Reading Feynman Into Nanotechnology: A Text for a New Science

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Abstract
As histories of nanotechnology are created, one question arises repeatedly: how influential was Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom"? It is often said by knowledgeable people that this talk was the origin of nanotech. It *preceded* events like the invention of the scanning tunneling microscope, but did it inspire scientists to do things they would not have done otherwise? Did Feynman's paper directly influence important scientific developments in nanotechnology? Or is his paper being retroactively read into the history of nanotechnology? To explore those questions, I trace the history of "Plenty of Room," including its publication and republication, its record of citations in scientific literature, and the comments of eight luminaries of nanotechnology. This biography of a text and its life among other texts enables us to articulate Feynman's paper with the history of nanotechnology in new ways as it explores how Feynman's paper is read.

Keywords: Feynman; nanotechnology; history of technology

Introduction

I imagine that humanists must often look with envy at those who emend or expose a well-established historical fact. Think of those who have shown that a fact is not really factual: Lorenzo Valla, for example, debunking the "Donation of Constantine" in the fifteenth century by using textual analysis.

Much more rare is the opportunity to emend the facts of the recent history of science. Because these facts have been written not long ago, they lack the hoary status of myths to be exposed as such. In addition, we expect the recent history of science to be well grounded empirically in history, and well grounded empirically in science. So the potential for mischief with the recent history of science is slimmer than for other kinds of history, isn't it?

Take, for example, one well-established point about the origin of nanotechnology. Richard P. Feynman's 1959 talk to the American Physical Society, "There's Plenty of Room at the Bottom" (Feynman 1960a), preceded numerous crucial events that made nanotechnology possible, including the invention of the scanning tunneling microscope, the atomic force microscope, and the Eigler-Schweizer experiment of precisely manipulating thirty-five xenon atoms. Those inventions and other events led to nanolithography, computers with nanoscale components, the precise control of individual atoms, and other developments that Feynman called for in December 1959. It is easy to see why people say that "Plenty of Room" was the ur-text that started nanotech:

- Eric Drexler says that "The revolutionary Feynman vision … launched the global nanotechnology race" (Drexler 2004:21).

- An entry in the *Encyclopedia of Twentieth-Century Technology* explains that "the impetus for nanotechnology came from a famous talk by the Nobel physicist Richard Feynman in 1959" (Thomas 2004).

- In his collection of Feynman's papers, Jeffrey Robbins calls Feynman "the father of nanotechnology" by virtue of his "Plenty of Room" paper (Feynman 1999:117).

- A comment in another collection of Feynman's papers mentions that this paper "is often credited with starting the field of nanotechnology" (Hey 1999:xii).

- One major biography of Feynman says that "Nanotechnologists… thought of Feynman as their spiritual father" (Gleick 1992:356).

- Michelle Feynman's collection of her father's letters says that his talk "envisioned a new field of science now called nanotechnology," and it indexes correspondence on "Plenty of Room" under "nanotechnology" (Feynman 2005:116, 482).

- According to Adam Keiper's introductory article on nanotech, "Usually… the credit for inspiring nanotechnology goes to a lecture by Richard Phillips Feynman" [i.e., "Plenty of Room"] (Keiper 2003:18).

- The National Nanotechnology Initiative's glossy brochure on nanotech reminds us that "One of the first to articulate a future rife with nanotechnology was Richard Feynman" (Amato 1999:4).

- The technology visionary Ray Kurzweil writes that "Most nanotechnology historians date the conceptual birth of nanotechnology to Richard Feynman's seminal speech in 1959, "There's Plenty of Room at the Bottom" (Kurzweil 2005:227).

- President Clinton paid homage to Feynman in his vision of the National Nanotechnology Initiative: "Caltech is no stranger to the idea of nanotechnology, the ability to manipulate matter at the atomic and molecular level. 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?'" (Clinton 2000).

This habit of crediting Richard Feynman's talk for instigating nanotechnology can be found in a large range of works, from those authoritative documents above to articles by semi-obscure scholars (e.g., Toumey 2004a, 2004b and Hessenbruch 2004:141).

Actually, there is something devilishly subtle in the reading of those statements. The first three are unequivocal in saying that nanotechnology started with "Plenty of Room," but a careful reading of the others shows that they are less adamant on this point. Most of them indicate that it is widely *believed* that Feynman's paper instigated nanotech, which is different from the sentiment of Drexler, Robbins and Thomas. If a reader concludes that nanotech began with Feynman's paper, on the grounds that this historical link is widely believed to be true, regardless whether it is true, then later developments can be retroactively appreciated as intentional fulfillments of Feynman's 1959 vision. One can see Feynman anywhere in the history of nanotechnology (cf. Junk & Riess 2006).

I imagine three different ways of reading "Plenty of Room" into the history of nanotech. According to the first, it can be affirmed that certain important people might *not* have thought what they thought, and might *not* have done what they did, if Richard Feynman had not bequeathed "Plenty of Room" to us. This is a theory of Apostolic Succession: Feynman set the intellectual parameters of nanotechnology in his talk in such a way that those who came after him have consciously and deliberately executed his vision. Feynman is the First Apostle of nanotechnology, "Plenty of Room" is his precise blueprint, and nanotech is the intentional execution of his vision. As W. Patrick McCray puts it, there is something very appealing about creation stories that begin with a "singularity," that is, a "lone inventor or small teams who create a revolutionary breakthrough," and Feynman's talk is appreciated as such a singularity (McCray 2005:180-181).

Secondly there could be a nano-Mendel way of appreciating Feynman. In the case of Gregor Mendel, no one denies that this man discovered the principles of genetics before anyone else, or that he published his findings in a scientific journal. But Hugo DeVries, Carl Correns and Erich von Tschermak said that they later re-discovered those principles on their own, without being influenced by Mendel's work, or even being aware of him (Stent 1972). Gregor Mendel deserves credit for priority, but that ought not to be over-interpreted as directly inspiring or influencing the later geneticists. If we value Richard Feynman the same way, we relieve him of the responsibility of planning and predicting nanotechnology in minute detail.

The third possibility is to read Feynman the way some people read Nostradamus. Remember that the sixteenth-century seer envisioned and described many things in such a way that some people now see current events as fulfillments of his prophesies, which is to say, proof that Nostradamus truly saw the future. Reading him lets some people make sense of events in our own time by retroactively linking them to a mysterious man in a far-away past. But there is not much predictive specificity in his writing. The classic problem of reading Nostradamus is that the relation between his prophesy and later events is so thoroughly ambiguous that events can never be interpreted to *dis*-prove his visions. You can read him after the fact as a source of true prophesy, if you are so inclined, but the built-in ambiguity prevents anyone from demonstrating conclusively that he was writing false prophesy.

What this means for Richard Feynman and his 1959 talk is that we can add intellectual credit to a man from the recent past – who already has plenty of well-earned credit – by finding prophesies-come-true in the passages of "Plenty of Room." But then what do we do with the passages that seem to have been contradicted or made irrelevant by developments in nanotechnology? There are not a lot of these in "Plenty of Room," but there are some. If we take nanotechnology to be the fruit of the thoughts that Feynman expressed in December 1959, does this mean that nanotech is valid and good to the extent that parts of his talk have been realized, and invalid or suspect to the degree that nanotechnology digresses from what he said?

Feynman as nano-Apostle implies a very tight causal relation between the text of "Plenty of Room" and subsequent developments in nanotech. Feynman as nano-Mendel gives him credit for seeing certain things before others did, but not for directly influencing or inspiring all later developments. The nano-Nostradamus interpretation lets us see Feynman everywhere in nanotech, but this is a very sloppy way to relate an early text to later events. Bad for nano and pointless for one's memory of Richard Feynman.

Can we separate the early history of nanotechnology from Feynman's talk, and ask instead whether "Plenty of Room" is retroactively read into the history of nanotechnology?

My question does not challenge Richard Feynman's well-known influence in quantum physics. One of the cornerstones of nanotechnology is quantum physics, and Feynman was one of the greatest of the quantum physicists, so one can find traces of his scientific contributions in various parts of nanotechnology. But I am asking about the influence of one particular text, namely, "There's Plenty of Room at the Bottom." This is the specific piece that some people say represents the beginning of nanotech, not his experimental work or theoretical breakthroughs.

We can also ask about Feynman's follow-up talk, "Infinitesimal Machinery" (Feynman 1983, 1993, 2006). Here he restated his 1959 vision and elaborated it. If "Plenty of Room" was truly the text that instigated nanotech, then we might expect important people to cite and appreciate "Infinitesimal Machinery" as a kind of *Deuteronomy* which restated and reinforced "Plenty of Room."

A related question concerns the legacy of Eric Drexler, particularly his 1981 paper, "Molecular Engineering" (Drexler 1981). Drexler insists that the core of Feynman's vision is large-scale precision manipulation and combination of atoms and molecules (now called molecular manufacturing), and he says that he himself continues the rightful essence of Feynman's vision. After all, it was Feynman who wrote: "I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on" (Feynman 1960a:34). What could be more Drexlerian? In Drexler's view, the term "nanotechnology" has been debased by other activities which deviate from molecular manufacturing, and, consequently, it is urgent to return to the essence of Feynman's vision of nanotechnology (Drexler 2004; Regis 2004:205), or Drexler's understanding of Feynman's vision.

Almost everyone would agree that Drexler's work as a popularizer, especially in *Engines of Creation* (Drexler 1986), has caused large numbers of people to become interested in nanotechnology. I do not challenge this. I ask whether Feynman's influence on scientific developments in nanotech had a secondary amplification in Drexler's influence. Did Eric Drexler influence important scientists so that they might *not* have thought what they thought or might *not* have done what they did, if not for inspiration from him? After all, Drexler reminds audiences that his technical publications, beginning with the 1981 "Molecular Manufacturing" paper, demonstrate that he is more than a popularizer (e.g., in Drexler and Smalley 2003:39, 41; Drexler 2004:22).

This question is interesting in light of the bitter Drexler-Smalley exchange of December 2003. Ed Regis had written that Richard 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 (Regis 1995:275; Regis 2004:204). In the special issue of *Chemical & Engineering News* that carried the Drexler-Smalley debate, wherein Smalley vehemently disagreed with Drexler, pouring loads of scorn and contempt on him, Smalley explicitly acknowledged that *Engines of Creation* caused him to take an active interest in nanotechnology (Drexler & Smalley 2003:40). So if Drexler directly inspired one important scientist in nanotechnology, could he have also influenced others?

I concentrate on the nano-Apostle reading because the attributions I cited above either assert that Feynman was the First Apostle of nanotech or otherwise credit that idea. At this point we have a set of hypotheses:

1. That Richard Feynman's "Plenty of Room" directly inspired important nanoscientists, and that this inspiration is evident in important scientific developments (i.e., Feynman as nano-Apostle);

2. That "Infinitesimal Machinery" amplified the importance of that inspiration.

3. That Eric Drexler's "Molecular Engineering" paper directly inspired important scientific developments in nanotechnology, thereby continuing and multiplying the influence of Feynman's "Plenty of Room".

Let us be specific about "important scientific developments." There are thousands of scientific publications about nanotechnology, plus a large number of patents, and several Nobel Prizes. We could argue endlessly about which developments were more important than others. For purposes of this paper, I select three that most people would agree have been crucial to nanotechnology: the invention of the scanning tunneling microscope, the invention of the atomic force microscope, and the first manipulation of individual atoms using the STM to move thirty-five xenon atoms into place. These three events occurred well after the publication of Feynman's "Plenty of Room." Binnig and Rohrer patented the scanning tunneling microscope and executed the first successful STM experiment before Drexler's paper appeared, but the other two events happened after the publication of Drexler's "Molecular Engineering." And so I ask whether we can find evidence of either a Feynman or a Drexler influence in these developments.

I have two principal sources of information for pursuing this question: first, a citation history from the *Science Citation Index* for "Plenty of Room," "Infinitesimal Machinery," and "Molecular Manufacturing"; and, secondly, a series of comments I solicited from scientists involved in those three developments, asking them how Feynman and Drexler influenced or inspired them.

I pursue these questions with a brief examination of the text of Feynman's "Plenty of Room," a history of its publication and republication, a record of their citations in scientific literature, and a series of comments from some of the scientific luminaries of nanotechnology. I do the same, in a more abbreviated style, for Drexler's "Molecular Engineering." After that I present a story about Conrad Schneiker's advocacy of the scanning tunneling microscope as a "Feynman Machine," that is, a different way of putting Richard Feynman into the history of nanotechnology. Finally I raise some questions about how we read his talk into nanotech.

Feynman's 1959 Talk

On 29 December 1959, Richard P. Feynman spoke to the American Physical Society at its meeting at Caltech in Pasadena, California. Paul Shlichta of the Jet Propulsion Lab attended Feynman's talk and later said that, "The general reaction was amusement. Most of the audience thought he was trying to be funny… It simply took everybody completely by surprise" (Appenzeller 1991:1300; see also Regis 1995:63-71).

The text of Feynman's talk has an introduction, a conclusion, and ten topical subheadings in between. In the introduction, Feynman says "what I want to talk about is the problem of manipulating and controlling things on a small scale" (1960a:22). He then describes in detail how to execute a process for writing letters that are reduced by 25,000 times using an electron microscope. (Indeed Feynman was right: it has since become a common practice to write very small letters with an electron beam.) One would then make plastic molds of the writing, reproduce them in silicon, and finally read the copies of the writing with an electron microscope (1960a:22-23).

After that, his text shifts into a different tone: “I will not now discuss how we are going to do it, but only what is possible in principle – in other words, what is possible in principle according to the laws of physics” (1960a:24). His possibilities-in-principle include reducing writing to a binary code written in atoms, improving “the electron microscope by a hundred times,” making computer components with diameters of 10 to 100 atoms, modeling information systems on biological systems, manufacturing extremely small devices (“infinitesimal machines”) and manipulating individual atoms. Five times he tells his audience that he does not know how to do a procedure, but that the procedure violates no laws of physics, and thus he challenges scientists to figure out how to do it. In the view of Colin Milburn, “the talk is composed as a series of science fiction stories” (Milburn 2002:282).

One memorable passage concerns a series of devices for manipulating very small things. Feynman notes that workers who handle radioactive material use a mechanical set of master-slave hands. The worker operates the master set, which controls the slave set, which handles the radioactive substance. Often the slave set is smaller than the master set. Feynman proposes that a master set should control several smaller slave sets, which would each build and control more slave sets even smaller, and so on until a series of these master-slave devices could manipulate very small matter in very large quantities (Feynman 1960a:34). “It is rather a difficult program, but it is a possibility” (1960a:30).

Milburn has pointed out that a 1942 short story by Robert Heinlein concerns an inventor who builds devices like this. The main character is named Waldo, and so his machines are called “Waldos.” Feynman’s friend Al Hibbs told him about the Heinlein story shortly before “Plenty of Room” was written (Milburn 2002:283-284; Junk & Riess 2006). Because of those connections, “Waldo” is a common shorthand for the device Feynman described.

“Plenty of Room” combines some predictions of what *will* happen (“we could arrange atoms one by one the way we want them,” for example), with a wish list of things that *ought to* happen (“Is there no way to make the electron microscope more powerful?”). There are also caveats about problems of scale like dissipating heat and losing precision. For some of these items, the author presents a clear blueprint for doing them, but for others he gets into a rhythm of saying that he does not exactly know how to do something, but that it is not impossible in principle.

Publication History of “Plenty of Room”

Engineering & Science, the Caltech magazine, printed a transcript of a tape of Feynman’s talk in its February 1960 issue (Feynman 1960a). It carried a subtitle: “An Invitation to Enter a New Field of Physics.” The magazine’s cover photo showed the author above a caption saying “Feynman in a New Field.” *Saturday Review* ran a synopsis in April 1960 with the title “The Wonders That Await a Micro-Microscope” (Feynman 1960b), and *Popular Science* ran a cute condensed version called “How to Make an Automobile Smaller than This Dot” in November 1960 (Feynman 1960c). This article had a few comments that had not been in the *Engineering & Science* article, but it retained the heart of Feynman’s argument. In addition, another Caltech magazine published a slightly abridged version of “Plenty of Room” in Fall 1960, with the text divided into sections and headings different from the first publication (Feynman 1960d).

Ed Regis writes that “Plenty of Room” was mentioned in *Science News* and *Life* in 1960 (Regis 1995:72-73). This paper appeared again in 1961 as the final essay in an edited volume titled *Miniaturization* (Feynman 1961), but without the subtitle. The *Technion Yearbook*, published by American supporters of the Technion (the Israel Institute of Technology), included Feynman’s talk in its 1962 volume (Feynman 1962).

More than twenty years later, on 23 February 1983, Feynman spoke again on the topic of atomic-level miniaturization at the Jet Propulsion Lab in Pasadena. His talk was titled “Infinitesimal Machinery,” and he described it as “There’s Plenty of Room at the Bottom, Revisited” (1993:4). He reaffirmed the general spirit of his 1959 talk and re-iterated certain parts almost verbatim, including the reduction of writing and using an electron microscope to read it. Feynman pointed out that some parts of “Plenty of Room” had been realized, e.g., “we could store a lot of information in small spaces, and in a little while we’d be able to do so easily. And of course, that’s what happened” (Feynman 1993:4).

In addition, he candidly acknowledged that some predictions from the original talk were more problematic. Recalling Waldos, he said “I doubt that that’s a sensible technique” (1993:5); and there had been “no progress” in the “misguided prediction” of making very small machines (1993:5-6). Still, he believed that it was possible to build incredibly small machines: “with our present technology, we can make thousands of these motors at a time, all separately controllable” (1993:6). This discussion included caveats about heat dissipation, loss of precision control at a very small scale, and friction resulting from molecular recognition, e.g., tungsten-tungsten bonds.

This talk was videotaped, and copies are in circulation, thanks to the Feynman Collection in the Caltech Institute Archives (Feynman 1983). Feynman presented an abbreviated version of the same ideas on 25 October 1984 at the Esalen Institute in Big Sur, California, and this too was videotaped (Feynman 1984). This version was much less formal than the first: “Infinitesimal Machinery” was retitled “Tiny Machines”; Feynman did his presentation in a polo shirt, white shorts, and bare feet; and after the talk he fielded questions about miscellaneous topics like anti-gravity devices. Referring back to “Plenty of Room,” he said “Tiny Machines” was “in some respects an old talk” (Feynman 1984).

Indeed it was, for it included the earlier comments about depositing writing by reversing the lens of an electron microscope, like looking through a telescope backwards, and he returned to Waldos for manipulating very small pieces of matter (Feynman 1984).

In 1986, Conrad Schneiker, a graduate student at the University of Arizona, wrote a book manuscript titled *NanoTechnology with Feynman Machines*, and he included “Plenty of Room” as an appendix (Schneiker 1986b). If Schneiker’s book had been published, Feynman’s paper would have appeared as “The ORIGINAL NanoTechnology Paper” (Feynman 1986). Schneiker felt that the scanning tunneling microscope could be used to fulfill one of Feynman’s more important predictions in “Plenty of Room,” namely, the manipulation of individual atoms and molecules. Thus the term “Feynman Machine.”

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 the *Engineering & Science* text (Feynman 1991). The next year, the *Journal of Microelectromechanical Systems* republished “Plenty of Room” in its first issue (Feynman 1992a). It alluded to the *Miniaturization* volume as its source, but gave an incorrect date of 26 December 1959 for the original talk. Also in 1992, the proceedings of the first

Foresight conference included “Plenty of Room” as an appendix, derived directly from *Engineering & Science* (Feynman 1992b).

Jeffrey Robbins included “Plenty of Room” in his collection of Feynman’s short papers in 1999 (Feynman 1999a:117-139), and Anthony J.G. Hey made it a part of his volume of Feynman’s work on computation (Feynman 1999b:63-76). This paper has become easily available at several web sites, including Zyvex, the Caltech Institute Archives, and the National Nanotechnology Initiative.

“Infinitesimal Machinery” was published in the *Journal of Microelectromechanical Systems* in 1993, ten years after Feynman had delivered the talk at JPL (Feynman 1993). It is not mentioned in the leading Feynman biographies by Gleick (1992) and Mehra (1994), both of which have short chapters on “Plenty of Room.” In fact Gleick wrote that “Feynman… never returned to the subject,” indicating that Gleick was unaware of the 1983 and 1984 talks (Gleick 1992:356). “Infinitesimal Machinery” was likewise invisible in Laurie Brown’s Feynman bibliography, either as a talk or as a publication (Brown 2000). Ed Regis’s book on Drexler accurately described it as a talk that Feynman delivered twice, in 1983 and 1984 (first as “Infinitesimal Machinery,” and then as “Tiny Machines,”) but Regis apparently did not know about the hard-copy publication. Anthony J.G. Hey also mentions it as “an updated version of his talk,” without referencing the 1993 publication (Hey 1999:x).

“Infinitesimal Machinery” was later reprinted in a nanotech reader in 2006 (Feynman 2006). As best I can tell, this was the only the second publication of that piece.

Publication History of Richard P. Feynman's
"There's Plenty of Room at the Bottom" and "Infinitesimal Machinery"

Year	*Publication*
1960a	There's Plenty of Room at the Bottom. *Engineering and Science*, Feb. 1960, pp. 22-36.
1960b	The Wonders That Await a Micro-Microscope. *Saturday Review*, 2 April 1960, pp. 45-47.
1960c	How to Build an Automobile Smaller Than This Dot. *Popular Science*, Nov. 1960, pp. 114 ff.
1960d	There's Plenty of Room at the Bottom. *California Institute of Technology Quarterly*, Fall 1960, 2(1):2-10.
1961	There's Plenty of Room at the Bottom. In *Miniaturization*, ed. by H.D. Gilbert (NY: Reinhold 1961), pp, 282-296.
1962	There Is Plenty of Room at the Bottom. *Technion Yearbook*, 19:29-33, 137-141.
1983	Infinitesimal Machinery (videotape of 23 February 1983). Pasadena CA: Caltech Archives.
1984	Tiny Machines (videotape of 25 October 1984). Mill Valley CA: Sound Photosynthesis.
1986b	The ORIGINAL NanoTechnology Paper (sic; reprint of "There's Plenty of Room at the Bottom"). In *NanoTechnology with Feynman Machines*, by Conrad W. Schneiker, unpublished book manuscript of 215 pages, pp. 133-149.
1991	There's Plenty of Room at the Bottom. *Science*, 29 November 1991, 254:1300-01.
1992a	There's Plenty of Room at the Bottom. *J. of Microelectromechanical Systems*, 1(1):60-66.
1992b	There's Plenty of Room at the Bottom. In *Nanotechnology: Research and Perspectives*, ed. by B.C. Crandall & J. Lewis (Cambridge, MA: MIT Press, 1992), pp. 347-363.
1993	Infinitesimal Machinery. *J. of Microelectromechanical Systems*, 2(1):4-14.
1999a	There's Plenty of Room at the Bottom. In *The Pleasure of Finding Things Out: The Best Short Works of Richard Feynman*, ed. by J. Robbins. Cambridge MA: Perseus, pp. 117-139.
1999b	There's Plenty of Room at the Bottom. In *Feynman and Computation*, ed. by Anthony J.G. Hey (Cambridge MA: Perseus, 1999), pp. 63-76.
2006	Infinitesimal Machinery. In *Nanotechnology: Science, Innovation, and Opportunity*, ed. by L.E. Foster (Upper saddle River NJ: Prentice Hall, 2006), pp. 247-268.

Citation History of "Plenty of Room"

To assess the historical importance of these two papers, I did a series of citation searches in the *Science Citation Index*, with a supplemental search in *Dialog*, between November 2004 and March 2005. My intention was that the frequency of citations in scientific journals would give a measure of how influential they were for subsequent developments in nanotechnology. The period of 1980 through 1990 was especially important because this was when Gerd Binnig and Heinrich Rohrer invented the Scanning Tunneling Microscope, Binnig invented the Atomic Force Microscope (with valuable contributions 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 existed, Richard Feynman's name is sometimes spelled correctly, and sometimes not: Feynman, Feynmann, Feymnan and Feyman. There are also multiple ways to indicate his initials, e.g., R, R P, 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 1960 *Engineering & Science* text of "Plenty of Room" is listed four different ways, even though all four are obviously the same publication. A *Dialog* search overlaps both the hard copy and electronic versions of the *Science Citation Index*, but provides slightly different results. An important article in *Physics Today* (Krumhansl & Pao 1979) does not appear in any of these indexes that search for Feynman as an author cited. Neither does Michael Roukes's warm appreciation of "Plenty of Room" in the September 2001 *Scientific American* special issue on nanotechnology (Roukes 2001). Similarly, J. Fraser Stoddart has cited both the 1960 *Engineering & Science* text of "Plenty of Room" and the April 1960 *Saturday Review* condensed version (Stoddart 1993; Amabilino, Stoddart & Williams 1994; Philp & Stoddart 1996), but the *Science Citation Index* sees only the *Engineering & Science* article, leaving the *Saturday Review* article invisible.

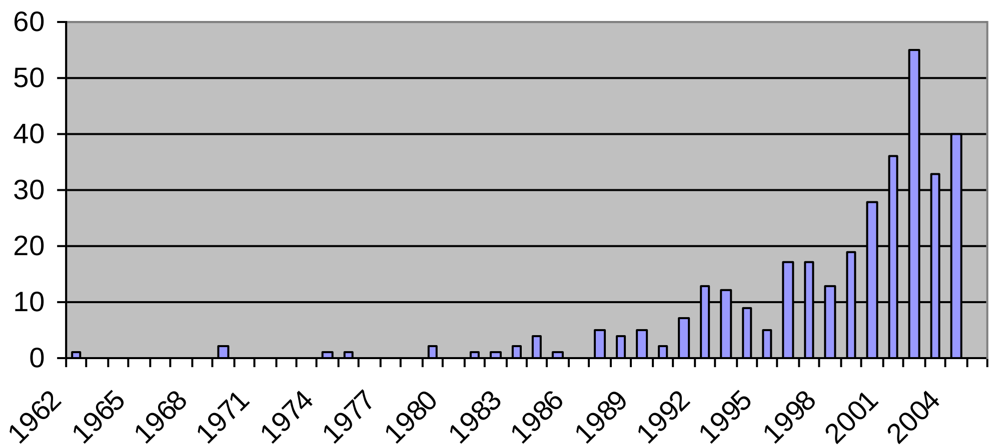
A further complication is that the ISI database changes from time to time, as the editors add some new journals and drop others. They follow a principle they call Bradford's Law, which states that "the core literature of any given scientific discipline… [is] composed of fewer than 1000 journals" (Thompson ISI: 2004). But this core shifts over time as some journals become more important, and others less so (2004). A citation search across four decades does not necessarily scan the same periodicals for each year.

These citation data are certainly incomplete to some degree, so I conclude that we should consider them an *approximation* of the citation history of "Plenty of Room." A perfect record of the citations is unrealistic, no matter how diligent the empirical scavenger is.

My citation search began with the texts from *Engineering & Science* in 1960, the *California Institute of Technology Quarterly* in 1960, *Miniaturization* in 1961, and the *Technion Yearbook* in 1962, since these were the only ones in the scientific literature that preceded the big three scientific developments in nanotech. I also searched for citations to the two 1992 republications – *Journal of Microelectromechanical Systems* and the Foresight volume – to see whether they increased the number of citations to Feynman's paper. The two 1999 texts, in the 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," as if referring to the original talk, not the 1960 publication.

The results in **Table 1** show a total of 3 citations in the 1960s and 4 in the 1970s. This scant record in the two decades before the arrival of the STM and the AFM corroborates some impressionistic comments. Tim Appenzeller wrote, "The fact that many of Feynman's ideas have now become reality doesn't mean they caught on at the time" (Appenzeller 1991:1300). He quotes Ralph Merkle: "It didn't really connect with people until the technology caught up with it" (1991:1300). And according to Adam Keiper, "Although Feynman's lecture is, in retrospect, remembered as a major event, it didn't make much of a splash in the world of science at the time" (Keiper 2003:18-19).

TABLE 1: CITATIONS TO "PLENTY OF ROOM"



The early articles that cited “Plenty of Room” presented different ways to read Feynman. The first, by John R. Platt, enthusiastically endorsed Feynman’s point that “recent advances in physics and chemistry” made it possible to build better electron microscopes for biology (Platt 1962:859). Platt then called for a national lab for biological instrumentation, on a par with other national labs. Articles by Robert Keyes (1969, 1975) and Joseph Yater (1979, 1982) discussed on-going work in information technology to make faster, better computers. They referenced Feynman to say that improvements were possible (Keyes 1969:36; Keyes 1975:741; Yater 1979:626; Yater 1982:528). Freiser and Marcus also addressed information technology, including ultra-dense packing of atomic-scale components and using individual atoms as storage units. But then they turned skeptical about Feynman’s predicitons: “Such speculations appear to be completely vacuous so far as the real world is concerned” (Freiser & Marcus 1969:89).

A 1970 article raised the question of seeing individual atoms with an electron microscope:

> The attempt to render single atoms visible has been one of the central themes in the development of the electron microscope. Substantial improvements in the resolving power of these instruments has taken place in the last two decades, but it has not been possible to obtain an image of a single, isolated atom (Crewe, Wall & Langmore 1970:1338).

The authors then presented images of what are “presumably” individual atoms. They cited neither Feynman nor Platt regarding the historical significance of their accomplishment.

On the other hand, in November 1979 Krumhansl and 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” (Krumhansl & Pao 1979:26). As they took the reader through their article, which introduced a special issue of *Physics Today*, they pointed to passages from “Plenty of Room” that anticipated exciting developments. Here “Plenty of Room” was respected as a very influential text.

The *Physics Today* article was also the one in which Eric Drexler first learned about "Plenty of Room." Drexler told me this in an email of 24 November 2004: "I encountered a mention of "There's Plenty of Room at the Bottom" in *Physics Today* while researching references for my 1981 *PNAS* article." Then in 1981, said Drexler, "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" (see also the account of this in Regis 1995:61). Drexler cited the 1961 *Miniaturization* text in "Molecular Engineering" (Drexler 1981) because that was the one Krumhansl and Pao had credited.

One experiment directly inspired by Feynman's paper was the writing of a passage of text whose letters were each approximately 10^{-7}m. At the end of "Plenty of Room," Feynman had challenged scientists to "take the information on the page of a book and put it on an area 1/25,000 smaller in linear scale in such manner that it can be read by an electron microscope" (Feynman 1960a:36). Twenty-five years later, Thomas Newman and R. Fabian Pease did so in their lab at Stanford University, using an electron beam to write the first page of Charles Dickens's *A Tale of Two Cities* on a silicon nitride surface. They wrote to Feynman on 11 November 1985 to inform him of their accomplishment and collect the prize of one thousand dollars he had offered. In his reply, Richard Feynman wrote, "You have certainly satisfied my idea of what I wanted to give the prize for… Can application to computers be far behind?" (Feynman 2005:392). Their accomplishment was published in 1987 (Newman, Williams and Pease 1987).

At a U.S. Senate subcommittee hearing on 26 June 1992, Senator Al Gore referred to "Plenty of Room" in connection with Eric Drexler's testimony. Gore said that Feynman "essentially outlined the whole field, and even researchers at the cutting edge today were sort of surprised when they went back and read the speech, and found out that the basic concept had been available for a long time" (Regis 1995:10). So "Plenty of Room" had plenty of cachet in 1992, but it was understood by Gore to have been rediscovered retroactively.

References to "Plenty of Room" in academic journals did not get into double digits in any given year until 1992, after the STM and the AFM were invented, after Eigler and Schweizer had manipulated individual atoms, and after *Science* had published a special issue on nanotechnology (Binnig et al. 1983; Binnig & Rohrer 1985; 1986; 1987; Binnig, Quate & Gerber 1986; Eigler & Schweizer 1990). From 1996 onwards, the citations remained consistently in double digits, and they usually increased from year to year.

The 1992 republications in the *Journal of Microelectromechanical Systems* and *Nanotechnology: Research and Perspectives* (the Foresight volume edited by Crandall and Lewis) increased access to "Plenty of Room." Citations for the former represent 14% of all citations from 1993 through November 2004, and those for the latter account for 2.1%.

Regarding the 1993 publication of "Infinitesimal Machinery" (Feynman 1993), I found a total of two citations from the *Science Citation Index* : one from 1997, and another from 1998. In addition, Michael Roukes referred to it in his article in the September 2001 *Scientific American* special issue on nanotechnology (Roukes 2001:44).

Nano Luminaries Comment on Feynman

Complementing this citation search is a series of statements I solicited from leading nanoscientists in November and December 2004. I asked them whether "Plenty of Room" had inspired or influenced their work, and when they first heard of that paper, plus some related questions.

I received replies from four of the people associated with the STM, the AFM, and the manipulation of atoms, namely, G. Binnig, D. Eigler, C. Quate, and H. Rohrer. I received nothing at the time from C. Gerber, and was unable to locate E. Schweizer.

These nano luminaries, as I call them, responded to my queries by saying uniformly that Feynman's "Plenty of Room" had no influence on their work on the STM, the AFM, or the manipulation of atoms. Rohrer said that their STM work was influenced "not whatsoever" by Feynman's paper. "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 [Prize]."

Regarding the general influence of "Plenty of Room" on nanotech as a whole, Rohrer responded, "I think it had no influence whatsoever." Rohrer has written a short unpublished comment on "Plenty of Room" in which he praised the boldness and brilliance of Feynman's vision, but he reminded the reader that nanotech's scientific community proceeded without knowing about "Plenty of Room." "Feynman's lecture remained practically unnoticed during nearly three decades, while the miniaturization progressed in the same time at a fantastic pace, driven by the needs of the data processing industry" (Rohrer Undated). He added that "Feynman machines," by which he meant machines that make smaller machines, are *not* crucial to nanotechnology.

Gerd Binnig stated that:

> I have not read" ["Plenty of Room"]… 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.

Binnig and Rohrer briefly mentioned "Plenty of Room" at the end of their 1987 account of the work that earned them their 1986 Nobel Prizes. The STM, they say, "opens quite generally, new possibilities for experimenting… in short, to use the STM as a Feynman Machine" (Binnig and Rohrer 1987:624). 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 (Binnig & Rohrer 1982) and the AFM (Binnig 1990), and two recent articles describing Binnig's role in inventing the STM have no mention of Feynman as an influence or inspiration (ETQ 2004; Goldstein 2004).

Calvin Quate, who was involved in the AFM developments, wrote that "None of this work 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."

Don 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 re-read "Plenty of Room," said Eigler,

> I 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.

Eigler 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.

Eigler gave a nod to Feynman in a 1991 article, saying that using the STM to manipulate atoms and molecules is, "a goal that has intrigued scientists for decades" (Stroscio & Eigler 1991:1319).

To extend this question beyond the people associated with the big three breakthroughs in nanotech, I wrote to other notables, and received replies from Chad Mirkin, James Tour, George Whitesides and Stan Williams. Did Feynman's paper influence their work? "No," said Mirkin. "Not at all," according to Tour. Whitesides wrote that "it really had no influence." According to Williams, "my research has not been directly influenced by that talk or the ideas presented in it."

When did they first read "Plenty of Room" or hear about it? "It was well after the invention of the Scanning Tunneling Microscope," recalled Stan Williams, and for Chad Mirkin, "After we invented Dip Pen Nanolithography." Tour replied, "I never read it." Whitesides stated, "I don't know that I have ever read all of it."

When asked whether "Infinitesimal Machinery" had influenced their work, Mirkin said, "No." Rohrer wrote that "I am not aware of this talk" and Eigler said "I am not familiar with this work." Tour replied, "I never heard of it." Williams's answer was, "I am not even aware of this talk." "I have never read it," said Whitesides.

For general comments on Feynman's role in nanotechnology, Whitesides commented that,

> His enthusiasm for small science has certainly boosted its [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).

Assessing "Molecular Engineering"

In addition to that record of the influence of "Plenty of Room," there is a parallel story about a hypothetical *in*direct influence. Eric Drexler began formulating his views on nanotechnology before knowing about Feynman's paper (Regis 1995:61). Then in November 1979 he read "Microscience," the Krumhansl and Pao (1979) article in *Physics Today* that cited Feynman. He started his first publication on nanotech, "Molecular Engineering," by referring to "Plenty of Room" at the beginning of the first sentence of the first paragraph (Drexler 1981:5275), and he invoked Feynman again in *Engines of Creation* (Drexler 1986:40-41). Subsequently he has described his own views as the legitimate continuation of Feynman's views (Drexler 2004).

Drexler argued that Feynman's 1959 vision instigated nanotechnology (Drexler 2004:21), and that the heart of that vision was atom-by-atom control of nanomachines to build things (2004:22), i.e., molecular manufacturing. "The Feynman vision," he continued, "motivates research on assemblers and molecular manufacturing and has generated a substantial technical literature" (2004:22).

Drexler then postulated a certain post-Feynman history of nanotechnology. The term "nanotechnology" was abused by stretching it beyond the core Feynman vision so as to include much "unrelated research" (2004:21). "The excitement of the Feynman vision attached itself to the word, tempting specialists to re-label their nanoscale research as nanotechnology" (2004:23). In his own words:

> 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 (email from Drexler to Toumey, 5 April 2005).

And if it wasn't bad enough that the rightful vision was diluted, Drexler continued, it was then purged from the definition of nanotech after Bill Joy raised his fear of self-replicating nanobots (Joy 2000, or "There's Plenty of Gloom and Doom at the Bottom"), which caused the leaders of the National Nanotechnology Initiative to worry that the public would fear nanotech (Drexler 2004:23). Those leaders, said Drexler, responded by trying to discredit Joy, telling the public that molecular manufacturing was not feasible (2004:23-25). That tactic, he suggested, was tantamount to "attempts to suppress molecular manufacturing research" (2004:24; see also Berube 2004 for another account of Drexler's views).

If Drexler's program of molecular manufacturing is the continuation of the essence of Feynman's vision in "Plenty of Room," and if Drexler has been a faithful echo of Feynman, then has that echo amplified Feynman's influence by inspiring further scientific work, e.g., the way Richard Smalley said Drexler motivated him? Here I am not attempting to assess the over-all value or truth of Drexler's vision. I concentrate on the notion that the ideas in Feynman's "Plenty of Room" received further circulation within the scientific community because of Drexler's "Molecular Engineering."

Where might we find such a line of influence? "To see research that explicitly builds on my ideas," Drexler wrote, "look at protein engineering" (email message, Drexler to Toumey, 5 April 2005). Protein designers William F. DeGrado (1997) and Carl Pabo (1983) have indeed cited Drexler's paper in their work, and Drexler pointed to them as examples. DeGrado commented that "I actually only became aware of his (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" (email from DeGrado to Toumey, 11 April 2005). Pabo's 1983 article followed Drexler's suggestions in considerable detail in a passage about strategies for designing proteins. In a recent email message (Pabo to Toumey, 15 April 2005), Pabo's acknowledgment to Drexler was stronger than DeGrado's:

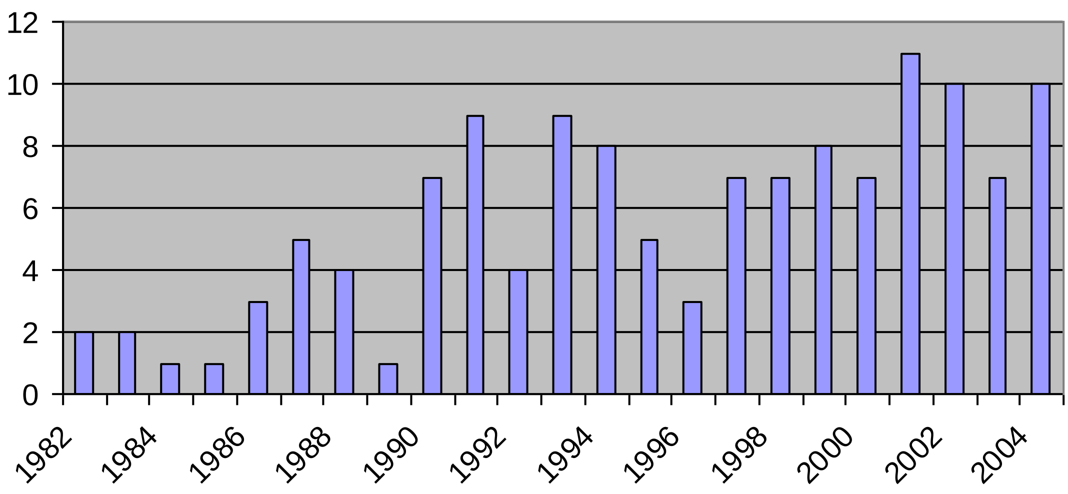
> In my *Nature* News & Views article [i.e., Pabo 1983], I make a point of mentioning Drexler's paper since it was a key source of my motivation in first thinking about this problem. Eric's 1981 *PNAS* article clearly made the point that it might be possible to design new proteins reliably even before we could develop methods for reliably folding existing proteins (email message, Pabo to Toumey, 15 April 2005).

Drexler's "Molecular Engineering" paper appeared after the invention of the STM but before the AFM and the manipulation of individual atoms. He has since developed the themes in that article by writing much more on nanotech, beginning with *Engines of Creation* in 1986. I focus on the 1981 article for three reasons: because of its early date; because the themes of his later works are consistent with this first one; and because it appeared in a very prestigious journal, *Proceedings of the National Academy of Sciences*. 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.

Table 2 shows the results of my citation search for "Molecular Engineering." In scientific journals, annual references to Drexler's 1981 paper remained in single digits until 2001. During the years of the invention of the AFM, and Eigler and Schweizer's work of dragging 35 xenon atoms into place, "Molecular Engineering" never received more than 5 citations in one year.

Thirty-one articles cited both Feynman's paper and Drexler's. This represents 9.2% of all the "Plenty of Room" citations (n = 336) and 24% of the references to "Molecular Engineering" (n = 129). I take this to mean that Drexler leads his readers to Feynman, which should not surprise anyone, but those who start with Feynman are less likely to credit Drexler. Incidentally, for the first thirteen years that "Molecular Engineering" was referenced in the scientific literature (1982-94), this paper had almost as many citations as "Plenty of Room": 63 for Feynman, and 56 for Drexler.

TABLE 2: CITATIONS TO "MOLECULAR ENGINEERING"



Nano Luminaries Comment on Drexler

Some of the nano luminaries who commented on Feynman's influence also had views about Drexler. Because of the way I framed my questions, their statements addressed his general influence, and were not specific to "Molecular Engineering."

Heinrich Rohrer, who at one point had invited Drexler to the IBM Zurich Research Lab, 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." Don Eigler seconded that view, saying "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, Chad Mirkin, James Tour, George Whitesides and Stan Williams stated clearly that Drexler's writings had *not* influenced their scientific work or that of other scientists they knew. Each of them located Drexler's influence in the area of popularization, which they sharply distinguished from science. Mirkin's and Whitesides's comments about Drexler as a popularizer were neutral, but Tour and Williams expressed hostility. Here is Williams's view:

> His [Drexler's] claims have done the field a lot of harm. 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.

To explore a more positive side of Drexler's impact, I identified Christof M. 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. He explains that he has four reasons for choosing DNA: (1) the A-C-G-T information system is very versatile; (2) the double helix is mechanically rigid; (3) the DNA molecule is chemically stable; and (4) there are good tools like enzymes for manipulating DNA (Niemeyer 1997; 1999; 2000; 2001a; 2001b; 2002; Niemeyer, Burger & Peplies 1998; Niemeyer, Adler, Gao & Chi 2002).

In Niemeyer's articles on this topic, "Molecular Engineering" is usually referenced on the first page 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" (Niemeyer 2001b:4136; see similar statements at Niemeyer 1997:585; 1999:119; 2000:609; 2001a:3189; 2002:395; Niemeyer, Burger & Peplies 1998:2265; Niemeyer, Adler, Gao & Chi 2002:223). Niemeyer also cites Feynman's "Plenty of Room" in some of those journal articles (1997; 1999; 2000; 2001a; Niemeyer, Burger & Peplies 1998), and he occasionally references Drexler's *Nanosystems* too (Drexler 1992; Niemeyer 2001a; 2001b).

The Evil Anti-Feynman

I first presented my conclusions about "Plenty of Room" at a conference on the history of nanotechnology at the Chemical Heritage Foundation in Philadelphia in March 2005. At that time I sent a courtesy copy of my unpublished paper to several people who had provided me with valuable help, including Doug Smith, editor of the Caltech magazine *Engineering & Science*. Smith later replied that the magazine wanted to publish it. This surprised me very much, considering that Richard Feynman's colleagues, friends and former students at Caltech – actually, the Caltech community as a whole – might read my paper as an attempt to diminish Feynman's reputation.

"Apostolic Succession," a shorter, earlier version of this paper, appeared in the June 2005 issue of *Engineering & Science* (Toumey 2005a). Since it was a magazine article, some of the usual attributes of an academic paper were deleted. The two tables of citations were retained, but all of the references were removed, and the text was shortened. This worried me at the time. Some academics wear their references like armor to protect themselves from hostile reactions. The more references, the thicker the armor, or so one feels. I do this too sometimes, especially when saying something provocative. So I wondered whether the Caltech readers of *Engineering & Science* would think that my conclusions made me the Evil Anti-Feynman, and if so, whether I would have to defend myself naked, without my references to shield me.

After "Apostolic Succession" was published, I received some interesting reactions. Jonathan V. Post, a 1973 Caltech graduate who worked with Richard Feynman, emphasized that Feynman "explicitly led me to my nanotechnology research, i.e., a 1977 dissertation on "molecular cybernetics" at the University of Massachusetts. This was, he says, the "world's first nanotechnology Ph.D. dissertation," and it gave Post "priority over Drexler." The way Post puts it, Eric Drexler is the father of nanotech, Richard Feynman is the great-grandfather, and between them there are "on the order of a dozen grandfathers of nanotechnology," including Post (Post email to Toumey, 11 June 2005).

Stephen L. Gillett, another Caltech alumnus from the early 1970s, contacted me to say that Drexler's influence deserves more respect than most people give it. His message responds to the passage in "Apostolic Succession" where I quote the nano luminaries' disdain for Drexler.

A third person in the Caltech community felt that "Plenty of Room" was much more influential in scientific circles than I had concluded, but that this influence took the form of discussions, rather than references in published articles. I agree that, to some extent, Feynman's talk must have had an influence, especially at Caltech, that cannot be measured in my citation count. Michael Roukes of Caltech credited "Plenty of Room" by saying that "it has profoundly inspired my two decades [approximately 1981 to 2001] of research on physics at the nanoscale," (Roukes 2001:42), which of course affirms that person's comment.

This idea has intrigued and frustrated me. How does one assess that kind of informal influence, or even trace it, unless people speak up as did Michael Roukes? How can one say that a paper was influential for a period of more than twenty years during which it was hardly ever cited? The usual way to say that a text has influenced a person, in both the sciences and the humanities, is to cite it in a book or article. And so I feel that this person's comment is credible, but practically impossible to verify.

Then again, my citation search shows that references to "Plenty of Room" exploded in the early 1990s, just after the Eigler-Schweizer experiment and the November 1991 special issue of *Science*. It makes sense that some scientists might have been strongly influenced by Feynman's talk in that decade, even if few were influenced by it before then.

Also, there was this message from a fourth person at Caltech, who wrote to *Engineering & Science*:

> Mr. Toumey has taken a very minor and rather insignificant factoid, and through magnification and distortion, and the expenditure of considerable energy and resources, achieved a large increase in the entropic state of the universe, resulting in a significant damage to the environment in the form of wasting large amounts of high quality paper, and diverted a large population of bright people from thinking about anything important; a real form of damage to the intellectual environment as well… I expect he can be appreciated in the way paleontologists value the contributions of dung beetles, who will pick away at the flesh until the bones of the dead are bright, white, and clean.

Exactly what I had feared: myself as the Evil Anti-Feynman. After I picked myself up from the floor and thought about how to escape my new identity, I wrote a reply to the writer. I defended my work and my conclusions, but my tone was conciliatory, even friendly in parts. His response to my reply was similarly conciliatory. We do not see eye to eye on everything, but we have gotten the animosity out of our correspondence.

It also helped that I produced a different piece on Feynman at this time. Because of my interest in Richard Feynman, the journal *Techné* arranged for me to write a review of *Perfectly Reasonable Deviations from the Beaten Path*, the new collection of Richard Feynman's letters, edited by his daughter Michelle Feynman (Feynman 2005). As a commentary on his life as revealed in his letters, my review showed that I admire Richard Feynman very much (Toumey 2005b). When I wrote my review of *Perfectly Reasonable Deviations*, I had not intended to use it as an antidote to the problem of the Evil Anti-Feynman, but it nevertheless seems to have deflected some of the negative reactions to "Apostolic Succession."

Connecting Binnig & Rohrer to Feynman

Given that Binnig, Rohrer, Quate, Eigler and others did not use Feynman's paper to accomplish their notable work in the early days of nanotechnology, we are left with an intriguing reversal of the nano-Apostle hypothesis: what did Richard Feynman know and think about *their* work? Also, even if these scientists did not at first think of the scanning tunneling microscope as a fulfillment of Feynman's predictions, who did? These two questions lead us to the story of Conrad W. Schneiker.

The L5 Space Society was a network of people based in Tucson, Arizona, who enthusiastically supported the colonization of space and the search for extraterrestrial life. One of its founders, H. Keith Henson, was in contact with Eric Drexler, who was studying space science at MIT in the 1970s, and Drexler visited Tucson to do some research with Henson. One Tucson-based member of the L5 Space Society was Conrad Schneiker, who had graduated from Arizona in 1978 with a B.S. in Engineering Mathematics, after which he spent several years as an occasional graduate student, first in Engineering and then in Optical Sciences. In a series of ephemeral unpublished papers beginning in 1983, he repeatedly referenced Richard Feynman's "Plenty of Room" to support the idea of "automated mass production of a wide range of miniature machinery and other microtechnology (MT) structures in very large quantities" (Schneiker 1983:1). His writing at this time faithfully echoed Eric Drexler 1981 *PNAS* paper, "Molecular Engineering," which he cited almost as often as Feynman's paper. In addition, he read some early drafts of Drexler's *Engines of Creation*, which at one point had a working title of "The Future and How to Make It Work." Wrote Schneiker, "I highly recommend it; it is by far the best reference on MMT" ["molecular microtechnology"] (Schneiker 1983:19). Schneiker heard the term "nanotechnology" from H. Keith Henson (Schneiker email to Toumey, 5 June 2005), whose contacts with Drexler were closer than Schneiker's. The 1983 manuscript by Schneiker repeated Feynman's notion of Waldos, a series of increasingly smaller master-slave remote-controlled mechanical hands. But, he said, many intermediate steps could be skipped (Schneiker 1983:5).

A 1984 journal article by Schneiker cited both Feynman's "Plenty of Room" and Drexler's "Molecular Engineering" to advocate "microrobots" and "molecular-scale robots" (Schneiker 1984a:190), while a pair of short manuscripts from the same year also invoked Feynman and Drexler (Schneiker 1984b; Henson & Schneiker 1984).

In 1983 or '84 he heard about the scanning tunneling microscope, around the time he was working for a software company in the Los Angeles area. He also audited some courses at Caltech at that time. In four brief unpublished papers in 1985, Schneiker connected two ideas, namely, Feynman's vision of precision control of molecules and atoms, and the scanning tunneling microscope. The first of those papers was dated 26 February of that year (Schneiker 1985a, 1985b, 1985c, 1985d). The STM was the instrument that would enable one to fulfill Feynman's vision, he said repeatedly. "With suitable modifications," he wrote, "the STM can be used to directly manipulate individual atoms and molecules… The Feynman path to NanoEngineering is feasible NOW, in one step" (1985a:1); "Feynman Machines… [are] atomic scale machine tools" (1985b). He did not explain in detail how the STM would do these things. Later papers by Becker and colleagues (1987), Foster and colleagues (1988), and Eigler and Schweizer (1990) had much more information on this. Schneiker also injected a subtle criticism of Drexler's "Molecular Engineering" (Drexler 1981), saying that the simplicity of the STM made Drexler's program unnecessarily complicated and time-consuming (1985a:1; 1985b:2; 1985c:2; 1985d:3).

Shortly after that, back in Tucson, Schneiker tried to find people in Electrical Engineering at the University of Arizona who might be interested in the STM, and they referred him to Stuart Hameroff in the Medical School. Hameroff, in the Department of Anesthesiology, was pursuing the idea that consciousness took the form of information stored and processed in molecules known as microtubules that are found within living cells (Hameroff 1987). Schneiker served as Hameroff's graduate research assistant between 1985 and '87. They collaborated on the first STM at Arizona, and Schneiker explained to Hameroff how it could be used to improve our knowledge of biological molecules.

In 1986, the same year that *Engines of Creation* was published, Conrad Schneiker wrote a seven-page paper which was converted into a poster which Hameroff presented at a conference on the scanning tunneling microscope in Santiago de Compostela, Spain, in July 1986. The title of the paper and poster was "NanoTechnology with STMs, Feynman Machines, and von Neumann Machines" (Schneiker 1986a). Three months later, Schneiker and Hameroff delivered a paper on "NanoTechnology Workstations" at a conference on molecular electronic devices in Arlington, Virginia. This paper, published in 1988, recapitulated parts of Feynman's "Plenty of Room," and then described "Feynman Machines" as "teleoperated or computer controlled machine tools able to mechanically operate on structures in the submicron or nanometer domain" (Schneiker & Hameroff 1988:71). Their paper nominated the scanning tunneling microscope to be a Feynman Machine; it explained how the STM worked; and it suggested how the STM could be combined with other instruments to image and manipulate atoms.

Also in 1986, Conrad Schneiker assembled a book manuscript of 215 pages titled *NanoTechnology with Feynman Machines* (Schneiker 1986a). It contained a reprint of Feynman's "Plenty of Room," retitled as "The ORIGINAL NanoTechnology Paper" (Feynman 1986b). This manuscript was intended to be part of a longer book titled *Ultimate Computing*, by Hameroff, Schneiker, and a third co-author, but the work was split into two or more separate manuscripts. Schneiker's manuscript was never published.

In short, Schneiker created seven documents in 1985 and '86 (plus an eighth that I have been unable to find) which made the case that the STM would enable one to control molecules and atoms as Feynman had urged. While it is regrettable to an historiographer that Schneiker's papers on the STM as a Feynman Machine were unpublished in 1985-87, his views from those early papers appeared in articles in 1988 and '89 (Schneiker & Hameroff 1988, Schneiker et al. 1988, Schneiker 1989). The content of those articles is consistent with the earlier unpublished papers. Citations in published works for some of Schneiker's unpublished papers provide an additional historical trace, e.g., Hameroff's *Ultimate Computing* (Hameroff 1987) and a review in the *Journal of Applied Physics* in January 1987 (Hansma & Tersoff 1987).

Hameroff's book, *Ultimate Computing: Biomolecular Consciousness and NanoTechnology*, appeared in 1987. Chapter Ten was titled "NanoTechnology" (following Schneiker's spelling which capitalized the T). This chapter began with an account of Feynman's talk, and most of its 33 pages consisted of a celebration of the wonders of the STM, including the potential for precision control of molecules and atoms. Much of the content of this chapter was close to the 1986 paper on "NanoTechnology Workstations" (Schneiker & Hameroff 1988), and in fact used many of the same illustrations that appeared in the 1986 paper. The book also contained a 13-page bibliography on the STM.

Hameroff liberally credited Schneiker's unpublished papers and said that Schneiker had "supplied most of the material on nanotechnology" (Hameroff 1987:xxi). He reiterated that point in 2003, when *Ultimate Computing* became available on-line, by referring to "help and guidance from Conrad Schneiker who also provided the prescient information about nanotechnology and quantum references" (Hameroff 2003). In Hameroff's words, from the 1987 publication of *Ultimate Computing*:

> A feasible solution [to the problem of finding Feynman machines] has been advanced by a present day nanotechnologist whose contributions may eventually eclipse all others. Conrad Schneiker may have found the bridge to the nanoscale (Hameroff 1987:243)… Schneiker's breakthrough was to realize that STM tips can be used as ultraminiature, ultraprecise robot fingers that can both "see" and be used to directly manipulate individual atoms and molecules along the lines suggested by Feynman. The scaling down process proposed by Feynman (machines building smaller machines, and so on) [Hameroff's parentheses] can be reduced to just one step! According to Schneiker's concept, STMs can directly link up to the nanoscale to implement, construct, and evaluate Feynman machines and other nanotechnologies (Hameroff 1987:251).

Schneiker became a visiting scientist at IBM Zurich in the summer of 1987 thanks to Dieter Pohl, a manager of the STM group there (Schneiker email to Toumey, 5 June 2005). Pohl recalls that "I thought that he would be a good discussion partner who could contribute to the creation of new concepts in nano-scale research. We indeed had many good discussions but most of his ideas were too futuristic for real research" (Pohl email to Toumey, 15 June 2005). One, however, resulted in a patent for a device to control the distances between tip and surface in a multi-tip tunneling device (Pohl & Schneiker 1991). Schneiker was the lead author on a review article on "scanning tunneling engineering" in the *Journal of Microscopy* in 1988 (Schneiker et al. 1988), and, before long, Hameroff and Schneiker were participating in research which used STMs to image biological materials (Simic-Krstic et al. 1989; Voelker et al. 1988).

At a Santa Fe Institute workshop on artificial life, held at Los Alamos in September 1987, Schneiker again presented his case that the scanning tunneling microscope was a "Feynman Machine." He added a detailed history of nanotechnology, featuring both theoretical and experimental work from the previous three decades. "Atomically precise mechanical manipulation of matter has finally been achieved in some very special and very limited cases," he wrote (Schneiker 1989). This probably refers to the Bell Labs accomplishment of placing an atom on a germanium surface, reported in January 1987 (Becker, Golovchenko & Swarzentruber 1987).

I'd like to draw attention to one short sentence from Schneiker's Los Alamos paper: "Needless to say, Feynman was delighted when I first informed him about STMs and their capabilities" (Schneiker 1989:458). Schneiker had previously written the same thing in two of his unpublished short papers from 1985 (1985b:1; 1985d:2), the first of which was dated 4 April 1985, but the Los Alamos paper represented the first time this comment was published. In a pair of emails (Schneiker to Toumey, both 5 June 2005), he explained his interests and his connection with Feynman:

> I was generally interested in things relating to ultra-microminiaturization well before I learned what Drexler was up to. Prior to learning about Drexler's nano-assembler-centric view of what later was called nanotech, I was familiar with the works of [K.R.] Shoulders, Pat Gunkel's "The Promise of Space," Feynman's chapter in the book

> *Miniaturization* and so on. I first heard the term nanotechnology from Keith Henson, a co-founder of the L-5 Space Society… When I was living and working in the Pasadena area (around the years 1983-1985), Feynman, [Carver] Mead, and [John] Hopfield allowed me to audit their courses on the physics of computing. That's when I had most of my discussions with Feynman. Somewhat to my surprise, Feynman had not heard of STMs when I had first asked him about them, but he was delighted to learn about them. Later he mentioned STMs in one of his lectures. He also mentioned STMs in a talk (I think it was about quantum computing) he gave at Caltech (I think it was for a student physics club) as a possible means for making atomically precise structures.

To expand upon Schneiker's comment about Feynman's knowledge of the STM, I examined Feynman's comments on infinitesimal machines and quantum mechanical computers, where the STM would obviously be germane. Richard Feynman said nothing about the STM in his 1983 "Infinitesimal Machinery" talk (Feynman 1983; 1993). In "Tiny Machines," the second version of "Infinitesimal Machinery" from 25 October 1984, he spoke at length about methods and instruments for very small writing, and he told the audience that it was done by using an electron microscope in reverse, like looking through a telescope backwards. This repeats a passage from "Plenty of Room." He also restated his 1959 vision of a series of Waldos, which likewise comes from "Plenty of Room" (Feynman 1984). Neither "Infinitesimal Machinery" nor "Tiny Machines" mentioned the STM.

By 1983, Feynman began to describe certain features of nano-scale computers. A talk of 14 April 1983, published in February 1985 as "Quantum Mechanical Computers," returned to the idea that, in a very small computer, "one bit will be represented by a single atom being in one of two states" (Feynman 1985:13). This article was more concerned about the computer logic than the hardware. To finesse the question of how to build such a computer or position individual atoms, it reverted to a certain tone in parts of "Plenty of Room": "It seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms" (1985:20). "Quantum Mechanical Computers" was also republished in 1986 (Feynman 1986a).

The scanning tunneling microscope would have been very relevant to "Infinitesimal Machines" and "Quantum Mechanical Computers." The lack of any reference to the STM in these statements from 1983 through early 1985, particularly in connection with his vision of manipulating individual atoms, hints that Feynman was unaware of the STM's potential to move atoms around, as was almost everyone else at that time.

Likewise, this comment from John Baldeschweiler, in response to my questions, seems to corroborate that point:

> We started building our STM system at Caltech in 1982 and continued developing and improving the technology for the next ten years so we certainly had systems in place while Richard Feynman was still alive. As far as I know, he never expressed to me an interest in the method, nor did he observe it in operation. I don't know how familiar he was with the capabilities of STM (or other variants of the method such as Atomic Force Microscopy, AFM), since we never had a conversation on the subject (email from Baldeschwieler to Toumey, 13 December 2005).

Then a pair of documents shows that in 1985 and '86, Conrad Schneiker and other people were feeding information to Richard Feynman about the STM's ability to do nanotechnology. Paul Hansma of UC – Santa Barbara wrote to Feynman on 16 October 1985 to invite him to visit Santa

Barbara. He explained to Feynman that he and his colleagues had built two scanning tunneling microscopes and were in the process of building a third,

> …to investigate the possibility of writing very small dots and lines… Thus we have a special interest in your inspiring work… Curiously enough, some of the earlier research in our group was anticipated by "There's Plenty of Room at the Bottom" (Hansma letter to Feynman, 16 October 1985, Feynman Papers in the Caltech Institute Archives, Box 25, Folder 13).

Hansma continues,

> We are excited about the possibility, as suggested by Conrad Schneiker, of using a tunneling microscope as a miniature robot arm. At present it can locate and hover over individual atoms and molecules. In the future perhaps it can identify and manipulate them.

Hansma's invitation also included a crude STM image of selenium atoms, approximately 1.5 nm by 1.5 nm, plus two articles from Hansma's research group (Coleman et al. 1985; Moreland et al. 1983). In a voicemail message to me on 10 October 2005, Paul Hansma recalled that Schneiker probably arranged for Hansma to invite Feynman to Santa Barbara (Hansma reply on voicemail to Toumey's letter, 10 October 2005).

The Feynman Papers in the Caltech Institute Archives include Richard Feynman's copy of Binnig and Rohrer's 1984 article on "Scanning Tunneling Microscopy" (Binnig & Rohrer 1984) and their January 1985 "Nano-Aperture" (Binnig et al. 1985), although it is not clear when Feynman acquired them. In addition, the August 1984 report of a conference on "Chemically-based Computer Systems," attended by Feynman, included this comment:

> Tunneling can be taken advantage of – it has recently been used by G. Binning (sic), H. Rohrar (sic), C. Gerber and E. Weibell (sic), at the IBM Research Laboratory in Zurich, Switzerland, to design a microscope for the study of surfaces. The microscope reportedly reveals unprecedented detail; it works on the principle that the surface to be studied forms one electrode while a probe that scans above it forms the other… This device is called a Scanning Tunneling Microscope and can resolve vertical distances as small as 0.1 Å and horizontal differences as small as 6 Å! (Yates 1984:45-46).

Remember that Schneiker had created a book manuscript on "NanoTechnology with Feynman Machines" that was never published (Schneiker 1986b). In his letter to Richard Feynman of 21 July 1986, he reminded Feynman that he was preparing "a book on micromachines and nanotechnology, which I may have mentioned when we talked earlier this year" (Feynman Papers, Box 27, Folder 11). "Since it takes your classic paper 'Plenty of Room at the Bottom' as its starting point and since most people are unfamiliar with it…", Schneiker asked Feynman for permission to reprint it. Enclosed with this letter was Schneiker's July 1986 paper on "NanoTechnology with STMs, Feynman Machines, and von Neumann Machines" (Schneiker 1986a). A one-sentence letter from Feynman to Schneiker, 8 August 1986, gave permission to reprint "Plenty of Room" as an appendix in Schneiker's *NanoTechnology with Feynman Machines* book manuscript (Feynman Papers, Box 27, Folder 11).

It is very likely that by 1984 Feynman knew of the STM's ability to image surfaces, but not its ability to manipulate individual atoms. The Feynman-Schneiker connections includes these points of reference:

- In unpublished papers of 4 April and 31 July 1985, and at the Los Alamos workshop of September 1987, Schneiker wrote and said that he had informed Feynman about the STM as a Feynman Machine, i.e., able to manipulate individual atoms;

- Paul Hansma's letter to Feynman of 16 October 1985 spoke of "the possibility, as suggested by Conrad Schneiker, of using a tunneling microscope as a miniature robot arm," and Hansma also thinks that Schneiker was the intermediary who arranged for the invitation to Feynman;

- Enclosed with Schneiker's letter to Feynman, 21 July 1986, was Schneiker's unpublished paper on "NanoTechnology with STMs, Feynman Machines, and von Neumann Machines," dated ten days earlier.

These papers and letters do not exclude the possibility that Feynman learned about the STM from someone else. Still, they show that: [1] Schneiker was well informed about the STM before 1985; [2] that he was excited about the "Feynman Machine" idea by 4 April 1985; [3] that he had shared this idea with Feynman before that date; [4] that Paul Hansma recognized Schneiker's views on the STM-Feynman Machine connection by October 1985; and [5] that Feynman received Schneiker's "Nanotechnology with STMs" paper in July 1986.

Carl Feynman, Ph.D., son of Richard Feynman, tells me that he and his father visited IBM Yorktown Heights to see an STM in action. He recalls that:

> I said something along the lines of how cool it was to be able to see atoms, and he said no, all we were sure we were seeing was patterns of conductivity variation on an atomic scale, and they might or might not be atoms (email from C. Feynman to C. Toumey, 11 April 2006).

According to Carl Feynman, that visit probably took place in the summer of 1986, although it might have been summer 1985. The later date seems more likely, considering that Richard Feynman was uninterested in John Baldeschweiler's STM at Caltech, and he said nothing about it in the 1985 and 1986 texts of "Quantum Mechanical Computers."

We can compare Schneiker's ideas with Drexler's from those years. Recall that Eric Drexler had connected Feynman's "Plenty of Room" to his own program of "molecular engineering" in his 1981 *PNAS* article (Drexler 1981), and then restated this connection in his 1986 book, *Engines of Creation*. He briefly commented on the STM in a footnote at the back of the book:

> A device reported in 1982, called the scanning tunneling microscope, can position a sharp needle near a surface with an accuracy of a fraction of an atomic diameter. Besides demonstrating the feasibility of such positioning, it may be able to replace molecular machinery in positioning molecular tools (Drexler 1986:245).

I take this to mean that Conrad Schneiker was way ahead of Eric Drexler in seeing the value of the STM for realizing Feynman's predictions. We can also contrast that with the evolution of

Gerd Binnig's and Heinrich Rohrer's views. Their 1985 article in *Scientific American* described the scanning tunneling microscope as a device to image atoms, but did not say that it could also manipulate them (Binnig & Rohrer 1985). Their 1986 overview of the STM concerned mostly imaging, but it ended with a brief mention of two experiments in surface modification and two in nanolithography (Binnig & Rohrer 1986). ("Surface modification" was the term then used for the manipulation of atoms). The paper which is usually cited as the first modification of an atomic surface is that of R. Becker and colleagues at AT&T Bell Labs, who reported depositing matter on a germanium crystal surface in January 1987 (Becker et al. 1987), after which J. Foster and colleagues at IBM Almaden described pinning an organic molecule onto a graphite surface in January 1988 (Foster et al. 1988). Conrad Schneiker's "Feynman Machine" statements preceded both of these events.

One more item: recall that Stuart Hameroff had presented Schneiker's paper (Schneiker 1986a) at the July 1986 STM conference in Spain. Hameroff told me that "I was at the 1986 STM conference in Spain… That is probably where Binnig and Rohrer heard of/saw [Schneiker's poster]…, as I recall talking with both of them" (Hameroff email to Toumey, 5 June 2005). Binnig sent Hameroff a postcard on 17 November 1986 saying:

> A sophisticated combination of STM and optical microscopy is still missing and a very good idea. Good luck and success. Best regards, Gerd Binnig.

This comment apparently referred to Schneiker's paper/poster (Schneiker 1986a), which had advocated a combination of scanning tunneling microscopy and optical microscopy. When Binnig and Rohrer first used the term "Feynman Machine," in their Nobel acceptance speech, they referenced two sources for the idea that the STM was a Feynman Machine: Feynman's "Plenty of Room" and an unpublished paper by Hameroff, Schneiker and other co-authors (Binnig & Rohrer 1987:624-625).

So Conrad Schneiker was one of the first people to see that the STM could fulfill Richard Feynman's prediction of precisely manipulating individual atoms; he says that he was the one who told Feynman about the STM and its potential as a "Feynman Machine," and there is circumstantial evidence to support this claim; and, finally, Hameroff discussed Schneiker's ideas with Binnig and Rohrer in July 1986.

Did Gerd Binnig and Heinrich Rohrer learned about Feynman's "Plenty of Room" from Schneiker via Stuart Hameroff? Wouldn't this be an elegant symmetry: not only does Feynman learn about Binnig and Rohrer from Schneiker; Binnig and Rohrer learn about Feynman's "Plenty of Room" from Schneiker, by way of Hameroff.

Alas, this symmetry eludes proof. Heinrich Rohrer told me that he distinctly remembers both Stuart Hameroff and Conrad Schneiker, and it "could be" that he learned about "Plenty of Room" from them. But, he says, he thinks someone else was the source (Rohrer email to Toumey, 15 July 2005).

Conrad Schneiker's role in STM research tailed off by the early 1990s but he remained active in another line of work advocated by Richard Feynman in "There's Plenty of Room at the Bottom." Feynman, like everyone else, had not imagined the scanning tunneling microscope in his 1959 talk. Instead, he called for better electron microscopes (Junk & Riess 2006:826-827). Along those lines, Schneiker invented and patented devices for low-voltage electron beam emitters, electron beam lenses, and for focusing neutron beams at the micro scale. Today he works on prognostic systems to monitor nanoscale integrated circuits, another activity related to Feynman's vision. His long-term aim is to make miniature and mass-producible scanning electron microscopes with near-atomic resolution. And so the man who first understood the Feynman Machine continues to develop Richard Feynman's prescient vision.

Reading Nanotech

There are surely some additional citations that I have not found, and perhaps some more scientists who have been directly influenced or inspired by Feynman or Drexler, paralleling the Feynman-Roukes, Feynman-Drexler-Smalley and Feynman-Drexler-Pabo-DeGrado 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, occurred without being influenced by Feynman or Drexler.

That conclusion leads to some final thoughts. First, we have an alteration of the sequence of influence. Both the nano-Apostle and the nano-Nostradamus interpretations posited this order: first there was "Plenty of Room"; then there was much interest in it; and finally that caused the birth of nanotechnology. But my analysis suggests that first there was "Plenty of Room"; then there was very little interest in it; meanwhile, there was the birth of nanotechnology, independent of Feynman's paper; and finally there was a retroactive interest in "Plenty of Room."

After formulating this conclusion, I presented my ideas to Carl Feynman, son of Richard Feynman. If I had overlooked something about the early influence of "Plenty of Room," and if there was a cadre of scientists who had gone into nanotechnology because of the direct influence Feynman's paper, then perhaps Carl Feynman would know about it and could correct me.

In a telephone conversation of 29 March 2005, I summarized my conclusions. Carl Feynman responded, "That seems completely true." I asked him about conversations about "Plenty of Room" with his father. 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 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 "Plenty of Room"? "I don't think so, except for Drexler," he answered.

The nano-Apostle interpretation applies to a small number of scientists in the first three decades after "Plenty of Room" was published, but does not account for more than a small portion of the history of nanotechnology. In my view, nano-Mendel describes the main relationship of "Plenty of Room" to the history of nanotechnology.

In 1972, Gunther Stent asked why certain discoveries of Michael Polanyi, Gregor Mendel and Oswald Avery went unappreciated at the time. He offered this explanation of "prematurity": "A discovery is premature if its implications cannot be connected by a series of simple logical steps to canonical, or generally accepted, knowledge" (Stent 1972:84). Might this explain why "Plenty of Room" went unappreciated?

Remember Feynman's repetitive theme in several sections of "Plenty of Room": X violates no known laws of physics, so X is possible. It does not say "here is how to take this insight of mine so as to invent a machine or execute an experiment." Instead, the sense of that theme is "I am sure that X can be done, so physicists ought to do it." Much of "Plenty of Room" lacks a series of simple logical steps to canonical knowledge, as Stent put it.

Some passages satisfy Stent's principle. Feynman proposed a detailed method for using an electron beam to write small letters, and this has indeed come to fruition. The section on making small Waldos that would make even smaller Waldos gave the reader the necessary simple logical steps to canonical knowledge, but it did not work. I would be curious to know whether anyone tried to make such a series of Waldos, and how far they got. Does anyone know?

Stent's principle opens an indelicate question: what do you mean by causation? When one says that a certain paper was the *origin* of a new science, or that it *caused* subsequent events, or that it *influenced* other people, these terms have different meanings in different disciplines. I turn to the German categories of academic culture to explore this point.

Most academic disciplines belong to either the *naturwissenschaften* (natural sciences) or the *geisteswissenschaften* (humanities and humanistic social sciences) in the German plan. The goal of the former is to demonstrate causal relationships. There are several forms of causation, but the darling of them all is direct causation: A causes B. To put "Plenty of Room" into the history of nanotechnology, the most scientifically elegant explanation would be the simplest. "Plenty of Room" is the *origin* of nanotech in the sense that it *directly caused* important subsequent events. McCray calls this a singularity (see above): a definitive event at a specific moment that causes a "revolutionary breakthrough" (McCray 2005:180-181). One can see how appealing this is according to the values of the *naturwissenschaften*.

Causation, however, is sometimes elegant, sometimes not. Another legitimate explanation is indirect causation. For example, Feynman caused Drexler to shape his thoughts a certain way, and then Drexler caused Smalley, Pabo, DeGrado, Niemeyer and others to think and act a certain way. I have indicated that this is part of the truth of the history of nanotech.

A third causation is multiple: A, B and C are independent causes which together result in D. Each is necessary, but none is sufficient by itself. It could well be that a scientist is inspired by Feynman's paper, but then needs the work of Binnig and Rohrer or others to convert an inspiration into a scientific result.

Another twist is the trick of proving a negative. "A causes B" is lovely when true. "A does *not* cause B" is unsatisfactory because it opens something that the *naturwissenschaften* prefer to close. My argument that "Plenty of Room" did *not* constitute the origin of nanotech is unattractive by the standards of the *naturwissenschaften*.

Coexisting with the *naturwissenschaften* are the *geisteswissenschaften*. The goal of the *geisteswissenschaften* is *verstehen*. This is usually translated as "understanding," with the caveat that *verstehen* is preferably deep, rich and nuanced. Causation per se is less important in the *geisteswissenschaften*.

Verstehen too can take different forms. One is text-based. What do the documents say, and how do they say it? This is why I indicated that the historical influence of "Plenty of Room" is complicated by Richard Feynman's habit of saying that something is not impossible in principle.

Another form is sociological. There are forces or conditions that steer one element of a society to embrace a certain package of understandings, even as another element embraces other understandings. Thus one can see that the Caltech community might appreciate one version of the origin of nanotech and the IBM community could see a different version, while Eric Drexler's network sees a third (which begins as a variation on the Feynman-centered theme).

A different way to seek *verstehen* is the cultural anthropologist's skepticism about origin stories, because many turn out to be origin myths. If this is a sin of too much skepticism, you can see that I am a sinner.

We can ask how "Plenty of Room" *caused* the origin of nanotech, but it might be more fruitful to ask *why* it was rediscovered at a certain time in history. Perhaps this 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 it to the genius, the personality, and the eloquence of Richard P. Feynman. In the words of Colin Milburn, "Nanotechnology is supposedly a real science *because* it was founded and authorized by the great Richard Feynman" (Milburn 2002:283; see also McCray 2005:181). Michael Krieger says that "Plenty of Room" and "Infinitesimal Machinery" have been appreciated mostly for "reflecting the rich, revered, idiosyncratic imagination for which Feynman was renowned" (Krieger 2006:243).

But is the Feynman cachet really transferable to other scientists' work? And how selective is the process of enhancing one's work by retroactively claiming the benefit of the Feynman cachet? "Plenty of Room" describes multiple possibilities, including the nano-etching of texts; the storing and retrieving of data in an atom-size code; the need to improve electron microscopes; the wonders of biological information systems; the miniaturization of computers; the difficulties of miniaturization; a mechanical surgeon that could be swallowed; a system of Waldos; a system of "a billion tiny factories" working together; Van der Waals attractions; superconductivity; and simplified synthetic chemistry, to name only twelve 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?

A body of research on the legacy of Gregor Mendel shows that the *re*discovery of his work owed more to personal and theoretical arguments in genetics than to its intellectual value (Weinstein 1977; Brannigan 1979; Olby 1979, 1989). Mendel's 1866 paper was more prominent in the first two decades after its publication than is commonly believed; Feynman's 1959 talk less prominent in its first twenty years than conventional accounts say; but the appreciation of each served causes beyond the scientific ideas in those works. Both Mendel's and Feynman's cachet were appropriated to support points of view that were not necessarily grounded in the original works. Let that remind us to try to distinguish the truly heroic scientific achievements in their own lifetimes from after-the-fact interpretations.

This brings us to the problem of making Richard Feynman the nano-Nostradamus. There is plenty of room in "Plenty of Room" to read the text selectively, especially with the "it's not impossible" riff. This pattern enables a reader to see later events in the history of nanotechnology as fulfillments of Feynman's predictions, which is to say, proof that Feynman truly saw the future. But those predictions are framed as future developments that are "not impossible," which is not equivalent to Stent's simple logical steps.

Truly one can point to prophesies-come-true in "Plenty of Room." But what do we do with the passages that seem to have been contradicted or made irrelevant by developments in nanotechnology? There are not a lot of these in "Plenty of Room," but there are some. If nanotechnology is taken to be the fruit of the thoughts that Feynman expressed in December 1959, then is nanotech valid and good to the extent that parts of his talk have been realized, and invalid or suspect to the degree that nanotechnology has deviated from what he said (Junk & Riess 2006)? This of course is preposterous, and one way to finesse the partly-right-and-partly-wrong character of the talk is to appreciate it selectively. The reader can see what he or she wants to see in the text, just like reading Nostradamus.

It seems to me that it is undesirable both for the science of the nanoscale and for one's memory of Richard Feynman to constrain nanotechnology within the framework of Feynman's 1959 talk. Nanotechnology has a scientific value that does not always fit into the confines of "Plenty of Room" (Junk & Riess 2006). Richard Feynman's scientific contributions possess so much well-known value that they do not need to be embellished by exaggerating the historical influence of "Plenty of Room." And his real contributions are hardly diminished by its less prescient passages.

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

One last issue: considering that this information discounts the usual Feynman-centered account of the origins of nanotechnology, does this enhance a different narrative? If so, which one? The principal effect of the comments from the nano luminaries will be to point historians to an instrumentation-centered narrative. To repeat D. Eigler's comment, "When it comes to nano, start looking at Binnig instead of Feynman." When we ask what nanotechnology descended from, we could salute the STM as one of its founding ancestors.

Alternatively, one could accept that the history of nanotechnology will not fit neatly into the standards of the *naturwissenschaften*. Nanotech need not be one thing with one beginning and one neat line of historical causation. It could be a deep, rich, nuanced and sometimes contradictory body of scientific thought and practice that we understand partly by seeing it through different historical documents, and through different readings of the same document, namely, Richard P. Feynman's "There's Plenty of Room at the Bottom."

Coda

Do I enhance one myth immediately after challenging another? Perhaps. I am not the best person to judge my work objectively, but I can suggest a way to get beyond my account of Feynman's paper, and everyone can participate in this.

Let us have a competition among humanities professors. To augment the Feynman account, the historians at Caltech could find more citations to "Plenty of Room" from before the invention of the STM, especially from a source excluded from the *Science Citation Index*. They could send them to their colleagues at MIT and ask "How's this?" The MIT people would say "not bad," but then produce a "Plenty of Room" reference from a journal even more obscure than the first. This scavenger hunt is open to all.

Then to challenge the STM-centered story that I prefer, one could seek statements from reputable nanoscientists who would say that their scientific achievements were accomplished without any influence from Binnig, Rohrer, or the scanning tunneling microscope. In an extreme form of this kind of information, paralleling my quotations about "Infinitesimal Machinery," they could say they never even heard of the STM.

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References

Amabilino, D.B., J.F. Stoddard and D.J. Williams. 1994. "From Solid-State Structures and Superstructures to Self-Assembly Processes." *Chemistry of Materials*, 6:1159-1167.

Amato, I. 1999. *Nanotechnology: Shaping the World Atom by Atom*. Washington, DC: National Science & Technology Council.

Appenzeller, T. 1991. "The Man Who Dared to Think Small." *Science*, 29 Nov. 1991, 254:1300-01.

Baird, D., and A. Shew. 2003. "The Mythology of Nanotechnology: Changing the Epistemology of Science." Unpublished paper, September 2003.

Becker, R.S., J.A. Golovchenko and B.S. Swarzentruber. 1987. "Atomic-scale Surface Modifications Using a Tunneling Microscope." *Nature*, 29 January 1987, 325:419-421.

Berube, D. 2004. "Denialism: Drexler vs. Roco." *IEEE Technology and Society Magazine*, Winter 2004, pp. 22-26.

Binnig, G. 1990. "Atomic Force Microscope and Method for Imaging Surfaces with Atomic Resolution." United States Patent RE33,387. Washington DC: USPTO.

Binnig, G., H. Rohrer, C. Gerber and E. Weibel. 1983. "7X7 Reconstruction on Si(111) Resolved in Real Space." *Physical Review Letters*, 50(2):120-123.

Binnig, G., C. Gerber, H. Rohrer and E. Wiebel. 1985. "Nano-Aperture." *IBM Technical Disclosure Bulletin*, January 1985, 27(8):4893.

Binnig, G., C.F. Quate and C. Gerber. 1986. "Atomic Force Microscope." *Physical Review Letters*, 56(9):930-933.

Binnig, G. and H. Rohrer. 1982. "Scanning tunneling Microscope." Unites States Patent 4,343,993. Washington DC: USPTO.

Binnig, G. and H. Rohrer. 1984. "Scanning Tunneling Microscopy." *Physica*, 125B:37-95.

Binnig, G. and H. Rohrer. 1985. "The Scanning Tunneling Microscope." *Scientific American*, August 1985, pp. 50-56.

Binnig, G. and H. Rohrer. 1986. “Scanning Tunneling Microscopy.” *IBM. J. of Res. Develop.*, 30(4):355-369.

Binnig, G. and H. Rohrer. 1987. “Scanning Tunneling Microscopy – From Birth to Adolescence.” *Reviews of Modern Physics*, Part 1, 59(3):615-625.

Brannigan, A. 1979. “The Reification of Mendel.” *Social Studies of Science,* 9:423-454.

Brown, L.M. (ed.). 2000. *Selected Papers of Richard Feynman.* Singapore: World Scientific.

Clinton, W. 2000. *President Clinton’s Remarks at Science and Technology Event*. Online: http://mrs.org/pa/nanotech/clinton.html (accessed 8 Sept. 2004).

Coleman, R.V., B. Dranke, P.K. Hansma and G. Slough. 1985. “Charge-Density Waves Observed with a Tunneling Microscope.” *Physical Review Letters*, 55(4):394-398.

Crewe, A.V., J. Wall and J. Langmore. 1970.”Visibility of Single Atoms.” *Science*, 12 June 1970, 168:1338-1340.

DeGrado, W.F. 1997. “Proteins from Scratch.” *Science,* 3 October 1997, 278:80-81.

Drexler, K.E. 1981. “Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation.” *Proc. Natl. Acad. Sci.*, 78(9):5275-78.

Drexler, K.E. 1986. *Engines of Creation: The Coming Era of Nanotechnology.* Garden City NY: Anchor.

Drexler, K.E. 1992. *Nanosystems*. NY: Wiley.

Drexler, K.E. 2004. “Nanotechnology: From Feynman to Funding.” *Bulletin of Science, Technology & Society*, Feb. 2004, 24(1):21-27.

Drexler, K.E. and R. Smalley. 2003. “Nanotechnology.” *Chemical & Engineering News*, 1 December 2003, pp. 37-42.

Eigler, D.M. And E.K. Schweizer. 1990. “Positioning Single Atoms with a Scanning Tunneling Microscope.” *Nature*, 5 April 1990, 344:524-526.

ETQ (The Economist Technology Quarterly). 2004. “Touching the Atom.” *Economist Technology Quarterly*, 18 September 2004, pp. 42-43.

Feynman, R.P. 1960a. “There’s Plenty of Room at the Bottom.” *Engineering and Science*, Feb. 1960, pp. 22-36.

Feynman, R.P. 1960b. “The Wonders That Await a Micro-Microscope.” *Saturday Review*, 2 April 1960, pp. 45-47.

Feynman, R.P. 1960c. “How to Build an Automobile Smaller Than This Dot.” *Popular Science*, Nov. 1960, pp. 114 ff.

Feynman, R.P. 1960d. “There’s Plenty of Room at the Bottom.” *California Institute of Technology Quarterly*, Fall 1960, 2(1):2-10.

Feynman, R.P. 1961. “There’s Plenty of Room at the Bottom.” In *Miniaturization*, ed. by H.D. Gilbert (NY: Reinhold 1961), pp, 282-296.

Feynman, R.P. 1962. “There Is Plenty of Room at the Bottom.” *Technion Yearbook*, 19:29-33, 137-141.

Feynman, R.P. 1983.Infinitesimal Machinery (videotape of 23 February 1983). Pasadena CA: Caltech Archives.

Feynman, R.P. 1984. Tiny Machines (videotape of 25 October 1984). Mill Valley CA: Sound Photosynthesis.

Feynman, R.P. 1985. “Quantum Mechanical Computers.” *Optics News*, February 1985, pp. 11-20.

Feynman, R.P. 1986a. “Quantum Mechanical Computers.” *Foundations of Physics*, 16:507-521.

Feynman, R.P. 1986b. “The ORIGINAL NanoTechnology Paper” (sic; reprint of “There’s Plenty of Room at the Bottom”). In *NanoTechnology with Feynman Machines*, by Conrad W. Schneiker, unpublished book manuscript of 215 pages, pp. 133-149.

Feynman, R.P. 1991. “There’s Plenty of Room at the Bottom.” *Science*, 29 November 1991, 254:1300-01.

Feynman, R.P. 1992a. “There’s Plenty of Room at the Bottom.” *J. of Microelectromechanical Systems*, 1(1):60-66.

Feynman, R.P. 1992b. “There’s Plenty of Room at the Bottom.” In *Nanotechnology: Research and Perspectives*, ed. by B.C. Crandall & J. Lewis (Cambridge, MA: MIT Press, 1992), pp. 347-363.

Feynman, R.P. 1993. “Infinitesimal Machinery.” *J. of Microelectromechanical Systems*, 2(1):4-14.

Feynman, R.P. 1999a. “There’s Plenty of Room at the Bottom.” In *The Pleasure of Finding Things Out: The Best Short Works of Richard Feynman*, ed. by J. Robbins. Cambridge MA: Perseus, pp. 117-139.

Feynman, R.P. 1999b. “There’s Plenty of Room at the Bottom.”In *Feynman and Computation*, ed. by Anthony J.G. Hey (Cambridge MA: Perseus, 1999), pp. 63-76.

Feynman, R.P. 2005.*Perfectly Reasonable Deviations from the Beaten Path: The Letters of Richard P. Feynman*, ed. by Michelle Feynman. Cambridge MA: Perseus.

Feynman, R.P. 2006. “Infinitesimal Machinery.”In *Nanotechnology: Science, Innovation, and Opportunity*, ed. by L.E. Foster (Upper saddle River NJ: Prentice Hall, 2006), pp. 247-268.

Foster, J.S., J.E. Frommer and P.C. Arnett. 1988. “Molecular Manipulation Using a Tunneling Microscope.” *Nature*, 28 January 1988, 331:324-326.

Freiser, M.J and P.M. Marcus. 1969. “A Survey of Some Physical Limitations on Computer Elements.” *IEEE Transactions on Magnetics*, June 1969, 5(2):82-90.

Gleick, J. 1992. *Genius: The Life and Times of Richard Feynman*. NY: Pantheon.

Goldstein, H. 2004. “A Beautiful Noise.” *IEEE Spectrum*, May 2004, pp. 50-52.

Hameroff, S.R. 1987. *Ultimate Computing: Biomolecular Consciousness and NanoTechnology*. Amsterdam: North-Holland.

Hameroff, S.R. 2003. *Ultimate Computing: Biomolecular Consciousness and NanoTechnology*. Electronic [pdf] version. Online: http://www.consciousness.arizona.edu/hameroff/ultimate_comp/introtoultcomp.htm, (accessed 23 May 2005).

Hansma, P.K. and J. Tersoff. 1987. “Scanning Tunneling Microscopy.” *Journal of Applied Physics*, 61(2):R1-R23.

Henson, K. and C.W. Schneiker. 1984. The Annual Von Neumann-Feynman Award.” Unpublished manuscript of 22 May 1984. 3 pages.

Hessenbruch, A. 2004. “Nanotechnology and the Negotiation of Novelty.” In *Discovering the Nanoscale*, ed. by D. Baird, A. Nordmann & J. Schummer (Amsterdam: IOS Press, 2004), pp. 135-144.

Hey, A.J.G. 1999. “Feynman and Computation: An Overview.” In *Feynman and Computation*, ed. by A.J.G. Hey (Reading, MA: Westview, pp. ix-xxiii..

Joy, B. 2000. “Why the Future Doesn’t Need Us.” *Wired*, April 2000, pp. 238-262.

Junk, A. and F. Riess. 2006. “From an Idea to a Vision: There’s Plenty of Room at the Bottom.” *American Journal of Physics*, 74(9):825-830.

Keiper, A. 2003. “The Nanotechnology Revolution.” *The New Atlantis*, Summer 2003, pp. 17-34.

Keyes, R.W. 1969. “Physical Problems and Limits in Computer Logic.” *IEEE Spectrum*, May 1969, 6(5):36-45.

Keyes, R.W. 1975. “Physical Limits in Digital Electronics.” *Proceedings of the IEEE*, May 1975, 63(5):740-767.

Krieger, M. 2006. “Epilogue.” In *Nanotechnology: Science, Innovation, and Opportunity*, ed. by L.E. Foster (Upper Saddle River NJ: Prentice Hall, 2006), pp. 243-245.

Krumhansl, J.A. and Y.H. Pao. 1979. “Microscience: An Overview.” *Physics Today*, November 1979, pp. 25-32.

Kurzweil, R. 2005. *The Singularity Is Near: When Humans Transcend Biology*. London: Penguin.
McCray, W.P. 2005. "Will Small Be Beautiful? Making Policies for Our Nanotech Future." *History and Technology*, 21(2):177-203.
Mehra, J. 1994. *The Beat of a Different Drum: The Life and Science of Richard Feynman*. Oxford: Clarendon.
Milburn, C. 2002. "Nanotechnology in the Age of Posthuman Engineering: Science Fiction as Science." *Configurations*, 10:261-295.
Moreland, J., S. Alexander, M. Cox, R. Sonnenfeld and P.K. Hansma. 1983. "Squeezable Electron Tunneling Junctions." Applied Physics Letters, 15 August 1983, 43(4):387-388.
Newman, T.H., K.E. Williams, and R.F.W. Pease. 1987. "High Resolution Patterning System with a Single Bore Objective Lens." *Journal of Vacuum Science Technology B*, 5(1):88-91.
Niemeyer, C.M. 1997. "DNA as a Material for Nanotechnology." *Angewendte Chemie – International Ed. in English*, 36(6):585-587.
Niemeyer, C.M. 1999. "Progress in 'Engineered Up' Nanotechnology Devices Utilizing DNA as a Construction Material." *Applied Physics A*, 68:119-124.
Niemeyer, C.M. 2000. "Self-assembled Nanostructures Based on DNA: Towards the Development of Nanobiotechnology." *Current Opinion in Chemical Biology*, 4(6):609-618.
Niemeyer, C.M. 2001a. "Bioorganic Applications of Semisynthetic DNA-Protein Conjugates." *Chemistry – A European Journal*, 7(15):3189-95.
Niemeyer, C.M. 2001b. "Nanoparticles, Proteins, and Nucleic Acids: Biotechnology Meets Materials Science." *Angewendte Chemie – International Ed. in English*, 40(22):585-587.
Niemeyer, C.M. 2002. "The Developments of Semisynthetic DNA-Protein Conjugates." *Trends in Biotechnology*, 20(9):395-401.
Niemeyer, C.M., W. Burger and J. Peplies. 1998. "Covalent DNA-Streptavidin Conjugates as Building Blocks for Novel Biometallic Nanostructures." *Angewendte Chemie – Int'l Ed. in English*, 37(16):2265-68.
Niemeyer, C.M., M. Adler, G. Song and C. Lifeng. 2002. "Supramolecular DNA-Streptavidin Nanocircles with a Covalently Attached Oligonucleotide Moiety." *J. Biomolecular Structure & Dynamics*, 20(2):223-230.
Olby, R. 1979. "Mendel No Mendelian?" *History of Science*, 17:53-72.
Olby, R. 1989. "Rediscovery as an Historical Concept." In *New Trends in the History of Science*, ed. by R. Visser, H. Bos, L. Palm & H. Snelders (Amsterdam: Rodopi, 1989), pp. 197-208.
Pabo, C. 1983. "Designing Proteins and Peptides." *Nature*, 20 January 1983, 301:200.
Philp, D. and J.F. Stoddard. 1996. "Self-Assembly in Natural and Unnatural Systems." *Angew. Chem., Int. Ed. in English*, 35:1154-1196.
Platt,, J.R. 1962. "National Laboratories for Biology?" *Science*, 8 June 1962, 136:859-861.
Pohl, W.D. And C. Schneiker. 1991. "Distance-controlled Tunneling Transducer." U.S. Patent Number 5,043,577 [see also U.S. patents 5,210,714 and RE36,603].
Regis, E. 1995. *Nano: The Emerging Science of nanotechnology: Remaking the World – Molecule by Molecule*. Boston: Little, Brown.
Regis, E. 2004. "The Incredible Shrinking Man." *Wired*, October 2004, pp. 179-181, 204-205.
Rohrer, H. Undated. "There Is Plenty of Room at the Bottom." Undated unpublished comments on Feynman"s "Plenty of Room" by H. Rohrer; sent to C. Toumey by email from H. Rohrer in November 2004.
Roukes, M. 2001. "Plenty of Room, Indeed." *Scientific American*, September 2001, pp. 42-49.

Schneiker, C.W. 1983. "Prospects and Applications for Genesis and Ultra Mass Production of Sub-Millimeter Machines, Devices, and Replicating Systems." Unpublished manuscript of 10 August 1983. 41 pages.

Schneiker, C.W. 1984a. "Some Research Topics for a New Space Development Programme." *J. of the British Interplanetary Society*, 37:190-192.

Schneiker, C.W. 1984b. "Beyond Fifth Generation Machines: Feynman Replicators." Unpublished manuscript of 1 December 1984. 8 pages.

Schneiker, C.W. 1985a. "The Modified Scanning Tunneling Microscope as a Nanometer Scale Machine Tool and Multimode Interface for Precision Assembly, Manipulation, Analysis and Control of Solid State Atomic Systems." Unpublished manuscript of 26 February 1985. 4 pages.

Schneiker, C.W. 1985b. "EUREKA! – Atomic Scale Machine Tools." Unpublished manuscript of 4 April 1985. 4 pages.

Schneiker, C.W. 1985c. "NanoScience & NanoEngineering: Foundation for a New Renaissance." Unpublished manuscript of 22 April 1985. 4 pages.

Schneiker, C.W. 1985d. "NanoTechnology." Unpublished manuscript of 31 July 1985. 30 pages.

Schneiker, C.W. 1986a. "NanoTechnology with STMs, Feynman Machines, and von Neumann Machines." Unpublished paper, 11 July 1986. Feynman Archives at Caltech, Box 27, Folder 11. 7 pages. (Note: this paper was converted into a poster by C. Schneiker, presented by S. Hameroff, at an STM Conference in Santiago de Compostela, Spain, July 14-18 1986.)

Schneiker, C.W. 1986b. *NanoTechnology with Feynman Machines*. Unpublished book manuscript of 215 pages.

Schneiker, C.W. 1989. "NanoTechnology with Feynman Machines: Scanning Tunneling Engineering and Artificial Life." In *Artificial Life, Volume VI: Santa Fe Institute Studies in the Sciences of Complexity* [proceedings of a September 1987 workshop in Los Alamos NM], ed. by C. Langton (Reading MA: Addison-Wesley, 1989), pp. 443-500.

Schneiker, C.W. and S. Hameroff. 1988. "NanoTechnology Workstations, Based on Scanning Tunneling/Optical Microscopy: Applications to Molecular Scale Devices." In *Molecular Electronic Devices* [Proceedings of the Third International Symposium on Molecular Electronic Devices, Arlington VA, 6-8 October 1986], ed. by F.L. Carter, R.E. Siatkowski & H. Wohltjen (Amsterdam: North-Holland, 1988), pp. 69-90.

Schneiker, C., S. Hameroff, M. Voelker, J. He, E. Dereniak and R. McCuskey. 1988. "Scanning Tunneling Engineering." *Journal of Microscopy*, 152(2):585-596.

Simic-Krstic, Y., M. Kelley, C. Schneiker, M. Krasovich, R. McCuskey, D. Koruga and S. Hameroff. 1989. "Direct Observation of microtubules with the scanning tunneling microscope." *FASEB Journal,* 3:2184-2188.

Stent, G.S. 1972. "Prematurity and Uniqueness in Scientific Discovery." *Scientific American*, December 1972, pp. 84-93.

Stoddard, J.F. 1993. "Molecular Recognition and Self-Assembly." *Anales de Quimica*, 89(1):51-56.

Stroscio, J.A. and D.M. Eigler. 1991. "Atomic and Molecular Manipulation with the Scanning Tunneling Microscope." *Science*, 29 Nov. 1991, 254:1319-26.

Thomas, T.R. 2004. "Nanotechnology, Materials and Applications." In *Encyclopedia of Twentieth-Century Technology, Vol. 1*, ed. by C. Hempstead & W. Worthington [New York: Routledge, 2004), pp. 521-523.

Thompson ISI. 2004. "The Journal Selection Process." Online: www.isinet.com/essays/selectonofmaterialforcoverage/199701.html (accessed 17 December 2004).

Toumey, C. 2004a. “Narratives for Nanotech: Anticipating Public Reactions to Nanotechnology.” *Techné*, 8(2):88-116.

Toumey, C. 2004b. “Nano Hyperbole and Lessons from Earlier Technologies.” *Nanotechnology Law & Business*, 1(4):397-405.

Toumey, C. 2005a. “Apostolic Succession: Does Nanotechnology Descend from Richard Feynman’s 1959 Talk?” *Engineering & Science,* 68(1):16-23.

Toumey, C. 2005b “Feynman Unprocessed” (review of *Perfectly Reasonable Deviations from the Beaten Path: the Letters of Richard P. Feynman*). *Techné,* 8(3):76-86

Voelker, M., D. He, E. Dereniake, R. McCuskey, C. Schneiker and S. Hameroff. 1988. “Scanning Tunneling Microscopy (STM) for Biomolecular Imaging and Interactions.” *Biophysical Journal*, 53(2; Part 2):396a.

Weinstein, A. 1977. “How Unknown was Mendel’s Paper?” *Journal of the History of Biology,* 10(2):341-364.

Yater, J.C. 1979. “Rebuttal to “Comments on ‘Power Conversion of Energy Fluctuations’.” *Physical Review A*, August 1979, 20(2):623-627.

Yater, J.C. 1982. “Physical Basis of Power Conversion of Energy Fluctuations.” *Physical Review A*, July 1982, 26(1):522-537.

Yates, F.E. 1984. “Chemically-Based Computer Designs: Report of a Conference on Molecular Computing.” Los Angeles: Crump Institute for Medical Engineering Report, CIME TR/84/1, UCLA.