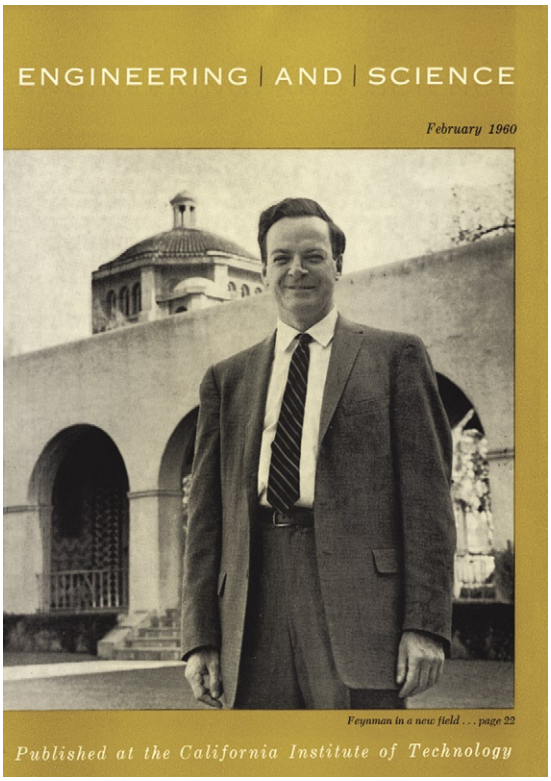
Apostolic Succession

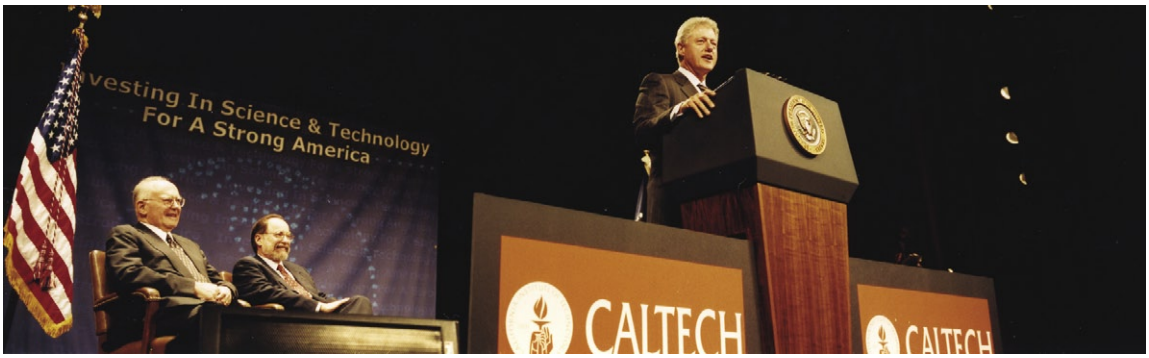
by Chris Toumey



Behind this cover lies "Plenty of Room at the Bottom," the article that launched nanotechnology—or did it?

As histories and mythologies of nanotechnology are created, and people try to establish which events and people were more important than others, one question arises repeatedly: how influential was Caltech physicist and Nobel Laureate Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom," which first appeared in print in the February 1960 issue of this very magazine? The article was, among other things, a vivid description of a precise science of manipulating matter at the molecular and atomic levels. It predates certain very important events like the invention of the scanning tunneling microscope, and it is frequently described as the text that instigated nanotechnology. In the words of noted futurist K. Eric Drexler, "The revolutionary Feynman vision . . . launched the global nanotechnology race." James Gleick, in his bestselling biography *Genius: The Life and Science of Richard Feynman*, says that "nanotechnologists . . . thought of Feynman as their spiritual father." The National Nanotechnology Initiative's glossy brochure reminds us that "one of the first to articulate a future rife with nanotechnology was Richard Feynman." His paper "has become one of 20th-century science's classic lectures. . . . It has also become part of the nanotechnology community's founding liturgy." And, in the January 2000 speech at Caltech that unveiled the initiative, President Clinton paid homage, saying "Caltech is no stranger to the idea of nanotechnology. . . . Over forty 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?'"

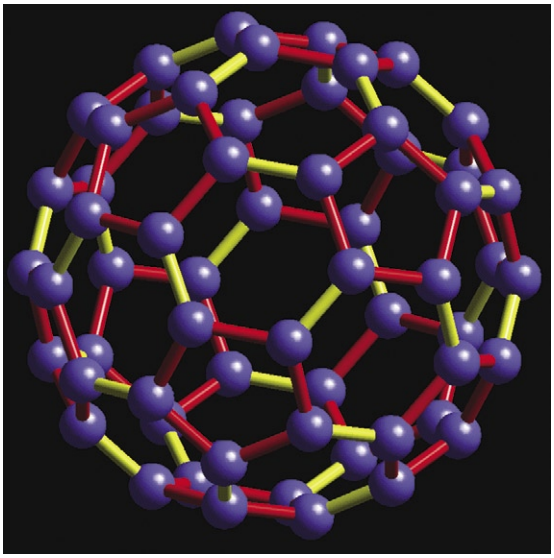
Actually, all of these statements except Drexler's are devilishly subtle. Careful reading shows that they do not claim unequivocally that "Plenty of Room" launched nanotechnology. Instead, they affirm that it is widely *believed* that Feynman's paper instigated nanotech, which then lets the reader infer that this was so. If a person thinks that nanotech began with "Plenty of Room," then later developments can be retroactively appreci-



President Clinton burnishes the Feynman mystique before a standing-room-only crowd in Caltech's Beckman Auditorium on January 21, 2000. Gordon Moore (PhD '54), chair of the Board of Trustees, and Caltech president David Baltimore look on.

ated as fulfillments of Feynman's vision, which is to say that certain important people might *not* have thought what they thought, and might *not* have done what they did, if he had not bequeathed it to us. I think of this as a question of apostolic succession: did Feynman set the intellectual parameters of nanotechnology in "Plenty of Room" in such a way that those who came after him have traced their own legitimacy to that text by consciously and deliberately executing his vision? We can also ask about Feynman's follow-up talk, "Infinitesimal Machinery," published posthumously in the *Journal of Microelectromechanical Systems* in 1993. If "Plenty of Room" was the text that instigated nanotech, then "Infinitesimal Machinery" was a kind of Deuteronomy that restated the vision and elaborated it. But if "Plenty of Room" had little or no inspirational value, and if "Infinitesimal Machinery" had even less, then we are steered into a different history. Even though Feynman's 1959 talk *preceded* many important developments, it was irrelevant to them. Instead of an apostolic succession of nano-thought, we would see that important events and ideas arose independently of Feynman's vision.

This reminds me of the case of Gregor Mendel. No one denies that Mendel discovered the principles of genetics before anyone else, or that he published his findings in a scientific journal. But Caltech Nobelist Thomas Hunt Morgan and others later rediscovered those principles on their own, without being influenced by Mendel's work, or even being aware of him. Mendel deserves credit for priority, but that ought not to be overinterpreted as directly inspiring or influencing the later geneticists.



Richard Smalley shared the chemistry Nobel for the 1985 discovery of fullerenes—more properly, "buckminsterfullerenes," for the inventor of the geodesic dome—a form of carbon in which the atoms form tiny spheres or ellipsoids. The C_{60} molecule shown here has the same symmetry as a soccer ball. Fullerenes can be built into bigger structures, doped with metals to become magnets or superconductors, and can do all kinds of things nanotechnologists might want to do.

A related question concerns Drexler's legacy, particularly his 1981 paper, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation," in the *Proceedings of the National Academy of Sciences* (*PNAS*). Drexler has insisted that the core of Feynman's vision was the large-scale precision manipulation and combination of atoms and molecules (now called molecular manufacturing), and he adamantly suggests that he himself continues the rightful essence of that vision. Feynman said, "I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on." What could be more Drexlerian? In Drexler's view, the term "nanotechnology" has been debased by other, nonmanufacturing activities, and, consequently it is urgent to return to the essence of Feynman's vision. Or, if you like, Drexler's understanding of Feynman's vision.

Almost everyone would agree that Drexler's work as a popularizer, especially his 1986 book, *Engines of Creation*, has caused large numbers of people to become interested in nanotechnology. I have no reason to challenge this. Instead, I ask whether Feynman's influence had a secondary amplification through Drexler. After all, Drexler reminds audiences that his technical publications, beginning with "Molecular Manufacturing," demonstrate that he is more than a popularizer.

This question is interesting in light of the bitter exchange between Drexler and Richard Smalley in December 2003. In *Nano: The Emerging Science of Nanotechnology: Remaking the World—Molecule by Molecule*, Ed Regis writes that Smalley used to describe himself as "a fan of Eric" and that he distributed copies of Drexler's books to influential decision-makers at Rice University. In the special issue of *Chemical & Engineering News* that car-

ried the Drexler-Smalley debate, Smalley vehemently disagreed with Drexler and poured loads of contempt on him, but explicitly acknowledged that *Engines of Creation* had caused him to take an active interest in nanotechnology. This eventually resulted in Smalley's 1996 Nobel Prize in Chemistry (with Robert Curl and Harold Kroto) for the discovery of fullerenes. So if Drexler directly inspired one important scientist in nanotechnology, could he have also influenced others?

At this point we have a set of hypotheses:

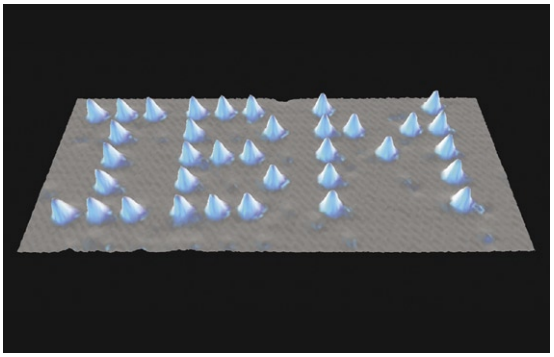
1. That "Plenty of Room" directly inspired important nanoscientists, and that this inspiration is evident in important scientific developments;
2. That "Infinitesimal Machinery" amplified the importance of that inspiration;
3. That "Molecular Engineering" directly inspired further important scientific developments, thereby continuing and multiplying Feynman's influence.

Popular Science ran a cute condensed version called "How to Make an Automobile Smaller Than This Dot" in November [1960] . . . "Plenty of Room" was also mentioned in *Science News* and *Life* in 1960.

Here I need to be more specific about "important scientific developments." There are thousands of scientific publications about nanotechnology, a large number of patents, and several Nobel Prizes. We could argue endlessly about which developments were most important. I've selected three: the invention of the scanning tunneling microscope (STM), the invention of the atomic force microscope (AFM), and the first manipulation of individual atoms using STM. These three events occurred well after the publication of "Plenty of Room." Gerd Binnig and Heinrich Rohrer (who shared the Nobel Prize in Physics in 1986) filed their STM patent in September 1980, but the other two events happened after the publication of "Molecular Engineering," in 1986 and 1990, respectively. Can we find evidence of either Feynman's or Drexler's influence in these developments? I have two principal sources of information for pursuing this question—a citation history from the *Science Citation Index* for "Plenty of Room," "Infinitesimal Machinery," and "Molecular Manufacturing;" and a series of comments I solicited from the scientists involved. I will start by examining Feynman's influence.

"Plenty Of Room," "Infinitesimal Machinery"

On December 29, 1959, Richard P. Feynman gave the talk at a meeting at Caltech of the American Physical Society. He presented a vision of the



precise manipulation of atoms and molecules so as to achieve amazing advances in information technology, mechanical devices, medical devices, and other areas. Attendee Paul Shlichta (PhD '56), then of Caltech's Jet Propulsion Laboratory, later said, "The general reaction was amusement. Most of the audience thought he was trying to be funny. . . . It simply took everybody completely by surprise." *Engineering & Science* printed a transcript in its February 1960 issue with the subtitle "An Invitation to Enter a New Field of Physics." *Saturday Review* ran a synopsis that April with the title "The Wonders That Await a Micro-Microscope," and *Popular Science* ran a cute condensed version called "How to Make an Automobile Smaller Than This Dot" in November. This article had a few comments that had not been in *E&S*, but it retained the heart of Feynman's argument. "Plenty of Room" was also mentioned in *Science News* and *Life* in 1960, and appeared in 1961 as the final essay, without the subtitle, in a volume titled *Miniaturization*, edited by Horace Gilbert.

Feynman spoke again on the topic of atomic-level miniaturization at the Jet Propulsion Lab on February 23, 1983. This talk was titled "Infinitesimal Machinery," and he explicitly described it as "There's Plenty of Room at the Bottom, Revisited." He reaffirmed his original views, and he elaborated on the methods and applications he had discussed 23 years earlier. Videotapes of this talk are available through the Caltech Archives.

Richard Feynman passed away in 1988. Subsequently, "Plenty of Room" began to reappear in books and journals. *Science* ran a one-page excerpt in its November 1991 special issue on nanotechnology, crediting *E&S* for permission to reprint. The next year, the *Journal of Microelectromechanical Systems* republished "Plenty of Room," with no subtitle, in its inaugural issue. It alluded to the *Miniaturization* volume as its source, but gave a date of December 26 for the original talk. (This is almost certainly a typographical error, since both the *E&S* and *Miniaturization* texts, and every other source I am aware of, had given the date as December 29.) Also in 1992, the proceedings of a Foresight Institute conference included "Plenty of Room" as an appendix, with the original subtitle, and derived the text from *E&S*. (Drexler founded the Foresight Institute, and remains chair

Opposite: Don Eigler and Erhard Schweizer of IBM's Almaden Research Center made nanotech history when they wrote their employer's name in xenon atoms on a nickel surface, using the weak attractive forces between the atoms in the STM needle's tip and the xenon atoms to nudge them into position. Their paper was published in *Nature* on April 5, 1990.

of its board of advisors.) In 1999, Jeffrey Robbins included "Plenty of Room" in his collection of Feynman's short papers, and Anthony J. G. Hey made it a part of his volume of Feynman's work on computation. It is also available at several websites at Caltech and elsewhere, including Zyvex and the National Nanotechnology Initiative.

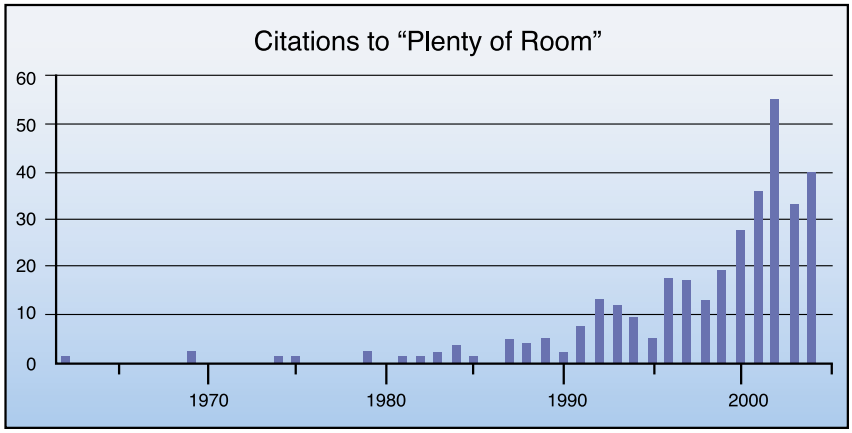
"Infinitesimal Machinery" was published in the *Journal of Microelectromechanical Systems* in 1993, 10 years after Feynman delivered the talk. As best I can tell, this was the only hard-copy publication. It is not mentioned in the leading Feynman biographies by Gleick and Jagdish Mehra (*The Beat of a Different Drum: The Life and Science of Richard Feynman*), both of which have short chapters on "Plenty of Room." In fact, Gleick wrote that "Feynman . . . never returned to the subject," indicating that he was unaware of the 1983 talk. "Infinitesimal Machinery" is likewise invisible in the various collections of Feynman papers.

To assess the historical importance of "Plenty of Room" and "Infinitesimal Machinery," I did a citation search on each in ISI's *Science Citation Index*, with a supplemental search in *Dialog*, in November 2004. My assumption was that the frequency with which they were mentioned in scientific journals would give a measure of how influential they were. The period of 1980 through 1990 was especially important because this was when Binnig and Rohrer invented the STM, Binnig invented the AFM (with assistance from Calvin Quate and Christoph Gerber), and Don Eigler and Erhard Schweizer first manipulated individual atoms with an STM.

Citation tracing is an inexact science. In the hard copies of the *Science Citation Index*, from the days before electronic search engines became available, Feynman's name is sometimes spelled correctly, and sometimes not: Feynman, Feynmann, Feymnan, Feyman, and so on. There are also multiple ways to indicate his initials—R, RP, P, and no initials at all. Presumably these variations represent typographical errors in the citations, which the *Index* reproduced faithfully without editorial emendation. In the electronic version, the *E&S* text is listed four different ways, even though all four are obviously the same publication. (The *Dialog* search overlaps both the hard-copy and electronic versions of the *Science Citation Index*, but provides slightly different results.) A further complication is that the ISI database changes from time to time, as the editors add new journals and drop others. They follow a principle they call Bradford's law, which states that "the core literature of any given scientific discipline . . . [is] composed of fewer than 1000 journals." But this core shifts over time, so a search across four decades does not necessarily scan the same periodicals every year. The data are certainly incomplete to some degree, so we should consider them an approximation—expecting a perfect record is unrealistic.

My search began with the texts from *E&S* in 1960 and *Miniaturization* in 1961, since these were the only ones that preceded my "big three" developments in nanotech. I also searched for the two 1992 republications in the *Journal of Microelectromechanical Systems* and the Foresight volume. (The texts in the two 1999 collections edited by Robbins and Hey cannot be distinguished from the rest of the contents of those books in a citation search.) Later I discovered that some authors give a date of 1959 when they cite "Plenty of Room," thus referring to the original talk, not the initial publication.

I found a total of three citations in the 1960s, and four in the 1970s—a scant record in the two decades before the arrival of the STM and the AFM. These early citations present a variety of ways of reading Feynman. The first, in a 1962 *Science* article by John Platt, enthusiastically endorsed Feynman's point that "recent advances in physics and chemistry" make it possible to build better electron microscopes for biology. Platt then called for a national laboratory for biological instrumentation. Articles by Robert Keyes in 1969 and 1975 and Joseph Yater in 1979 and 1982 discussed ongoing work to make faster, better computers. Their references to Feynman amounted to brief, generic statements that improvements are possible. Marvin Freiser and Paul Marcus also addressed information technology in a 1969 piece,



Citations to "Plenty of Room" in scientific journals were pretty sparse in those years, however.

Bill Joy, in the April 2000 issue of *Wired*, raised the fear of self-replicating nanobots ("Why the Future Doesn't Need Us," which could also be called "There's Plenty of Gloom and Doom at the Bottom").

but were extremely skeptical of Feynman's suggestion of using individual atoms as storage units: "Such speculations appear to be completely vacuous so far as the real world is concerned."

Finally, in 1979, James Krumhansl and Yoh-Han Pao used "Plenty of Room" as a touchstone for evaluating and appreciating "microscience," as they called it: "In the past twenty years there has been an explosive growth in 'microscience,' in exploring that room at the bottom Feynman mentioned." As they took the reader through their article, which introduced a special issue of *Physics Today*, they occasionally pointed to passages from "Plenty of Room" that anticipated exciting developments, thereby using Feynman's paper as a loose frame of reference for understanding "microscience."

Eric Drexler told me by e-mail that "I [first] encountered a mention of 'There's Plenty of Room at the Bottom' in *Physics Today* while researching references for my 1981 *PNAS* ['Molecular Engineering'] article." Then, "We [Drexler and Feynman] met once, when his son, Carl, brought him to a party in my apartment in Cambridge in 1981. We discussed the implications of the paper, taking the soundness of the basic ideas for granted." Drexler cited the 1961 *Miniaturization* text in "Molecular Engineering" because that was the one Krumhansl and Pao had credited.

References to "Plenty of Room" did not get into double digits in any given year until 1992. From 1996 onward, the citations remain consistently in double digits, and they usually increase from year to year. The 1992 republications in the *Journal of Microelectromechanical Systems* and the Foresight volume increased access to "Plenty of Room." Citations to these two represent 16.1 percent of all citations from 1993 through November 2004, with the former accounting for most of the increase.

I found a total of two citations for "Infinitesimal Machinery"—one from 1997, and another from 1998.

I then asked the men behind my "big three" whether "Plenty of Room" had inspired or influenced their work, when they first heard of it, and some related questions. I received replies from Binnig, Rohrer, Quate, and Eigler. These nanoluminaries, as I call them, said uniformly that it had no influence.

Rohrer said, "Binnig and I neither heard of Feynman's paper until Scanning Tunneling Microscopy was widely accepted in the scientific community a couple of years after our first publication, nor did any referee of our papers ever refer to it. . . . It might have been even after the Nobel." Binnig stated that "I have not read [it] . . . I personally admire Feynman and his work but for other reasons than for his work on nanotechnology (which actually does not exist) [Binnig's parentheses]. I believe people who push too much his contribution to this field do harm to his reputation. His contribution to science is certainly not minor and he needs not to be lifted . . . [posthumously] onto the train of nanotechnology." They did briefly mention "Plenty of Room" at the end of a 1987 account of their work, but it is clear that they were speculating about the future, rather than crediting Feynman for influencing the process of invention. Feynman's paper is absent in the references in the U.S. patents for the STM and the AFM.

Quate wrote that "None of [AFM] derived from the publications of Feynman. I had not read the Feynman article and I don't think Binnig or Rohrer had read it. All they wanted was a better method for examining microdefects in oxides."

Eigler had a different experience. He had read Feynman's paper before his famous manipulation of xenon atoms: "I can not say for certain, but I believe I read, or came to be aware of 'There's Plenty of Room' in the late 1970's or early 1980's while I was a graduate student. I know for a fact that I had read it a long time before first manipulating atoms with the STM. The reason I say this is because, within weeks of manipulating atoms for the first time, I went back to dig up Feynman's

paper. When I started reading the paper, I realized that I had read it a long time before." Nevertheless, he continued, "The technical aspects of my work have not been influenced by Feynman's paper." When he reread "Plenty of Room," he "found an extraordinary affinity between the written words of Feynman and my own thoughts . . . I was more than ever impressed with how prescient Feynman's thoughts were. I also clearly recall a profound sense of sadness that he had croaked just a tad too soon to see one of his provocative statements, i.e. 'all the way down . . .' realized in the lab." He concluded by saying that "Feynman's work would be on a dusty shelf without Binnig. It was Binnig who blew life into nano by creating the machine that fired our imaginations. Binnig created the tools that brought the nano world to our collective consciousness. . . . When it comes to nano, start looking at Binnig instead of Feynman."

I next wrote to several other nanonotables, and received replies from Chad Mirkin, James Tour, George Whitesides, and Stan Williams. Did Feynman's paper influence their work? "No," said Mirkin, who is the director of the Institute for Nanotechnology at Northwestern. "Not at all," according to Tour, a leader in molecular electronics at Rice. Whitesides (PhD '64), an organic chemist and materials scientist at Harvard, wrote that "it really had no influence." According to Williams, the director of the Quantum Science Research group at Hewlett-Packard, "my research has not been directly influenced by that talk or the ideas presented in it." Whitesides commented that Feynman's "enthusiasm for small science has certainly boosted [nanotechnology's] general attractiveness, and made it intellectually legitimate, especially in physics . . . I don't think that he was specifically important in the sense that Binnig/Rohrer/Quate were. My sense is that most people in nano became excited about it for their own reasons, and then . . . have leaned on Feynman as part of their justification for their interest." According to Williams, "I think he provided inspiration at the sociological level, but I don't think that he was a significant technical influence to the field. Scientists, including myself, would read his work after the fact and admire his prescience, but I don't think many people were inspired to go into the lab and perform a particular experiment by reading his work (other than his challenge to build a tiny motor)."

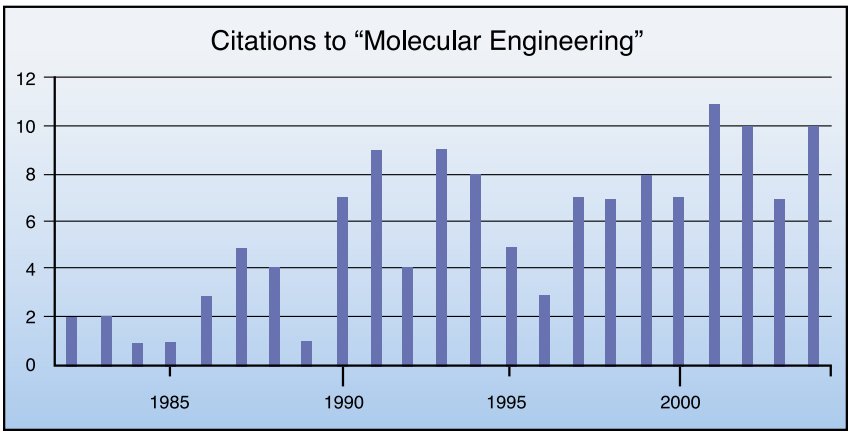
"Molecular Engineering"

There is a parallel story about Feynman's *in*direct influence. As mentioned before, Drexler began formulating his views on nanotechnology before knowing about Feynman's paper. Then he read Krumhansl and Pao's article in *Physics Today*. "Molecular Engineering," his first publication on nanotech, refers to "Plenty of Room" at the beginning of the very first sentence, and he invoked Feynman again in *Engines of Creation*.

Last year in "Nanotechnology: From Feynman to Funding," Drexler presented his views as the legitimate continuation of Feynman's, arguing that Feynman's bold vision instigated nanotechnology, and that the heart of that vision was atom-by-atom control of nanomachines to build things. "The Feynman vision," he wrote, "motivates research on assemblers and molecular manufacturing and has generated a substantial technical literature." He claimed that the term "nanotechnology" was abused by stretching it beyond the core vision so as to include much "unrelated research" and that "the excitement of the Feynman vision attached itself to the word, tempting specialists to relabel their nanoscale research as nanotechnology." (In an e-mail to me this April, he wrote, "I would, of course, never suggest that my studies of productive nanosystems inspired the bulk of what is now called 'nanotechnology.' This work continues laboratory research in chemistry, materials science, microscopy, and other areas, but under a new name. These fields long predate my contributions. Their chief connection is their adopted name and their inheritance of some of the excitement surrounding productive nanosystems.") And if it wasn't bad enough that the rightful vision was diluted, he continued, it was then purged from the definition entirely after Bill Joy, in the April 2000 issue of *Wired*, raised the fear of self-replicating nanobots ("Why the Future Doesn't Need Us," which could also be called "There's Plenty of Gloom and Doom at the Bottom"), thereby causing the leaders of the National Nanotechnology Initiative to worry that the public would fear nanotech. Those leaders, said Drexler, responded by trying to discredit Joy, telling the public that molecular manufacturing was not feasible. That tactic, he suggested, was tantamount to "attempts to suppress molecular manufacturing research."

If molecular manufacturing is the continuation of the essence of the vision, and if Drexler has been a faithful echo of Feynman, then has that echo inspired further work, the way Richard Smalley says Drexler motivated him? Regardless of the overall value or truth of Drexler's views, did the ideas in "Plenty of Room" receive further circulation within the scientific community because of "Molecular Engineering"?

Where might we find such a line of influence? "To see research that explicitly builds on my ideas," Drexler e-mailed me, "look at protein engineering." Noted protein designers William DeGrado and Carl Pabo have indeed cited Drexler in their work. Unlike DeGrado, who e-mailed me that "I actually only became aware of [Drexler's] paper after I had initiated my work in design, but I see it as an early statement of the objectives of protein design," Pabo's 1983 *Nature* article followed Drexler's suggestions in considerable detail in a passage about strategies for designing proteins. In a recent e-mail message to me, Pabo said Drexler "was a key source



of my motivation in first thinking about this problem. Eric's 1981 *PNAS* article clearly made the point that it might be possible to design new proteins reliably even before we could develop methods for reliably folding existing proteins."

"Molecular Engineering" appeared after the invention of the STM, but before the AFM and the manipulation of individual atoms. Again, if Drexler echoed Feynman, and if that echo influenced important scientific work in nanotech, then the citations of "Molecular Engineering" ought to complement Pabo's comments and give us a measure of that influence. Instead, references to it remained in the single digits until 2001. During the years of the invention of the AFM, and Eigler and Schweizer's feat of spelling out "IBM" with 35 xenon atoms, "Molecular Engineering" never received more than five citations in one year.

Thirty-one articles cited both Feynman's paper and Drexler's. This represents 9.2 percent of all the "Plenty of Room" citations and 24 percent of the references to "Molecular Engineering." I take this to mean that Drexler leads his readers to Feynman, which should not surprise anyone, but that those who start with Feynman are less likely to credit Drexler. (Incidentally, for the first 13 years that "Molecular Engineering" was out, it had almost as many citations as "Plenty of Room": 63 for Feynman, and 56 for Drexler.) Prior to the republications in 1992, a reference to the *E&S* text probably meant that the author had found it independently of Drexler. A citation of the 1961 *Miniaturization* text might be due to Drexler's advocacy, but not necessarily.

Some of the nanoluminaries who commented on Feynman's influence also had views about Drexler. Because of the way I framed my questions, their statements address his influence in general, and are not specific to "Molecular Engineering." Rohrer, who at one point had invited Drexler to the IBM Zurich Research Laboratory, wrote that Drexler had "no inspiration and no influence" on his work. "I am not aware," he continued, "of any influence which Drexler had on any scientific or technical development or on any scientist doing respectable work in nanoscience and -technology." Eigler seconded this view, explaining that, "To a person, everyone I know who is a practicing scientist thinks of Drexler's contributions as wrong at best, dangerous at worse. There may be scientists who feel otherwise, I just haven't run into them."

Similarly, Mirkin, Tour, Whitesides, and Williams stated clearly that Drexler's writings had *not* influenced their work, or that of other scientists they knew. Each of them saw Drexler as a popularizer, which they sharply distinguished from science. Mirkin's and Whitesides's comments were neutral, but Tour and Williams expressed hostility. In Williams's view, "The hype and the angst that have been a consequence of his claims provide the biggest obstacle I face when trying to present my work in public. I have had to spend a huge amount of my energy over the past 15 years or so putting distance between myself and Drexler so that what I do is not associated with him. In fact, when I founded my research group at Hewlett-Packard, we called it 'Quantum Science Research' to avoid any connection with the negative connotations of 'nanotechnology.' Eventually, because the word had found such widespread use in the public, we in the field essentially had to adopt it. Drexler has created unrealistic expectations that threaten the field more than aid it."

On the positive side, I identified Christof Niemeyer as the scientist who has cited "Molecular Engineering" most often—nine times in the past seven years. Niemeyer is a biochemist at Universität Dortmund who uses DNA as a platform for constructing nanoscale structures and systems. In his citations, "Molecular Engineering" is usually referenced on the first page of the article to support a statement like this: "The use of biomolecules for developing nanotechnology devices was already envisioned by early researchers, who suggested the use of biological macromolecules as components of nanostructured systems." He also cites Feynman in some of those articles. He draws no data, no case studies, and no quotations from Drexler's paper. The citations support the general point about assembling biological molecules into larger structures, but play no other role.

A Different Account Of Nanotech's Origins

There are surely some additional citations that I have not found, and there may be other scientists who have been directly influenced or inspired by Feynman or Drexler, paralleling the Feynman-Drexler-Smalley and Feynman-Drexler-Pabo lines of apostolic succession. Still, I conclude that much of the important scientific work that happened in the early years of nanotech, especially the big-three breakthroughs in instrumentation, owed little or nothing to either Feynman or Drexler.

I telephoned Feynman's son, Carl, on March 29, 2005, and presented my conclusion. He responded, "That seems completely true." I asked him about conversations about "Plenty of Room"

with his father, and he said, "I heard about it from my dad," but "there was no interest in it" in the scientific community in the early years. He added that when he was a freshman at MIT in January 1980, he heard "Eric Drexler was aware of it, and I was stunned" that anyone had heard of it. He also told me of a time he went with his father to IBM's Watson Research Center in Yorktown Heights, New York, where scientists showed them an STM and said they could see atoms. His father corrected them, saying they were observing the tunneling of electrons. He also said that Richard Feynman "never talked about the STM in connection with ['Plenty of Room']." Were there any scientists who went into nanotech because of reading it? "I don't think so, except for Drexler," he answered.

We can speculate about why "Plenty of Room" was rediscovered. Perhaps it shows us that a new science needed an authoritative founding myth, and needed it quickly. If so, then pulling Feynman's talk off the shelf was a smart move.

That conclusion leads to some final thoughts:

First, we have an altered sequence of influence. The theory of apostolic succession posited that first there was "Plenty of Room"; then there was much interest in it; and finally that caused the birth of nanotechnology. My analysis suggests something different: first there was "Plenty of Room"; then there was very little interest in it; meanwhile, there was the birth of nanotechnology, independent of it; and finally there was a retroactive interest in it. I believe we can credit much of the rediscovery to Drexler, who has passionately championed Feynman's paper.

The second thing is to ask *why* "Plenty of Room" is retroactively important. One obvious possibility is that someone's scientific work will have its prestige enhanced if it is connected to the genius, the personality, and the eloquence of Richard P. Feynman. But is the Feynman cachet really transferable in this way? We can contrast that with a more modest style of alluding to Feynman. As we have seen, Binnig and Rohrer included a brief comment in their 1987 history of the invention of the STM, and so did Joseph Stroscio and Don Eigler in their 1991 description of atomic manipulation. But in both cases the references were cursory at best, and the authors did not cite Feynman until well after they had achieved notable success in instrumentation. They gave him a reflexive nod—an acknowledgement that he had had similar ideas—but none of the work was justified by connecting it to him, either while it was being done or afterward.

Third, how selective is the process of enhancing one's work by retroactively claiming the Feynman cachet? "Plenty of Room" describes many things, including the nano-etching of texts; the storing and retrieving of data in an atom-size code; the wonders of biological information systems; the miniaturization of computers; a mechanical surgeon that could be swallowed; a system of increasingly smaller master-slave hands (also known as Waldos); a system of "a billion tiny factories" working together; superconductivity; and simplified synthetic chemistry, to name only nine ideas in that paper. If someone borrows Feynman's prestige by citing some of these thoughts while disregarding others, is this a distortion of Feynman's views?

Fourth, why is "Infinitesimal Machinery" unknown to those who enthusiastically embrace "Plenty of Room," especially since Feynman described it as "Plenty of Room, Revisited"?

And finally, if we discount the usual Feynman-centered account of the origins of nanotechnology, does this enhance a different tale? The nanoluminaries point to an instrumentation-centered narrative. To repeat Eigler's comment, "When it comes to nano, start looking at Binnig instead of Feynman."

We can speculate about why "Plenty of Room" was rediscovered. Perhaps it shows us that a new science needed an authoritative founding myth, and needed it quickly. If so, then pulling Feynman's talk off the shelf was a smart move because it gave nanotech an early date of birth, it made nanotech coherent, and it connected nanotech to the Feynman cachet. But even as we speculate like this, we should not lose sight of a line of events that happened entirely independently. The invention of the scanning tunneling microscope made it possible to see atoms clearly and move them around, and then it enabled a great volume of additional scientific research. When we ask from whence nanotechnology descended, we ought to salute the STM as the founding ancestor. □

PICTURE CREDITS: 17 – Bob Paz; 18 – Don Eigler & Erhard Schweizer; 19, 22 – Chris Toumey

Christopher P. Toumey, Centenary Research Associate Professor of Anthropology at the University of South Carolina, Columbia, earned his PhD in anthropology from the University of North Carolina in 1987. He studies the cultural anthropology of science and of religion. His first book, God's Own Scientists: Creationists in a Secular World *(1994), looked at the process by which science is "interpreted" to promote ultra-conservative views. His second book,* Conjuring Science: Scientific Symbols and Cultural Meanings in American Life *(1996), explores the broader question of how these symbols convey not only well-defined scientific meanings but also moral and political ones. He now works full-time with an interdisciplinary team at the university's NanoCenter, studying society's interactions with nanotechnology and how nanotech policy is formed.*

This article is based on a paper presented at the March 2005 Cain Conference on the history of nanotechnology at the Chemical Heritage Foundation in Philadelphia, Pennsylvania. The work was supported by a grant from the National Science Foundation.