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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.

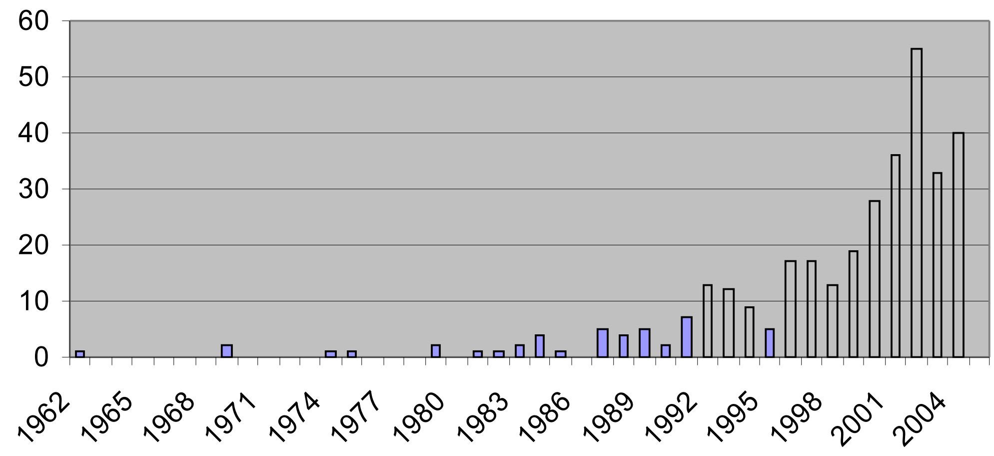
A further complication is that the ISI database changes from time to time, as the editors add some new journals and drop others. They follow a principle they call Bradford's Law, which states that "the core literature of any given scientific discipline… [is] composed of fewer than 1000 journals" (Thompson 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:

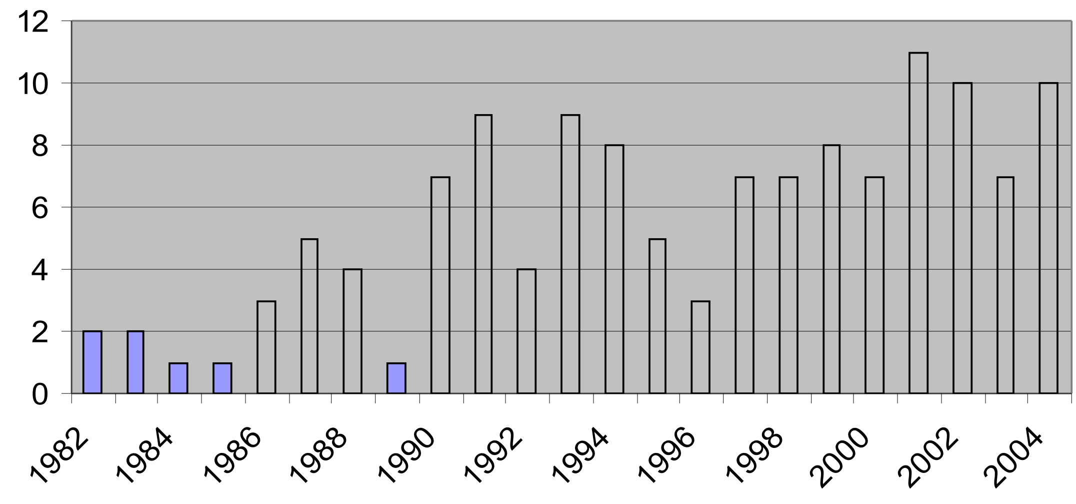
> In my *Nature* News & Views article [i.e., Pabo 1983], I make a point of mentioning Drexler's paper since it was a key source of my motivation in first thinking about this problem. Eric's 1981 *PNAS* article clearly made the point that it might be possible to design new proteins reliably even before 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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Legal and Technological Normativity: more (and less) than twin sisters

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Abstract
Within science technology and society studies the focus has long been on descriptive micro-analyses. Several authors have raised the issue of the normative implications of the findings of research into socio-technical devices and infrastructures, while some claim that material artifacts have moral significance or should even be regarded as moral actors. In this contribution the normative impact of technologies is investigated and compared with the normative impact of legal norms, arguing that a generic concept of normativity is needed that does not depend on the intention of whoever designed either a law or a technology. Furthermore this contribution develops the idea that modern law, which has been mediated by the technologies of the script and the printing press, may need to rearticulate its basic tenets into emerging technologies in order to sustain what has been called the paradox of the 'Rechtsstaat'.

Keywords: technological normativity, legal normativity, constitutive rules, regulative rules, rule of law, democracy

Introduction

Since the beginnings of modernity law has become the most important instrument for the regulation of human society, amounting to a rule *by* law. Its success can be attributed in part to its alliance with the technologies of the written script and the printing press, which extended the reach of modern law both in time and space, allowing an ever more detailed design of human intercourse. It also generated the need for a professional class of lawyers to sustain some form of legal certainty in the midst of proliferating texts. This class of lawyers guards the relative autonomy of law in relation to politics and morality, enabling what continental lawyers have called the 'Rechtsstaat' or 'État de droit' resulting in a 'Rule *of* Law', the terms used for the Anglo-Saxon equivalent.[1] This rule of law embodies the paradox of the 'Rechtsstaat', protecting citizens against the authority of the state by means of the authority of the same state, facilitated by the internal division of sovereignty (into legislation, administration and adjudication) that provides the setting for resisting governmental action in a court of law.

Emerging technologies like RFID-systems and interconnected sensor technologies prepare the ground for smart devices and the socio-technical infrastructures for Ambient Intelligence (AmI), somewhat equivalent with autonomic computing and ubiquitous computing. Though AmI is a vision that has not yet been realized and is hard to define, a set of recurring aspects can indicate the salience of the changes it could provoke in everyday life. AmI is suppose to imply embedded, ubiquitous, invisible technologies, hidden complexity, absence of keyboards meaning that the environment itself becomes the interface, real time monitoring, allowing context-awareness, customization and personalization, adaptive and last but not least proactive environments. In as far as such socio-technical environments are used to spy on us or induce compliance with technologically embodied regulations, they may threaten the system of checks and balances between governmental powers and the possibility to contest the inferences made by the profiling machines they employ. However, the dark scenarios that have been developed around this technology do not necessarily focus on governmental interference (Wright et al. 2008). AmI will most probably be controlled by the service providers that hope to make a profit on the seamless customization that is offered. If its vision comes true, many authors expect a further erosion of the concept of privacy by reducing it to the disclosure of personal data that can be traded at will (commodification of personal data), while, at the same time, the advanced data mining technologies that underlie smart infrastructures may result in refined and dynamic segmentation of society (social sorting) to an extent previously unheard of. If citizens are not aware of what can be done with the profiles inferred from their or other data and have no access to the techniques used to categorize them, such refined profiling could result in manipulation and unfair discrimination (Zarsky 2002-2003, Hildebrandt and Gutwirth 2008b). This contribution argues that to counter such threats we may have to rethink the idea of written law, making a first attempt to conceptualize a law that is articulated in technologies other than the (printed) script.

Having discussed the nature of the threats of autonomic profiling elsewhere (Hildebrandt 2008a, 2008d) I will focus this contribution on the development of a generic concept of normativity that can account for the impact of both technologies and law on human interaction. Such a concept should not be confused with morality, which seems to warrant an evaluation in terms of good and bad, while normativity merely describes the way a certain technology or legal rule induces or enforces, inhibits or rules out certain types of behavior. In the second section I will assess the way lawyers regard the regulation of society, after which I will develop a generic concept of normativity in the third section, resulting in a discussion of the regulation of the collective of humans and non-humans in section four. In the last section, five, I will provide some tentative conclusions.

1. The regulation of society: A lawyer's perspective[2]

1.1 What in fact is law?

The German legal historian Uwe Wesel made a salient point when he wrote: 'What in fact is law? Answering this question is as simple as nailing a pudding to the wall' (Wesel 1985).[3] Despite the accuracy of this proposition we need to clarify the role of law in the regulation of society, if only because democracy seems to depend on the enactment of legal rules by a democratic legislator.

Common sense understanding of legal norms – even amongst many lawyers - seems to circulate somewhere between the positivist accounts of three scholars of legal theory: 'the command theory of law' attributed to John Austin (1995, first published 1832), 'the pure theory of law' of Kelsen (1960, first published 1934), and 'the concept of law' of Hart (1994, first published 1961). Austin, writing in the first half of the 19th century, basically claimed that laws are commands of a sovereign, emphasising the relationship between law and the sovereign state. In opposition with natural law theories, law in his view is man-made and depends on the power of the sovereign to impose general rules on his subjects. Like Austin, Kelsen made a strict distinction between the 'is' and the 'ought' of the law. Writing in the first half of the 20th century, he described the 'is' of the law as a set of rules that form a pyramid of hierarchically ordered normative rules, which in the end all derive from one *Grundnorm*. This 'Basic Norm' guarantees the unity of the legal system and the validity of all the legal rules that should be seen as derived from it. Like Austin's command theory, law always depends on the authority of the state, but, according to Kelsen, this authority also depends on the law: the state is a legal construction. Building on Austin's opposition with natural law, Kelsen claims that the analysis of what law 'is' must be distinguished from what law 'ought' to be (*das richtige Recht*). To allow a moral evaluation of the law, according to Kelsen, one must first describe its normative content, taking into account the deductive logic that determines the connections between different legal norms. A similar positivist position is taken by Hart, writing in the second half of the 20th century, even though the nature of 'his' law is defined in terms of social interaction instead of 'purely' normative statements. While Kelsen's *Grundnorm* can be understood as a hypothetical rule that ensures the unity of the system and the validity of its elements, Hart's 'Ultimate Rule of Recognition' is firmly rooted in social acceptance or what he calls the internal aspect of legal rules. Hart discriminates between primary legal rules that define which conduct is prescribed, prohibited or allowed, and secondary legal rules that define the competence to recognize, change or adjudicate primary legal rules. The distinction between primary and secondary legal rules has developed into a canonical approach within law and legal theory. In short, Austin linked law to the power of the sovereign to impose general rules on his subjects, Kelsen elaborated the systematic character of the body of legal rules and their clear distinction from moral rules and political competence, and Hart understood law as a complex system of social norms, coining the difference between regulative and constitutive rules in terms of primary and secondary rules. Roughly speaking legal positivism seems to emphasize that legal norms are general rules, that they depend on the authority of the state and must be strictly separated from moral and political rules.

However, many scholars of law and legal theory have objected to these tenets of legal positivism, which has led to further refinements and alternative positions. Most famous is Dworkin's objection that it makes no sense to understand law as a system of rules, claiming that the interpretation of legal rules implies the guidance of principles, which do not share the binary application of rules. According to Dworkin (1991, first published 1986) the coherence that is inherent in law implies more than just logical consistency, requiring what he calls the integrity of law. With the notion of integrity he introduces moral standards into the law – even if these are inductively generated from previous legal decisions (enacted law, court judgements). Instead of thinking in terms of a legal system that is focused on logical coherence, he uses the metaphor of a chain novel to indicate the continuing story of law-making. His approach to law can be understood as hermeneutical, stressing the fact that any decision implies interpretation and needs both creativity and precision.

The emphasis on interpretation in contemporary legal discourse is not surprising as modern law centers around text and printed matter. The script and the printing press form the preconditions for the modern legal systems that depend on them (Hildebrandt 2002, 2008c). For lawyers, the fact that law is constituted and mediated by the printed script may be too obvious to warrant further investigation, but the profession would benefit from the realization that the (printed) script is indeed a technology, with massive implications for the scope, the content and the nature of the jurisdictions it supports. This is not only the case because the invention of the script – and later the printing press – extended the reach of legal rules beyond face-to-face relationships, forming the condition of possibility for translocal polities and jurisdictions, but also because the script introduces a linear sense of time due to the need to read from beginning to end, while the printing press evoked increasing rationalisation and systematization in order to cope with the explosion of available texts (Lévy 1990; Eisenstein 2005). Another salient feature of written law is a pervasive sense of delay deriving from the complexity of the legal system that needs to mind its coherence in the face of increasing regulation, thus nourishing reiterative doctrinal attempts to create order in the bran tub of newly enacted statutes and newly published case law. This delay is related to the distance between the author and the public, since the public – other than in the case of oral traditions - no longer needs to share time and place with the author to access the text (Geisler 1985; Ricoeur 1986). Written text is the externalization and objectification of the spoken word, bringing about the need for interpretation (Ricoeur 1986; Lévy 1990; Ihde 1990; Hildebrandt 2002, 2008c). Absent ostensive reference, the author is never sure how her text will be understood, while the reader cannot take for granted what the author meant to say. This provides for an inevitable latitude in the use of texts and turns law-making (enactment of legal codes as well as their application) into a creative process rather than mechanical application.[4] Constitutional review in the US has thus moved beyond the idea that the interpretation and application of constitutional safeguards can be based on the 'Framers' intention' or on the 'clear meaning' of the text: a text can not speak for itself and its meaning is not exhausted by a claim regarding the author's intention. This does not imply that its meaning fully depends on the reader's response, which would land us in arbitrary decisionism as to the application of legal texts. It rather means that in the interplay between author and the subsequent readers the texts acquires a meaning of its own that restricts the potential interpretations (if just any interpretation were possible the text would be meaningless), while also providing the possibility for novel applications (requiring creative actualisation in the relevant context).[5] Written law thus generates a dynamic, autonomous law that depends on and nourishes legal doctrine to provide continuity as well as flexibility in the application of law (Hildebrandt 2008c). Such continuity and flexibility are the conditions of possibility for the demand that law combines legal certainty, justice and effectiveness in the face of recurrent changes in the social and technological infrastructure of contemporary society.

1.2 Constitutive and regulative legal norms

To fine-tune our understanding of law we should discriminate between legal rules that are preconditional for – constitutive of – certain legal actions or legal facts, and rules that regulate existing actions or facts. If I violate a traffic rule that regulates driving a car, this does not mean that I cannot drive the car. The rule – e.g., forbidding speeding beyond 100 miles – is regulative of driving a car. However, if I violate a rule that stipulates the registration of marriage in the civil registry, I will simply not be married. In that case the rule is constitutive for marriage, because it stipulates what counts as a marriage, or in other words, which fact generates the legal consequences of marriage. The difference between constitutive and regulative rules derives from Searle (1995), who discriminates between brute facts, which can be the object of regulation, and institutional facts, which are constituted by social interaction. Searle defines brute facts as facts that can exist independently of human beings and their institutions, while his institutional facts depend on human institutions. Inevitably this boils down to a physicalist worldview that is supplemented with 'the social'. From that perspective, driving a car is a brute fact, as it is not constituted by law, while marriage is an institutional fact, as it cannot exist independent of social interaction. In this view, at some level, all institutional facts are based on brute facts. In terms of Searle we could explain this by saying that brute fact X counts as institutional fact Y, in context C (Colomb 2005). For instance, the brute fact of driving a car counts as the institutional fact of 'being a road-user' in the sense of the Traffic Code (which attributes legal consequences to this institutional fact) in the context of driving on a public road. A closer look thus discloses that the distinction is relative: depending on one's perspective, any brute fact can be rearticulated as an institutional fact, while institutional facts can be 'used' as brute facts to be regulated. The institutional fact of being a road-user in the sense of the Traffic Code is the object of regulation in the Traffic Code. This means that the distinction has an analytical appeal, as long as it is not taken to imply an ontological difference between facts that exist outside human perception and facts that are socially constructed. Other than that Searle argues, even a brute fact involves some form of constitution, namely the one effected by our biological wiring (Varela, Thompson et al.

1991). A bat perceives something else where we see a wall, even if the bat will avoid clashing into the wall just as well as we do (Nagel 1974). At the same time any type of social construction involves both humans and non-humans (Latour 1991). For instance, the social construction of a marriage requires the mediation of technologies that register the marriage as such: written or printed records in the case of a tradition that is mediated by the (printed) script; the wearing of specific types of jewelry like bracelets or a spot on the forehead (bindi), in the case of an oral tradition.

2. A generic concept of normativity

2.1 Three types of norms

Normativity is associated with social norms that have been either deliberately issued *for* or tacitly developed *in* the practices of a certain community/collective.[6] In both cases norms can be equated with constraints that induce or enforce certain types of behavior while inhibiting or ruling out other types of behavior. Deliberately enacted legal norms depend on the competence to legislate, which presumes a form of political authority, while the effectiveness of enacted law in the end depends on the extent to which the issued legal norms become part of the normative practices of the relevant community/collective. This implies that – as in the case of brute facts and institutional facts – the distinction between deliberately issued norms and norms that are part of a normative practice is *analytical and not ontological*. In a modern legal system, *to count as legal* a norm must be covered by state authority, but whether and to what extent it informs the normative practice of a community depends. So, we have three types of norms: legal norms that do not (yet) regulate or constitute the interactions in a particular practice, legal norms that do regulate and/or constitute the interactions in a particular practice and non-legal norms that do regulate and/or constitute the interactions in a particular practice.

2.2 Technological normativity

If we leave the domain of law we may find other types of normativity, pertaining to constraints that have not been deliberately issued but which nevertheless induce or enforce, inhibit or rule out certain types of behavior. Latour's discussion of the Berlin key is a case I point. This key forces the user to open the door by pushing the key through the keyhole to the other side of the door, and after entering the house, the door can only be closed by turning the key and thus locking the door. This key demonstrates how a technological device actually regulates and constitutes the interactions of a resident, the key, her door and others who wish to enter the house.[7] In this case the designer of the key has inscribed a program of action into the hardware, delegating the task of insisting on locking or not locking the door *to the key* (Latour 1993). If we look at the normative impact of technological devices or infrastructures we must admit that many of the effects they produce on our everyday behaviors have not been planned (Bijker 1995). Contemporary common sense would describe them as side-effects, even in the case that these unplanned effects outweigh explicitly intended effects. When speaking of technological normativity I do not focus on the intention of the designer, I simply refer to

> the way a particular technological device or infrastructure actually constrains human actions, inviting or enforcing, inhibiting or prohibiting types of behaviour.[8]

Such normativity does *not* depend on deliberate delegation since it may emerge unexpectedly in the interactions between devices, infrastructures and humans who make use of them (and are to a certain extent constituted by them). Such a concept of normativity should not be confused with the concept of morality, as this would imply an evaluation in terms of good or bad, whereas normativity merely refers to the way the patterns of our interactions are affected. As to the use of the term 'constraint', this should not be understood as a negative term: constraints are the condition of possibility of (inter)action, they do not only inhibit or rule out certain behavior, they also create or induce certain types of behavior.

If we take the example of a smart device to save energy in the house, we can illustrate how technological normativity can be either regulative or constitutive of human interaction.[9] Image we all have a 'smart meter' in the cupboard that measures the amount of energy we use and the amount of carbon this emits. This will allow more accurate billing, taking into account the costs to the environment of the type of energy used. One could imagine a smart home that automatically reduces the consumption of energy after a certain threshold has been reached, switching off lights in empty rooms and/or blocking the use of the washing machine for the rest of the day. This intervention may have been designed by the national or municipal legislator or by government agencies involved in environmental protection and implemented by the company that supplies the electricity. Alternatively the user may be empowered to program her smart house in such a way. Another possibility would be to have a smart home that is infested with real-time displays that inform the occupants about the amount of energy they are consuming while cooking, reading, having a shower, heating the house, keeping the fridge in function or mowing the lawn. This will allow the inhabitants to become aware of their energy consumption in a very practical way, giving them a chance to change their habits while having real-time access to the increasing eco-efficiency of their behavior. In combination with the 'smart meter' they can begin to anticipate the automatic intervention of the smart home, preventing unpleasant surprises, or they can program their smart home in a more refined way to stop them from crossing specified thresholds. Interestingly enough, the difference between an automatic intervention and a mere advice or provision of information compares well to the distinction between regulative and constitutive rules we discussed above. As long as the technologies enables us to make our own choices, inducing but not enforcing a change of habit, the technology is regulative of our behavior. To the extent that the technological infrastructure intervenes to rule out non compliance, the technology is constitutive of our behavior: for instance, if we do not comply we cannot continue to operate the dishwasher and have to wash the dishes by hand or wait for the next day.

2.3 Comparison of legal and technological normativity

In modern states legal norms depend on state authority, which means that they regulate and/or constitute the relationship between citizens and their government. This can be called the vertical or imperative dimension of legal norms, based on the coercive authority of the modern state. In a democracy legal norms also aim to regulate or constitute the relationships between those that share jurisdiction, which means that citizens feel obliged towards each other to comply with legal rules and principles. This can be called the horizontal or normative dimension of legal norms, best explained in terms of Wittgenstein's discussion of what it means to follow a rule (Taylor 1995; Winch 1958). Technological normativity does not depend on state authority in the sense that this authority creates the competence for the Berlin key to enforce locking the door from the inside. It does regulate and/or constitute the relationship between citizens and between citizens, devices and infrastructures. Does this mean that technological normativity has a normative dimension while lacking an imperative dimension? Like in the case of non-state societies the absence of coercive authority does not imply that power is not at play, rather on the contrary.[10] In non-state societies there is no coercive authority that can establish a measure of formal equality to empower weak parties, compensating for power imbalances by means of legal instruments like e.g. the 'equality of arms' of the fair trial of art. 6 ECHR (Hildebrandt 2006b). Non-state societies are constituted by peers who cannot depend on governmental intervention in the case of conflict, which warrants them to protect themselves against being overruled by more powerful peers. Absent a monopoly on violence the legal normativity of non-state societies has to be sustained by means of persuasive authority, revenge or war, rewarding the competitive advantages of those with economic or military power (Dubber 2005; Hildebrandt 2002, 2005). Like legal normativity in non-state societies, technological normativity does not depend on coercive authority but on the socio-technical arrangements that constitute or regulate specific practices like consuming electricity, driving a car, etc. Arrangements that generate practices that are *constituted* by specific technological artifacts *enforce* compliance with the norms embodied by these artifacts, while arrangements that generate practices that are *regulated* by specific technological artifacts *invite* compliance with the norms they embody. For instance, if sensors are integrated into our clothes that can measure e.g. heart rhythm, blood pressure, skin resonance and temperature, connected to a device that transmits these data to a database for profiling, extensive monitoring is enabled, providing interesting knowledge about a person's relative health, state of mind or inclinations. Such information may become available to employers, insurance companies, hospital energy services, close relatives and/or to the person herself. In the case of a diabetes patient, the inferred profiles may allow accurate prediction of dangerously low levels of insulin. If such real-time monitoring is coupled with automatic interventions, e.g. blocking access to certain foods or activities, the technology becomes constitutive for such access or activities. If the person receives real-time access to these data and the inferred profiles, perhaps supplemented with advice to prevent an attack, the technology becomes regulative of the relevant activities (like eating, doing sports, driving a car). Evidently self-monitoring – even without advice – may engender self surveillance, self discipline and boil down to an enforcement even more stringent than enforcement embodied in the automatic intervention of the smart environment (Foucault 1988). Nevertheless it makes sense to discriminate between socio-technical arrangements that are constitutive and those that are regulative of our interactions, if only to make clear that technology does not necessarily rule out choice in comparison to law.[11]

3. Regulating the collective: Technological normativity and constitutional democracy

3.1 The force of law and the force of technology

Emerging technologies like smart cars, biomedical monitoring, proactive homes and schools that integrate personalized e-learning with real-time profiling will have a major normative impact on citizens, constituting new possibilities to regulate their lives. The socio-technical arrangements that generate technological normativity may have far reaching implications for the way we live together as a collective. These implications may be far greater than those generated by legal normativity, being restricted at the present moment to a technological articulation in the (printed) script. The printed script has a very specific normativity, because it can invite but not enforce specific interpretations, thus entailing a radical *under*determinacy that may not be evident in smart, proactive technologies that depend on autonomic computing (Kephart and Chess 2003). In fact, even though the script is linked to the coercive authority of the modern state, it is also linked to the relative autonomy of law in relation to political power. This is the case because the proliferation of legal texts since the advance of the printing press produced a potential chaos of interpretations, generating a need for systemization and specialization. This is what resulted in the professionalization of legal practice in the course of the last five centuries. The fragility of the meaning of written text, faced with the need for legal certainty, thus facilitated the appearance of a monopoly on law for the professional class of lawyers (Koschaker 1997, first published 1947), mandated to safeguard the coherence of the legal system (in the interest of both the citizens that share jurisdiction and the government that wishes to implement its policies). The force of (written) law thus depends on the coercive authority of the state in combination with the labors of the lawyers' guild.

Above I have argued that the normativity of socio-technical infrastructures does not share the imperative aspect of legal normativity (sometimes referred to as the force of law),[12] because it does not depend on governmental authority. Technological normativity can, however, like legal norms, be understood in terms of constitutive or regulative effects. Interestingly enough, the extent to which socio-technical devices or infrastructures can constitute or determine our actions differs from the extent to which legal devices can achieve compliance. In the case of what Searle might call brute facts, like driving a car, though legal rules can constitute what it means to count as a road user or even a car driver, they cannot constitute the driving of a car in the sense that in the case of non-compliance one cannot drive. As has been indicated this incapacity is related to the technology in which modern law has been articulated: the script can regulate the behavior of a driver, it cannot determine it the way a smart car could. The script could, for instance, be constitutive for the competence to drive a car: violating the legal norms that constitute this competence would simply annihilate the *competence*, but it would still not annihilate the *capacity* to drive. A monitoring technology which detects driver fatigue (Jin, Park et al. 2007) could, in combination with a device that affects the accelerator or even the motor, prevent a driver from continuing her travels whenever the measure of fatigue moves beyond a certain threshold. The technology seems capable of enforcing compliance with rules to an extent previously unheard of.

This raises a number of questions. First of all one wonders whether this is a positive development, to be embraced in the struggle against non-compliance. Using technological means to attain what legal means cannot achieve, implies using them as neutral means of implementation, disregarding the normative impact of a mechanical application of legal rules. It sounds like legal or technological instrumentalism, whereby law and technology are seen as interchangeable instruments to reach specific policy objectives. As some legal scholars have indicated (Tien 2004; Brownsword 2005), this type of enforcement could in fact eradicate human freedom and accountability because one would be spared alternative choices of action (creating a world in which one simply cannot commit a crime). Does this mean we should understand compliance by means of technological devices as a negative development, to be warded off as long as possible? Such an attitude would imply that technologies can only be designed in one way, inevitably resulting in the determination of human interaction. It sounds like legal or technological substantivism, attributing determinist qualities to Technology while assuming a voluntarist understanding of Law. Rather than advocating the extreme positions of determinism or voluntarism I will argue a more creative and realist perspective on the relationship between law, technologies and human interactions, recognising the constraints they constitute while acknowledging the fundamental underdeteminacy of human action. As to the technological infrastructures this underdeterminacy is connected with what Ihde (1990) has called the multistability of technologies, meaning there is never just one way for a technology to take its place in the socio-technical tissue of the collective, and it is precisely such underdeterminacy (to be discriminated from indeterminacy) that requires a more active anticipation of different ways to integrate a technology with law.

The second question is how we could bring socio-technical devices and infrastructures under the rule of constitutional democracy: for, if we agree on the need for democratic procedures to regulate the enactment of legal normativity, technological normativity requires similar democratic legitimacy. This means that the relationship between law and technology is no longer one of enactment (law) and implementation (technology) but one of enactment and articulation (of law into a repertoire of technologies, one of which is the script). This may also imply a shift from the regulation of *society* to the regulation of the *collective* (Latour 1999): taking into account that we are living in a world of hybrids or actor-networks of humans and non-humans (folding into black boxes for as long as it goes). In his daring discussion of modernity Latour (1991) describes how we have delegated the representation of humans to politicians, while delegating the representation of non-humans to scientists. Facing the challenges of the normative impact of emerging technologies that will change our daily life beyond recognition, the ineffectiveness of this division of tasks is apparent. Taking democracy serious means that the scientists and engineers that produce hybrids like RIFD systems, genetic tests or technologically enhanced soldiers should be obligated to present their case to the public that is composed of those that will suffer or enjoy the consequences. In other words, the hybrids that are propelled into the collective must survive the scrutiny of the public that constitutes itself around what it considers to be a matter of concern (Dewey 1927; Callon 2001; Latour 2005; Marres 2005; Hildebrandt and Gutwirth 2007, 2008). When funding and developing specific technologies these publics should have the opportunity to voice their opinion, co-determining the direction of research as well as the introduction of such artifacts into everyday life infrastructures. Different types of technology assessment (TA) have been developed to involve lay persons into the early stages of technological design (Rip, Misa et al. 1995; TAMI 2004; Marris, Wynne et al. 2002), often entailing citizen participation. In other work we (Hildebrandt and Gutwirth 2007, 2008) have argued that such experiments could in fact build on the normative constraints embodied in the 'fair trial' that ensure what Rip (2003) has called agonistic learning processes and robust outcomes.

A third question regards the issue of the technological embodiment of legal norms. On the one hand the relative autonomy of law towards politics and morality seems to depend on the radical underdeterminacy inherent in the printed script, on the other hand written codes seem impotent when it comes to providing protection against the monitoring technologies that may soon inform many decisions taken about the chances we get and the risks we run in life (Hildebrandt 2008a, 2008b, 2008c; Zarsky 2002-2003). Will it be possible to re-embody the legal norms that protect us against invasion of our privacy, violation of the presumption of innocence, unfair discrimination *in the emerging technologies they aim to regulate*, while still retaining the underdeterminacy we value as the core of constitutional democracy? This is an important issue that should not be conflated with the use of technologies for the *implementation* of a law that is *articulated* in the written script. For instance, 'putting tracking devices on criminals awaiting trial to ensure that they do not flee a jurisdiction where they are going to be tried[13] is all about implementing a law that requires suspects to be available for trial. As an example, it follows the traditional separation between law (articulated in the script) and its implementation (considered to be a matter of administration rather than requiring the attention of the legislator or the courts). My point is a different one: if we need to protect ourselves against specific undesirable affordances of specific socio-technical infrastructures, such as AmI, we may need to articulate the legal protection into the technologies we aim to protect against. In the next section I will indicate how privacy enhancing technologies (PETs) and transparency enhancing technologies (TETs) could embody (not just implement) legal norms that aim to protect core tenets of constitutional democracy, like privacy, autonomy and non-discrimination.

3.2 Translating the paradox of the 'Rechtsstaat' into digital code

The paradox of what continental Europeans call the 'Rechtsstaat' or the 'État de droit' resides in the fact that in the substantive conception of the 'Rechtsstaat' law is not just an instrument for the implementation of government policies but also the instrument that protects citizens against arbitrary rule and against dominant frames of reference. The authority of the state is used as a check on the authority of the state: the internal division of sovereign powers allows one power to function as a counterveiling power on the other (Montesquieu 1973, first published 1748). Facing the complex entanglement of socio-technical infrastructures it seems that the need has arisen to translate this paradox into the emerging technologies that may otherwise rule our world. In his ground breaking *Code and other laws of cyberspace* legal scholar Lawrence Lessig (1999) explains in a convincing narrative, enriched with a great many arguments, that traditional law is losing ground against market forces, social norms and especially computer code. His telling description of cyberspace and the way it is constituted as a virtual world that is often real in its consequences has triggered many responses, ranging from adoration for his unconventional approach of law as just one way to regulate society to the complacency of legal scholarship that suspects the present legal paradigm can easily deal with the charges of the digital age. Since he wrote his best selling wake-up-call, quite some funding has been invested into Ambient Intelligence (ISTAG 2001) or the Internet of Things (ITU 2005), which – if realized – will turn our entire offline world online. The borders between cyberspace and our lifeworld will blur, presenting us with an even more pressing need to rethink the limits of (the rule of) law in the era of digitalization (Hildebrandt 2008a).

Lessig presents us with an interesting argument about the need to use computer code to support the legal framework of constitutional democracy. However, it seems that he views law and code as separate domains, not realizing that law’s present failure to sustain the paradox of the 'Rechtsstaat' may be connected to contemporary law's embodiment in the technology of the script. Also, he provides no answer for the democratic deficit that would arise if we use technologies instead of law to implement government policies.

Translating the paradox of the 'Rechtsstaat' into digital code – using a technology to protect us against undesired consequences while regulating its use - would thus require two things. First, the use of code must be legitimized in democratic procedure and second, the implications of automatic application must be faced and mitigated. Technologies that are constitutive for our interactions may enforce compliance beyond anything that a written law can achieve. For such technologies to be integrated in the legal tradition of constitutional democracy they must provide for the means to contest their own application. This will require transparency to empower citizens in their intercourse with the socio-technical infrastructure. For instance, the present focus on the protection of personal data, which often involves a right of access to personal data processed by large organizations, should be extended to a right of access to the group profiles that may be used for social sorting with far reaching consequences for the risks and opportunities attributed to a particular person (Hildebrandt 2006a, 2008d). More importantly, these rights of access need technological embodiment, otherwise they are just paper dragons. This will present major challenges for the industry that is developing Ambient Intelligence, which thrives on real time monitoring and autonomic application of profiling to personalize the environment to the inferred wishes of its users. Next to privacy enhancing technologies (PETs), which are concerned only with the hiding and tracing of one's personal data, transparency enhancing technologies (TETs) must be developed that concern access to the profiles that are being inferred permanently from the mass of data collected from all relevant users and their environment. This requires new forms of cooperation between lawyers, computer scientists, engineers and data mining experts, co-creating a law that is integrated into the technologies without giving up the dual demand for democratic legitimacy and contestability in court. Constructive Technology Assessment for lawyers.

4. Conclusions

The common sense conception of law views legal norms as general rules, depending on state authority and strictly separated from morality and politics. Challenging this kind of legal positivism, philosophers of law have developed a hermeneutical understanding of law, making interpretation the hallmark of law. In this contribution I have developed the idea that modern law is not only influenced by, but rather constituted by its technological mediators: the written and the printed script. I have argued that this mediation has transformed the reach of law and prepared the ground for law as an autonomous practice that is capable of resisting state authority with an appeal to state authority, thus presenting us with what is called 'the paradox of the 'Rechtsstaat'.

The proliferation of emerging technologies, especially smart devices and infrastructures, calls for a new – generic - conception of normativity, which allows one to recognize the normative force of technologies as well as the normative force of law. To this end norms have been described as the actual constraints placed on human actions, inviting or enforcing, inhibiting or prohibiting specific types of behavior. Within the scope of this working definition, both law and technology have a normative impact on human action. To refine our understanding of the similarities as well as the differences between legal and technological normativity I have discussed two aspects of (legal) norms, being an imperative and a normative aspect. While modern law stipulates that all legal rules have an imperative aspect that links the force of law to the authority of the state, technological normativity obviously does not depend on such authority. This does not mean that the force of technology is less powerful than the force of law. To explain this, two types of normativity have been discussed, depending on whether norms are constitutive or regulative of human action. Though both law and technology can be either constitutive or regulative, the extent to which law is constitutive is limited compared to some technologies. A smart car, for instance, could rule out non-compliance with rules about the maximum speed, whereas law leaves room for violation. This limitation is brought about by the fact that law is mediated by the printed script, which cannot enforce a speed limit the way another technological device could. However, this is no reason to oppose a determinist Technology versus a voluntarist Law. The multistability of technologies, which can be developed in different ways, for instance allows for the construction of a speed limit system that makes it harder to push down the gas pedal once the speed limit is exceeded. In this case the technology regulates car driving without actually determining it. The legal rule is thus embodied in the human-machine interaction it aims to regulate.

In a constitutional democracy the regulation of society requires democratic consent. In as far as technological devices and infrastructures have a normative impact they should be brought under the regime of democracy and rule of law. It makes no sense to leave decisions about the introduction of new technologies that encompass normative impact on civil society to scientists, engineers and the industries that aim to make a profit on them. Anticipation of normative impacts by means of constructive or participative technology assessment should inform policy choices at the political level, and the regulative force of technologies should be brought within the domain of law, requiring effective possibilities to contest the legality and the legitimacy of specific applications of legal rules by means other than the script. Thus, the paradox of the 'Rechtsstaat', which implies that the powers of the state can be contested in a court of law that is based on the authority of the state, should be translated into emerging technologies that are used to implement both the instrumental and the protective aspects of the law. Thus we may sustain the rule *of* law against a rule *by* law and against a rule *of* technology.

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Endnotes

1 This equivalence is of course relative in many ways, see Grote 1999. I will use the term 'Rechtsstaat' even if this is less familiar for Anglo-Saxon traditions, because so far the rule of law seems to be an affordance of the modern *state*.
2 The term regulation is used in a common sense way at this point, it is not meant to refer specifically to legal regulation, but can also refer to biological or technological regulation, e.g. the regulation of activities within the cell by genes, proteins or of safe driving by smart cars, speed bumps.
3 Wesel 1985, at 52: "Was ist eigentlich Recht? Eine Antwort ist ähnlich einfach wie der bekannte Versuch, einen Pudding an die Wand zu nageln (translation mh)".
4 About the difference between creative actualization and mechanical realization cp. Lévy, P. (1998). *Becoming Virtual. Reality in the Digital Age*. New York and London, Plenum Trade.
5 Though constitutional review in the US has actually and inevitably moved beyond a naïve understanding of the 'Framers' intention' and 'plain meaning', adherents to legal positivism will deny this. A pletora of relevant literature could be quoted here. Cf. e.g. Dworkin 2005 (first published 1996).
6 In my doctorate thesis I followed the terminology of Glastra van Loon, who speaks of norms having an imperative and/or a normative aspect (cf. Glastra van Loon, J. F. G. (1958). "Rules and Commands." *Mind* LXVII (268): 1-9, Glastra van Loon, J. F. (1985). "Norm en handeling. Hoe regelen wij ons handelen." *Ars Aequi* 34 (12): 697-704. The first aspect looks at the role a norm plays between a government and its subjects or citizens, while the second aspect looks at the role a norm plays between peers. The second understanding of norms comes close to Wittgenstein's idea of what it is to follow a rule (cf. Taylor 1995 *Philosophical Arguments*. Cambridge Massachusetts, Harvard University Press).
7 The story of the Berlin key is even more complicated and involves also the caretaker of the house, who has another key that is crucial for the plot. For the point that I am making a detailed account of how the key enforces specific behaviors is not relevant, see Latour 1993 for the elaboration.
8 One could rephrase by stating that technologies have specific affordances in relation to the subjects that use them. This refers to Gibson's salient understanding of the relationship between an organism and its environment (cf. Gibson 1986). In discriminating between inviting/enforcing and inhibiting/ruling out certain behaviors I seek a further qualification of what affordances trigger and allow.
9 See Luke Nicholson, Finding a smart way to save energy, *BBC News* 22 June 2007, at http://news.bbc.co.uk/2/hi/science/nature/6225938.stm, last accessed on 14th July 2007.
10 About the difference between power ('Macht') and authority ('Herrschaft') see Weber, M. (1976). *Wirtschaft und Gesellschaft. Grundriss der verstehenden Soziologie*. Tübingen.

11 This is not to deny the pervasive effects of self-monitoring; it should be interesting to investigate to what extent regulative legal rules initiate self-monitoring in comparison to the extent to which regulative technologies do.
12 See the lucid description of law's opacity in Derrida, J. (1994). *Force de loi*. Paris, Galilée.
13 This is a quote from one of the reviewers of this contribution, who wondered whether this would be the type of example that fits the point that I am making (quod non).

Three Species of Technological Dependency

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Abstract
One can find from a survey of the work of three prominent philosophers of technology in the late twentieth century, a very different kind of metaphor for describing the powerful, but not fully determinative influence that technology has on our lives. These three theories each centre on a concept I call "technological dependency." The most prominent exponents of technological dependency are Marshall McLuhan, Herbert Marcuse and Jacques Ellul. Although there are similarities between their descriptions of the phenomenon of dependency, their discussions of this phenomenon are focused around very different sub-metaphors for describing the nature of the dependency. McLuhan portrays our relationship with technology as capable of becoming a form of addiction or habit, Marcuse portrays it as a form of bribery, and Jacques Ellul portrays it as a form of religious cultism.

Keywords: social studies in science and technology, autonomous technology, instrumentalism, Marcuse, Ellul, McLuhan

Introduction

At two conferences held in 1993 and 1994, some of the world's leading activists, thinkers and writers convened to discuss the struggle against "megatechnologies" and technocracy. In the wake of these two conferences the Jacques Ellul Society was formed to discuss the challenges facing this struggle (Mills 1997, 238). Ellul remains a seminal figure for many involved in the growing, but still politically marginal, resistance movements against modern technology in North America. Similarly, Andrew Feenberg has recently revitalized interest in the work of Herbert Marcuse with the publication of three books specifically addressing his views on technology: *Questioning Technology* (1999), *Transforming Technology: A Critical Theory Revisited* (2002), and *Heidegger and Marcuse: The Catastrophe and Redemption of History* (2004). Interest in Marshall McLuhan's work has recently experienced a renaissance in Canada with the creation by the public broadcaster of the province of Ontario and the National Film Board of Canada of a documentary about his views on technology and a series of television spots called "The McLuhan Probes" (Sobelman 2002). Each of these influential 20th century intellectuals share a preoccupation with a general problem they identify that exists between society and technology that prevents the majority of people from significantly challenging technologies and processes of technological change, and which threatens to relegate technological criticism perennially to the margins of political debate.

The notion of "autonomous technology" has become widely accepted in the philosophy of technology as an alternative to determinism as a way of conceiving the relationship between people and technology. However, this notion suffers from an image problem. For instance, Langdon Winner notes of the growing field of social studies in science and technology that many of the researchers in this field reject the notion "as a now discredited determinism, eclipsed by their own models of a dynamic multicentred process of social selection" (2003, 239). Many agree that strict technological determinism is an unhelpful and extreme way of conceiving the relationship, but few wish to accept the other extreme of what Andrew Feenberg calls, "instrumentalism", with its naïve assumption that "that the subjects of action can be defined independently of their means" (63). He feels it is important that people recognize that all technology is "fundamentally biased toward a particular hegemony" (Feenberg 2002, 63). Words like "autonomous" and "bias" and "hegemony" still strike a chord that smacks enough of determinist themes to discourage social scientific researchers from feeling comfortable with such terms. I do not think this is merely a case of these researchers reaching for, as Winner puts it, "their preferred conceptual straw-man: technological determinism"(2003, 239). Instead, I think it grows from the use of misleading terminology like "autonomy", "bias", "hegemony", and phrases like "Technics-Out-of-Control" (Winner 1977), or "the 'media dictates culture' problem" (Kuhns 1971, 123) used for describing the relationship between people and technology.

One can find from a survey of the work of three prominent philosophers of technology in the late twentieth century, a very different kind of metaphor for describing the powerful, but not fully determinative influence that technology has on our lives. These three theories each centre on a concept I call "technological dependency." The most prominent exponents of technological dependency are Marshall McLuhan, Herbert Marcuse and Jacques Ellul. Although there are similarities between their descriptions of the phenomenon of dependency, their discussions of this phenomenon are focussed around very different sub-metaphors for describing the nature of the dependency. McLuhan portrays our relationship with technology as capable of becoming a form of addiction or habit, Marcuse portrays it as a form of bribery, and Jacques Ellul portrays it as a form of religious cultism. The following is an examination of these distinctive metaphors of technological dependency.

Technological Dependency

Carl Mitcham and Robert Mackey, in their early survey of the field of the philosophy of technology, point to three paradigmatic positions concerning our ability to "redirect" technology toward more humane or environmentally responsible ends. They describe these three positions as follows:

> If [Emmanuel G.] Mesthene is right that technology is physical possibility, then a redirection of technology requires only that we choose to realize the new end; a "recovery of nerve" is what is essential. However, if [Nathan] Rotenstreich is right, that technology is rooted in the authoritarian mentality, then any significant change in direction of technology would involve a general alteration in man's root attitude toward the world. Whereas if [Jacques] Ellul is correct, such redirection seems out of the question, because technology develops by its own intrinsic principles. (Mitcham and Mackey 1972, 30)

Mesthene's position is that it is simply a lack of moral will to do what we otherwise know is right, which prevents people from adequately rising to the task of addressing the challenges that technology presents. Rotenstreich's position parallels the hypothesis presented by the American historian Lynn White in his classic 1967 article in *Science* that a problematic Western metaphysical outlook is the real culprit behind many contemporary social woes, such as the environmental crisis. In stark contrast, Ellul's position argues that all people, regardless of their metaphysical outlooks, are enclosed "within the technical realm" that places certain practical restrictions on their ability to change fundamental aspects of that realm (Mitcham and Mackey 1972, 30).

These three basic positions represent the range of positions typically held by philosophers of technology when it comes to explaining the systematic failure of Western civilization to come to proper grips with its technological excesses. I have argued elsewhere that the Lynn White position is the position held by a majority of prominent environmental philosophers (Gerrie 2003). However, in the field of the philosophy of technology, it is common to find a position like that of Jacques Ellul. The common feature of such a position is the notion of technological dependency.

The notion of technological dependency represents any kind of theoretical claim that there are features of technological practice as such, which systematically prevent critical ethical judgement of such practice from happening. If one believes that the biases of such features are strong enough to prevent any meaningful ethical assessment to occur, then one is a supporter of the notion technological determinism. However, if one believes there is some room for countervailing action, then one is simply a supporter of some specific form of dependency theory.

John McDermott describes technological dependency as being rooted in the naive belief that "Technology is a self correcting system. Temporary oversight or 'negative externalities' will and should be corrected by technological means" (McDermott 1977, 184). Dependency theorists explain the origins and power of beliefs, like this, and other manifestations of what has come to be called "the technological imperative." They also help explain the apparent "self-generating properties of modern technology" (Winner 2003, 239) noted by many modern critics of technology. Technology scholar Wilson Dizard points to four key observations about the nature of technological change made by Jaques Ellul, the second of which points to such self-generating properties and the problem of technological dependency:

> All technical progress exacts a price; that is, while it adds something on the one hand, it subtracts something on the other.
> All technical progress raises more problems than it solves, tempts us to see the consequent problems as technical in nature and prods us to seek technical solutions to them.
> The negative effects of technological innovation are inseparable from the positive. It is naïve to say that technology is neutral, that it may be used for good and bad ends; the good and bad effects are, in fact, simultaneous and inseparable.
> All technological innovations have unforeseen effects. (Dizard, 1985, 11).

These four basic observations about technology are also made by Marcuse and McLuhan, with 1, 3 and 4 constituting what Feenberg calls a "substantivist" outlook (Feenberg 1999 9). However, it is the second observation, which they also share, that serves as the basis for their discussions of the idea of dependency. Theories of dependency provide a more detailed explanation of how technological activity as such can "tempt" or "prod" us toward addressing problems created by technological progress with more technological activity. According to Marcuse Ellul and McLuhan, in a technological civilization the predominant response will be to approach social issues involving technology in ways that persistently avoid seeing these issues as opportunities to also bring established technological practices into ethical question.

In other words, in a highly technological dependent society, the tendency will be to deal with most problems through "technological fixes." Alan Drengson describes this approach as follows: "I call this attempt to repair the harm of a technology by modification, a technological fix. If, on the other hand, we question the very purpose and intent behind the technology (e.g. of insecticides) and thereby develop alternative approaches that might require modifying our values and goals, then we recognize the limits of the technological fix" (Drengson 1984, 260). Technological dependency manifests itself in the belief in what Drengson calls the "myth of the technological fix" (1984) and as the chronic inability or unwillingness of people to ethically question the use of particularly problematic technologies, even in the face of mounting evidence that such technologies are critical parts of problematic forms of human behavior. It is the distinct theoretical explanations of this tendency to ignore what Winner calls the "painful ironies of technical choice" (2003, 239), which separate the theories of technological dependency of Marcuse, Ellul and McLuhan.

Three Images of The Nature Of Technological Dependency

Herbert Marcuse

According to Herbert Marcuse “A comfortable, smooth, reasonable, democratic unfreedom prevails in advanced industrial civilization” (Marcuse 1977, 107). His inclusion of the term democratic in this list is telling. Marcuse, a Marxist, was interested in explaining the lack of revolutionary consciousness in Western democratic societies. Orthodox Marxism had predicted that the more industrialized a society became, the greater the inherent contradictions between private owners and labor should become. For example, greater automation and efficiency should lead to downward pressures on wages and a widening gap between haves and have-nots. However, productivity increased rapidly in the West in the post-war period, but so did living standards for large numbers of people. Many working class people in Western societies seemed basically happy with the economic system and the abundance of goods that it could produce.

Marcuse tried to explain Marxist theory in a way that could explain the apathy of the Western working class but still make sense of the revolutionary spirit of the left and the notion of class conflict. What he came up with was a notion of the modern industrial economy as a vast bribe, which had the effect of keeping workers docile and accepting of the inherently unfair reality of private ownership. As he puts it, “This productivity mobilizes society as a whole, above and beyond any particular individual or group interests” (Macuse 1977, 108). The result is that “the productive apparatus and the goods and services which it produces ‘sell’ or impose the social system as a whole” (Marcuse 1977, 114).

According to Marcuse, the vast majority of people in a modern economy are, in a very real sense, “on the take.” This means that most are co-opted by what came to be called, in the parlance of the sixties, “the system.” However, the central image of payoff allows for an understanding of a degree of co-optation to enter into the analysis, which is in line with Marcuse’s fundamental Marxist starting point. Obviously those who are most richly rewarded by the industrial system will have greater interest in the preservation of the system, especially those in political power. As Marcuse notes, “The government of advanced and advancing industrial societies can maintain and secure itself only when it succeeds in mobilizing, organizing, and exploiting the technical, scientific, and mechanical productivity available to industrial civilization” (Marcuse 1977, 108). People in roles of political leadership and other “vested interests”, therefore, have a particular interest in keeping the system functioning “through the manipulation of needs” and “false needs” among the masses (Marcuse 1977, 108-109).

However, all individuals are fundamentally open, to some degree, to the lure of the productivity of the industrial system as a whole, as well as any of its particular blandishments and all individuals, therefore, can play some role in the support of that system. This conclusion leads Marcuse to raise the following fundamental question: “How can the people who have been the objects of effective and productive domination by themselves create the conditions of freedom” (Marcuse 1977, 111)? He notes that “all liberation depends on the consciousness of servitude, and the emergence of this consciousness is always hampered by the predominance of needs and satisfactions which, to a great extent, have become the individual's own" (Marcuse 1977, 111). The result is that to the degree which we are controlled by "economic forces and relationships", "the struggle for daily existence", and "politics" we are under the sway of a form of "repressive satisfaction" (Marcuse 1977, 111).

We might all wish to avoid biting the hand that feeds us, but some of us have more to lose then others. Marcuse's analysis suggests a scale, which ranges from those who are almost completely outside "the system," such as primitivists and hippies living off the grid on communes, all the way to the political and industrial elites who benefit greatly from the productivity of the system. Marcuse singles out intellectuals for particular distrust. As he states,

> The interrelation between scientific-philosophical and societal processes, between theoretical and practical Reason, asserts itself "behind the back" of scientists and philosophers. The society bars a whole type of oppositional operations and behaviour; consequently, the concepts pertaining to them are rendered illusory or meaningless. Historical transcendence appears as metaphysical transcendence, not acceptable to science and scientific thought. The operational and behavioural point of view, practiced as "habits of thought" at large, becomes the view of the established universe of discourse and action, needs and aspirations. The "cunning of Reason" works, as it so often did, in the interests of the powers that be. (Marcuse 1977, 117)

Although the phenomenon of general societal dependency is explained by Marcuse's image, this image still allows for gradations of interest in the survival of the system, and hence for gradations of responsibility for the reinforcement and maintenance of dependency.

The idea that we all essentially are co-opted by the system and corrupted by its productive possibilities is what led so many of Marcuse's readers to the conclusion that "dropping out" was the only way to bring about real change. Marcuse was the darling of the counter-culture movements of the sixties, perhaps, because his outlook encouraged such an absolutely jaundiced view of society. Unfortunately, such a view also, in the end, left very little room for any kind of resistance of any practical value because seemingly only dismantling the entire industrial system would bring an end to its corrupting powers.

Jacques Ellul

At the core of Ellul's outlook on dependency is the idea of technology as cult. At times Ellul seems to suggest, like Lynn White Jr., that the essential battle to be fought is over the appropriate metaphysical/religious outlook to adopt. However, what makes Ellul position distinct from the Lynn White hypothesis is his contention that there is something in the nature of technology itself, at least in the complex form it takes in advanced industrial societies, that prevents awareness of the need to engage in a critical analysis of one's most fundamental metaphysical and ethical presuppositions. Ellul describes the unique challenge that modern people face as follows:

> But when technique enters into every area of life, including the human, it ceases to be external to man and becomes his very substance. It is no longer face to face with man but is integrated with him, and progressively absorbs him. In this respect, technique is radically different from the machine. This transformation, so obvious in modern society, is the result of the fact that technique has become autonomous. (Ellul 1977, 122)

The notion of the "autonomy of technology" is the way that Ellul designates his understanding of technological dependency.

According to Winner, Ellul held that "a certain mode of thought and action, a particular way of defining problems and responding to them, was adopted by society and then became the dominant pattern that governed universally from that time forward" (126). This response pattern also "strongly and automatically repulses any alternative mode of activity" (Winner 1977, 126). Winner goes on to describe the degree to which technological dependency extends in its social influence as follows:

> The profound depth of this tendency is I believe, best illustrated by the fact that even those who now acknowledge a problem in man's relations with nature often move from that insight to become unreconstructed technological systems builders on a potentially colossal scale. (Winner 1977, 129)

So how exactly does technology as a whole circumvent our human ability to reflect critically on ultimate ends? Ellul's position is essentially sociological and, somewhat ironically, relies on the negative critique of religion espoused by nineteenth century positivists, whose metaphysical or anti-metaphysical position he finds so abhorrent. One of his central assumptions is that religion can, as many sociologists suggest, serve as a social focus of human effort. But, according to Ellul, technology can also play this role. He suggests that "The enormous effort required to put this technical civilization into motion supposes that all individual effort is directed toward this goal alone and that all social forces are mobilized to attain the mathematically perfect structure of the edifice" (Winner 1977, 122). According to many sociologists of religion, religions typically play the role of providing a life project to which one could contribute one's individual efforts in the service of something greater than oneself. According to Ellul, the necessity of the ongoing "augmentation" of the technological system means that it can also take such as role, with the result being the development of a pious attitude that it is fundamentally "wrong for a man to escape this universal effort" (Ellul 1977, 123).

According to Ellul modern individuals are faced "with a choice of 'all or nothing.' If we make use of technique, we must accept the specificity and autonomy of its ends, and the totality of its rules. Our own desires and aspirations can change nothing" (Ellul 1977, 124). According to Ellul technology, like a complex religious belief system, can only function as an interconnected system of beliefs and practices which one must accept as a whole. A second feature of contemporary industrial society also supports its ability to take on the role of a cult-like religion. Ellul describes this feature as follows:

> The second consequence of technical autonomy is that it renders technique as sacrilegious and sacred (*Sacrilegious* is not used here in the theological but in the sociological sense.) Sociologists have recognized that the world in which man lives is for him not only a material but also a spiritual world; that forces act in it which are unknown and perhaps unknowable; that there are phenomena in it which man interprets as magical; that there are relations and correspondences between things and beings in which material connections are of little consequence. This whole are is mysterious. (Ellul 1977, 124)

This numinous quality of technologies and technical knowledge augments the ability technology conceived as a whole to take on the role of a cult because it can tap into the same kind of awe that is the primitive source of religion. He notes as follows: "It has been said that modern man surrounded by techniques is in the same situation as prehistoric man in the midst of nature" (Ellul 1977, 130). But this suggests a third feature of technology that would make it particularly difficult to cast the light of ethical criticism on it. According to Ellul "The sacred is what man decides unconsciously to respect" (Ellul 1977, 125). Unlike the revealed religions, with their scriptures, overt dogmas and self-conscious apologetics in the face of religious competitors, technology as a religion operates primarily at a subconscious level and is therefore more like a cult than a public religion.

According to Ellul, technology is essential mysterious to anyone who is a non-expert in any of its facets but it has one more feature that makes its effect on our lives particularly difficult to detect. Although technology is like nature for the prehistoric person, a mysterious force, technology also "denies mystery a priori. The mysterious is merely that which has not been technicized" (Ellul 1977, 125). So technology can play, and according to Ellul has played, an important role in the assault on religious belief. He obviously has in mind the role that technological progress has played in helping support various forms of criticism of established religious customs and beliefs. The result is that technology, because it can be the source of a largely unconscious sense of respect, can play the role of a religion in providing a source of values, but it is also deadly to its overt competitors in this area.

The result is technological dependency. Ellul argues that "every civilization has rules of precise conduct, which are covered by the term *morality* in either its French or its Anglo-Saxon meaning. They determine what is good and what is bad and, consequently, admit or reject a given innovation" (Ellul 1977, 126). But when technology takes on important features of religion it circumvents our critical abilities because everything technological is imbued with an aura of the sacred. The result is, according to Ellul, that "Man is scandalized when he is told that technique causes evil; the scourges engendered by one technique will be made good by still other techniques. This is society's normal attitude" (Ellul 1977, 125).

In this new religion "scientists and worshippers of technology" will be very reluctant to reject any forms of technological power (Ellul 1977, 134). They will, instead, unconsciously defend the fundamental values of a "religion of technology" (Noble 1999). Therefore, according to Ellul, one must conclude that it is extremely unlikely that scientists will be capable "of any but the emptiest platitudes when they stray from their specialities" (Ellul 1977, 135). The more regular mode of most people, Ellul suggests, is to avoid questions of an overtly religious nature, such as questions concerning one's metaphysical presuppositions or core values. As Ellul puts it, "None of our wise men ever pose the question of the end of all their marvels. The 'wherefore' is resolutely passed by" (Ellul 1977, 136). There will also be a strong moral inducement to demonize those who overtly reject any forms of technological progress. Ellul puts this point as follows:

> But what good is it to pose questions of motives? Of Why? All that must be the work of some miserable intellectual who balks at technical progress. The attitude of the scientists, at any rate, is clear. Technique exists because it is technique. The golden age will be because it will be. Any other answer is superfluous. (Ellul 1977, 136)

In the end, the religion of progress as described by Ellul, would seem to pose a very serious threat to the autonomy of its adherents, because like real religions it will be capable of galvanizing extremely powerful emotional sentiments and a sense of awe and gratitude on the part of its adherents. However, unlike real religions it will be largely immune to any form of self-criticism.

Marshall McLuhan

For McLuhan, dependency involves a "subliminal and docile acceptance" of technology (McLuhan 1977, 103). The root of this docile attitude is a form of unconsciousness towards our technological activities and their effects. The problem is not one of false consciousness or false needs, but a lack of consciousness at all. The result is that "a man is not free if he cannot see where he is going" (103). The origin of numbness is a result of the nature of technology as McLuhan defines it. According to McLuhan all technologies are "extensions of some human faculty—psychic or physical" (McLuhan 1967, 26). And so in the same way that most people are normally unaware of thought when they are thinking, or of their hands when they are grasping, or of their mouths when they are speaking, they are normally unaware of their technologies in their regular use. In most natural and unmediated human activities one's focus is on the task itself and one's goals and not the means (the various parts of our body or mind) being used to achieve these goals. This means that it is precisely the tools with which we are most familiar that we will be most blind too.

For McLuhan there seem to be two causes of this normal lack of awareness. The first is the result of the simple intimacy that is an integral characteristic of technologies according to McLuhan. All technologies, as extensions of our physical and mental selves, literally represent extensions of our own bodies or mind. McLuhan's suggestion is that in our technological actions, just like in our unmediated actions, we are normally unselfconscious of the various parts of our functioning body and mind.

What McLuhan is suggesting is the mundane fact that in any human practice, trying to maintain an intense self-conscious awareness of how one is doing what one is doing is a guaranteed way to inhibit the effective achievement of the goal of the practice. McLuhan's use of imagery from the field of psychology might simply be a literary person's way of communicating this point. As McLuhan puts it,

> The principle of numbness comes into play with electric technology, as with any other. We have to numb our central nervous system when it is extended and exposed, or we will die. Thus the age of anxiety and of electric media is also the age of unconsciousness and of apathy. (McLuhan 1977, 106)

As McLuhan points out on many occasions, it is only when technologies have passed from normal use that they typically become objects of conscious appreciation, such as when they become objects in museums. It is for this reason that McLuhan likes to compare attempts at understanding the ethical impact of technologies to an attempt at driving a car by way of the rear-view mirror (McLuhan 1967, 100).

However, there is one further source of a possible lack of awareness to our technologies, which might make the neurological imagery of McLuhan not so far-fetched. According to McLuhan it is also the habitual nature of most technological activities that contributes to our lack of awareness of these activities. As he puts it, "It is this continuous embrace of our own technology in daily use that puts us in the Narcissus role of subliminal awareness and numbness in relation to these images of ourselves. By continuously embracing technologies, we relate to them as servomechanisms" (105). All technologies involve us in routine forms of practice. From the primitive pounding mill of village life, to the procedures of airways management in the modern societies, routine procedure is the name of the game when it comes to technology. And this very routine character of most technological practice can, according to McLuhan, contribute to a lack of awareness of the implications of such practice. As anyone who has a bad habit knows, one of the most difficult parts of the battle against such a habit is simply trying to maintain awareness that one is doing it.

McLuhan takes this notion of habit and of technology to an absolute extreme. According to McLuhan, "Socially, it is the accumulation of group pressures and irritations that prompt invention and innovation as counter irritants" (106). In the same way that processes of technological innovation can lead to useful instruments that solve specific problems, such a process has also lead to the ultimate general instrument for the solution of problems, the process of technological innovation itself as a universal tool. McLuhan goes to great lengths to emphasize this point. He cites in at least four places Alfred North Whitehead's statement: "The greatest invention of the nineteenth century was the invention of the method of invention" (McLuhan 1962, 45, 176; McLuhan 1967, 187; McLuhan 1988, 383). However, if the process of technological innovation can become a method it also can become a form of habitual technological practice of the type discussed by McLuhan. The exercise of this habit would obviously contribute to the technological irritants calling for further exercise of this habit. It also could, conceivably in a highly technological society, reduce the opportunity for seeking to deal with the problems thrown up by technology via the simple ethical reconsideration of some of one's technological actions. One can hear the complaint against the growing power of habitual practice in McLuhan's frequent use of the image of the sleepwalker or somnambulist (Marchand 1990, 229) to describe the most common response to the impact of technology on the lives of modern people. This image of somnambulist has also been used by Langdon Winner (2004).

However, this description leaves open the possibility that our particular extensions and their effects will be perceivable by others who are not regular users. The practical recommendation of McLuhan then, would be a familiar one. Any decision-making processes involving a technology must involve as wide participation of stake-holders as possible. Instead of implicating everyone in a "system" or a "faith", McLuhan suggests that our entanglement in technology is much more specific and individual. However, as many recovering addicts attest to working with others together to deal with one's addiction can be a very good way of coming to grips with a dependency. McLuhan's image of dependency, therefore, holds out the hope that existing systems of democratic participation might have the possibility of addressing technological dependency. As he states: "With our central nervous system strategically numbed, the tasks of conscious awareness and order are transferred to the physical life of man, so that for the first time he has become aware of technology as an extension of his physical body...with such awareness, the subliminal life, private and social, has been hoisted up into full view, with the result that we have 'social consciousness' presented to us as a cause of guilt feelings" (McLuhan 1977, 106). McLuhan's hoped that at some point the sheer intensity of our technological involvements will begin to force us to look more closely and deliberately at them in detail.

Conclusion

The phenomenon of technological dependency helps explain the systematic and widespread inability of the vigorous consideration of the ethical limitation of technology to occur. Marcuse's explanation for this phenomenon is that powerful incentives of the industrial system conspire to prevent actions that will limit the expansion of this system, whereas at the level of individual technologies, the obvious benefits of such technologies discourage inquiry into the less obvious harms. Ellul's explanation for this phenomenon is that most modern people are scandalized at the thought of criticizing technology and are easily intimidated and cowed by the arcane wisdom of the high priests of high technology. McLuhan sees technological practice as being so axiomatic and habitual in nature that it becomes, in effect, second nature. And like all habits, technological practices can inherently distract us from other kinds of activity, such as ethical reflection.

All three images provide useful explanations of particular manifestations of technological dependency and the necessity for addressing the various types of dependency. However, the positions of Marcuse and Ellul allow for the designation of certain privileged groups of individuals who can be thought to be especially responsible for the continuation of technological dependency. For Marcuse, it is the industrial and commercial elites who are still the primary beneficiaries of the continued operation of “the system.” For Ellul, it is the scientific high priests who are the ultimate beneficiaries of the feelings of reverential awe that have been instilled in the masses. This differential aspect of their images of dependency could possibly undermine a proper appreciation of the immense depth and pervasiveness of technological dependency, which both of their theories also posit. It also creates opportunities for the vilification of those who can be classified as elite and those who cannot, which could, in certain circumstances prevent possible awareness of the full breadth of technological dependency. For these two reasons, I find McLuhan’s image of technology as habit to be the most intriguing.

McLuhan’s outlook on dependency has the advantage of not encouraging us to become distracted in the complexities of social and political conflict to the detriment of understanding the role that technology plays in such conflict. Instead, it provides a compelling rationale for increased engagement of everyone in a process of discourse about technological decisions. McLuhan’s notion of dependency is, therefore, more in tune with the "multicentred process of social selection" (Winner 2003, 239) that is the preferred subject of investigation of many contemporary researchers in the field of social studies in science and technology. The problem for such researchers does not ultimately reside only in the overt forms of power of particular elite groups, such as industrialists or scientists. Instead, the danger lies clearly in the nature of technological practice itself. Therefore, it makes sense for people with different technological dependencies to share with each other in order for each side to benefit from the unique perspective of other people about the effects of one’s technological actions of which one is unaware or unwilling to recognize.

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