its prospects has been muddied by multiple definitions of the term and by controversy regarding the technical feasibility of basic long-term objectives. This article traces the history of ideas and terminology by showing how a deep polarization has developed in the community, thereby generating confused language and misdirected arguments that hinder public discussion both of current research objectives and of long-term benefits and risks (see the appendix).

Although now used more broadly, the term *nanotechnology* has been used since the mid-1980s to label a vision first described by Richard Feynman in his classic talk, "There's Plenty of Room at the Bottom" (R. Feynman, 1961). The Feynman vision projects the development of nanomachines able to build nanomachines and other products with atom-by-atom control (a process termed *molecular manufacturing*). This vision generalizes the nanomachinery of living systems by promising a technology of unprecedented power with commensurate dangers and opportunities.

The Feynman vision (and rhetoric echoing it) motivated the U.S. National Nanotechnology Initiative (NNI). An early NNI document (National Science & Technology Council [NSTC], 2000) stated under "Definition of Nanotechnology" that "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." An NNI promotional brochure (NSTC, 1999) spoke of "Feynman's vision of total nanoscale control," calling it "the original nanotechnology vision."

In his speech proposing the NNI, President Clinton (2000) invoked this vision on Feynman's home ground:

> My budget supports a major new National Nanotechnology Initiative, worth $500 million. Caltech is no stranger to the idea of nanotechnology —the ability to manipulate matter at the atomic and molecular level. More than 40 years ago, Caltech's own Richard Feynman asked, "What would happen if we could arrange the atoms one by one the way we want them?

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The Feynman Vision and Its Implications

Feynman looked far beyond the laboratory accomplishments of his day (R. Feynman, 1961). He suggested that miniature manufacturing systems could build yet more manufacturing systems: "I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on." Working on a small enough scale, these could build with ultimate precision: "If we go down far enough, all of our devices can be mass produced so that they are absolutely perfect [that is, atomically precise] copies of one another." He asked, "What would the properties of materials be if we could really arrange the atoms the way we want them?" He suggested that nanomachines could achieve this key objective by building things with atom-by-atom control: "It would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. . . . Put the atoms down where the chemist says, and so you make the substance."

The idea that nanomachines (picture nanoscale assembly-line robots) can build with atom-by-atom control is the foundation of the Feynman vision of nanotechnology—call it the Feynman thesis. This thesis has several obvious implications, some suggested by biological parallels. As Nobel Prize–winning chemist Richard Smalley observed in 1999, "Every living thing is made of cells that are chock full of nanomachines. . . . Each one is perfect right down to the last atom." Because cells build more cells, biology shows that nanomachine systems can build more nanomachine systems. And, indeed, he stated,

> It has become popular to imagine tiny robots (sometimes called assemblers) that can manipulate and build things atom by atom. . . . If the nanobot could really build anything, it could certainly build another copy of itself. It could therefore self-replicate, much as biological cells do. (Smalley, 2001)

Thus, the Feynman thesis implies the feasibility of nanoreplicators. As we will see, it is apparently this consequence that led Smalley to become the chief advocate of the view that the Feynman thesis itself is false.

Following Feynman

The Feynman vision motivates research on assemblers and molecular manufacturing and has generated a substantial technical literature (Bauschlicher, Ricca, & Merkle, 1997; Cavalcanti & Freitas, 2002; Drexler, 1981, 1987a, 1987b, 1991a, 1991b, 1992a, 1992b, 1994, 1995, 1999; Drexler & Foster, 1990; Freitas, 1998, 1999, 2002; Globus et al., 1998; Merkle, 1991, 1992, 1993, 1994, 1996, 1997a, 1997b, 1997c, 1997d, 1999a, 1999b, 2000; Merkle & Freitas, 2003; Musgrave, Perry, Merkle, & Goddard, 1991; Requicha, 2003; Skidmore, Parker, Ellis, Sarkar, & Merkle, 2001; Walch & Merkle, 1998). The first of these articles (Drexler, 1981) proposes protein engineering as a path to nanomachine development and is cited as seminal in the field of computational protein engineering (Hellinga, 1998; Pabo & Suchanek, 1986), which is, indeed, seen as enabling nanomachines (Steipe, 1998).

In 1996, the Foresight Institute established the $250,000 Feynman Grand Prize in Nanotechnology. Carl Feynman, MIT-trained computer scientist and son of Richard, authorized and participated in defining the conditions (C. Feynman, 1996), which require building a 100-nm scale robotic arm "demonstrating the controlled motions needed to manipulate and assemble individual atoms or molecules into larger structures, with atomic precision" (Foresight Institute, 1996). That is to say, winning the Feynman Grand Prize requires building the core mechanism of an assembler.

One would expect that the NNI, funded through appeals to the Feynman vision, would focus on research supporting this strategic goal. The goal of atom-by-atom control would motivate studies of nanomachines able to guide molecular assembly. Leading scientists advising the NNI would examine assemblers and competing approaches to their design and implementation to generate road maps and milestones. In the course of a broad marshaling of resources, at least one NNI-sponsored meeting would have invited at least one talk on prospects for implementing the Feynman vision.

The actual situation has been quite different. No NNI-sponsored meeting has yet included a talk on implementing the Feynman vision, and the most prominent scientist advising the NNI has (sometimes) declared the Feynman thesis to be false (Smalley, 2001). Understanding this perverse situation requires a brief review of history, ideas, and fears.

Vision Obscured

The problem started with the word. In labeling the Feynman vision *nanotechnology* (Drexler, 1986), the author chose a word with roots that let it fit any nanoscale technology no matter how old or mundane. The excitement of the Feynman vision attached itself to the word, tempting specialists to relabel their nanoscale research as nanotechnology. The trend began in the late 1980s, and by 2000, the prestige of the term was enormous: "The combination of high tech gee whiz, high social impact, and economic good sense gives the dream of nanotechnology the ability to inspire our nation's youth toward science unlike any event since Sputnik" (Smalley, 2000).

This expansive, scale-defined nanotechnology includes what had been termed thin films, fine fibers, colloidal particles, large molecules, fine-grained materials, submicron lithography, and so on. In a presentation to the President's Council of Advisors on Science and Technology on March 3, 2003, Dr. Samuel I. Stupp of Northwestern University gave as examples of nanotechnologies "pigments in paints; cutting tools and wear resistant coatings; pharmaceuticals and drugs; nanoscale particles and thin films in electronic devices; jewelry, optical and semiconductor wafer polishing." Any connection between this miscellany of technologies and a research program inspired by the Feynman vision is almost imperceptible.

Why did many nanoscale technologists become hostile to the Feynman vision? To begin with, most were from unrelated fields; they had no professional reason to understand the concept, and most did not. Then, having labeled their work "nanotechnology," they found that the term carried awkward baggage.

On the awkwardly positive side, work based on the Feynman vision had promised more than anyone could soon deliver—computers smaller than a bacterium, cheap and clean desktop manufacturing systems, medical devices able to repair human cells, and more (Drexler, 1986, 1992b; Freitas, 1999). Nanofiber researchers found that the public expected them to deliver nanorobots. What nanoscale technologist would want the burden of such expectations?

On the awkwardly negative side, consequences of the Feynman vision gave nanotechnology a sense of enormous danger: "Self-replicating nanobots [of the wrong sort] would be the equivalent of a new parasitic life-form, and there might be no way to keep them from expanding indefinitely until everything on earth became an undifferentiated mass of gray goo" (Smalley, 2001). What nanoscale technologist would want the burden of such fears?

For nanoscale technologists to unburden nanotechnology while claiming its prestige, the Feynman vision had to be accepted as a slogan but rejected as a present goal and a future reality. And, indeed, an Institute for Electrical and Electronics Engineers–sponsored evaluation of the NNI stated,

> The notion of the self-replicating assembler has become the defining characteristic of the split in an otherwise unified nanotechnology community. There are those who believe in the possibility of self-replicating nanosystems, and those who, at least for the moment, refuse even to consider discussing possible means of achieving such a goal. (Horek, 2000)

Vision Denied

President Clinton proposed the NNI in January, 2000, launching a political process that led to its funding by Congress late that year. In April, early in this delicate interval, *Wired* published Bill Joy's (2000) influential article, "Why the Future Doesn't Need Us," which referenced warnings regarding nanoreplicators (Drexler, 1986) and called for the suppression of nanotechnology research.

The nanoscale research community reacted with horror to this threat to funding. For a September workshop, Smalley (conflating several ideas) wrote,

> The principal fear is that it may be possible to create a new life form, a self-replicating nanoscale robot, a "nanobot". . . . These nanobots are both enabling fantasy and dark nightmare in the popularized conception of nanotechnology. . . . We should not let this fuzzy-minded nightmare dream scare us away from nanotechnology. . . . The NNI should go forward. (Smalley, 2000)

For the same workshop, another contributor (also seemingly ignorant of the relevant literature) declared, "Without any scientific bases, dire predictions of self-replicating species cause fear" (Tolles, 2000).

As we shall see, Smalley attempted to dismiss the "fuzzy-minded nightmare dream" of nanoreplicators. Because he acknowledged that nanomachines able to build with atom-by-atom control can serve as a basis for nanoreplicators (Smalley, 2001), he proceeded by attempting to refute the Feynman thesis itself.

Before turning to Smalley's argument, consider how organic, biological, and assembler-based chemistry work: In organic chemistry, reactive molecules move randomly in a solvent, colliding and sometimes reacting in ways that form new molecules by making and breaking chemical bonds. The art of the organic chemist is to select molecules and conditions that yield desired products. In biological chemistry, reactive molecules are often brought together with special-purpose nanomachines (enzymes, ribosomes) that align them to facilitate specific reactions. Compared to organic chemistry, this specialized control enables biology to build specialized structures (e.g., proteins) that are more complex. In assembler-based chemistry, nanomachines will bring molecules together to react only when and where they are wanted. Compared to biological chemistry, this strong control will enable assemblers to build structures of both greater complexity and generality. In organic, biological, and assembler-based chemistry, the fundamental chemical processes are similar.

Smalley, however, asserted that assemblers must do something quite different from what anyone has suggested: They must somehow separately grab and guide each individual atom in the region where the reaction occurs. Based on this, he set up and knocked down a straw-man "assembler" having many tiny fingers, one per moving atom, and declared the Feynman thesis false because "there just isn't enough room in the nanometer-size reaction region to accommodate all the fingers of all the manipulators necessary to have complete control of the chemistry. In a famous 1959 talk that has inspired nanotechnologists everywhere, Nobel physicist Richard Feynman memorably noted, 'There's plenty of room at the bottom.' But there's not *that* much room."

But Feynman does not ask that we separately grab and guide many neighboring atoms simultaneously. Chemistry (assembler-based or otherwise) does not require this: As molecules come together and react, their atoms remain bonded to neighbors and need no separate fingers to move them. "Smalley fingers" solve no problems and thus appear in no proposals; their impossibility is simply irrelevant. Smalley has offered no scientific criticism that addresses the actual concept. The Feynman thesis stands.

Vision Returning

Smalley himself invoked the Feynman thesis before the U.S. Senate, stating that we will "learn to build things at the ultimate level of control, one atom at a time" (Smalley, 1999) and then rejected it when dismissing risks in the pages of *Scientific American* by stating that "self-replicating, mechanical nanobots are simply not possible in our world. To put every atom in its place—the vision articulated by some nanotechnologists—would require magic fingers" (Smalley, 2001), yet he reversed himself to invoke it again before the President's Council of Advisors on Science and Technology, stating that "the ultimate nanotechnology builds at the ultimate level of finesse one atom at a time, and does it with molecular perfection" (Smalley, 2003). Thus, it seems that he has abandoned the argument in Smalley (2001) and returned to endorsing the Feynman thesis, at least as promotional rhetoric. Denial of the Feynman thesis has failed, but the community has yet to fully embrace its consequences.

Research in nanoscale technologies is growing worldwide. Despite a lack of strategic focus in the Untied States, several subfields are extending the human ability to build structures with atomic precision. These include advances in organic synthesis, molecular self-assembly, and even direct atom-by-atom construction using scanning probe microscopes. Some areas of nanoparticle and nanofiber research create atomically precise structures that could serve as building blocks for molecular machine systems. This rising tide of technology lifts human abilities ever closer to actualizing the abilities R. Feynman (1961) anticipated and decades ago described as "a development which I think cannot be avoided."

Molecular manufacturing will emerge more swiftly in the hands of those pursuing better focused development efforts. It will yield revolutionary improvements in computers (portable machines with a billion processors), medicine (devices able to find and destroy cancer cells), the environment (zero-emission industrial production), and arms (ultra-smart nonlethal weapons). Because its powers will be so broad, attempts to suppress molecular manufacturing research in open, democratic societies would amount to unilateral disarmament.

Risks are becoming a public issue (ETC Group, 2003). Nanoreplicators are feasible and their control is thus a legitimate concern. The Foresight Guidelines on Molecular Nanotechnogy show how runaway nanoreplication accidents (“gray goo”) can be avoided (Foresight Institute/Institute of Molecular Manufacturing, 2000). Deliberate development of nanoweapon systems, however, presents a threat that is both less remote and more challenging. The U.S. Nanotech Research and Development Act of 2003 (H.R. 766) draws on the language of the Foresight Guidelines in calling for the U.S. National Academy of Sciences to study both molecular manufacturing development and the possible regulation of self-replicating nanomachines.

Continued attempts to calm public fears by denying the feasibility of molecular manufacturing and nanoreplicators would inevitably fail, thereby placing the entire field calling itself nanotechnology at risk of a destructive backlash. A better course would be to show that these developments are manageable and still distant. Current research is, in fact, of low risk, and the economic, environmental, medical, and military arguments for continued vigorous pursuit of nanotechnologies are strong. In an open discussion, I believe that these arguments will prevail. It is time for the nanotechnology community to reclaim the Feynman vision in its grand and unsettling entirety.

Appendix
Nanoterms and Nanosystems

The terms *nanoreplicator*, *nanobot*, *assembler*, and *molecular manufacturing* are often used in confusing ways. As used here, an assembler is a mechanism for guiding chemical reactions by positioning reactive molecular tools by moving its tool-holding end in three dimensions like an industrial robot arm. A generic nanobot, then, may be an assembler or some other sort of nanoscale robotic mechanism. Molecular manufacturing is a process of construction based on atom-by-atom control of product structures, which may use assemblers (or more specialized mechanisms) to guide a sequence of chemical reactions. If an assembler were packaged together with all of the machinery needed to power it, direct it, and prepare its reactive molecular tools, and with all of the instructions needed to guide the construction of another identical microscopic package, it would then form the heart of (one kind of) nanoreplicator.

A nanoreplicator is thus a complex and specialized sort of nanomachine. A molecular manufacturing technology base is potentially self-replicating, but that potential can be harnessed in various ways—for example, to build desktop-scale nanofactories preprogrammed to produce a wide range of macroscopic products (including, on demand, parts for more nanofactories) (Drexler, 1992b). These contain no autonomous mobile robots.

The term *nanotechnology* itself now embraces a broad range of science and technology working at a length scale of approximately 1 to 100 nanometers, including the more specific goal it originally denoted.

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K. Eric Drexler is a researcher concerned with emerging technologies and their consequences for the future. In the mid-1980s, he introduced the term nanotechnology to describe the Feynman vision of nanomachines building products with atomic precision. Advanced nanotechnologies will make possible many dreams (and nightmares) first articulated in the literature of science fiction. After presenting the

basic concepts of molecular manufacturing in a scientific article (Proceedings of the National Academy of Sciences, 1981), he wrote Engines of Creation *(1986) to introduce a broad audience to the prospect of advanced nanotechnologies—their nature, promise, and dangers—and* Nanosystems *(AAP, 1992, Most Outstanding Computer Science Book) to provide a graduate-level introduction to the fundamental physical and engineering principles of the field. His research in nanotechnology ranges from computational modeling of molecular machines to engineering analysis of molecular manufacturing systems and their potential products. He has lectured in the United States, Europe, and Japan to audiences ranging from corporate research laboratories and the World Economic Forum to a satellite-linked network of elementary school classes. In support of U.S. federal policy development, he has provided presentations and briefings to (among others) the Senate Subcommittee on Science, Technology, and Space; the White House Office of Science and Technology Policy; and the vice chairman of the Joint Chiefs of Staff. He is a founder and current chairman of the Foresight Institute, a nonprofit educational organization established to help prepare for advanced technologies.*