My Conversations with Richard Feynman Regarding Nanotechnology

A personal view of Richard P. Feynman and the historical context of his 1959 American Physical Society talk, “There’s Plenty of Room at the Bottom”.

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Preliminaries:
Some Abbreviations and Notation

- TPORATB = “There’s Plenty of Room at the Bottom”.
- RF = “Richard Feynman”.
- {STM, AFM} = {scanning tunneling microscope, atomic force microscope}
- I use “{...}” to visually delimit {lists, compound phrases, long phrases, or other items} — especially when they occur {in mid-sentence or in combinations}. 
In the 1970s, I had happened across a second-hand copy of the 1961 book “Miniaturization”, which reprinted TPORATB.

While living near Pasadena (on and off) between 1983 and 1985, I had the opportunity to audit Richard Feynman’s and Carver Mead’s courses involving the physics of computing and neuromorphic computing.

So one day after class, I naturally started asking RF how he got to thinking along the lines of TPORATB.
His initial answer was:
... He was walking on a beach in Brazil thinking about miniaturization.
What got him thinking about that?
... He had been thinking about the ultimate limits of data storage.
What got him thinking about that?
... Thinking about the density of DNA data storage.
And so on.
After a few more of these sorts of “What got you thinking about that?” questions, he got mildly exasperated, drew himself up, and ...
Origins and Background} of TPORATB ...

... then he answered:

I used this!
Fortunately, that was a very transient reaction, and RF patiently indulged further questions. RF mentioned there were other people around the time of TPORATB with {similar interests and similar thinking}, although he didn’t recall any specifics.

This is an interesting aspect of TPORATB’s historical context of, so we’ll note some very likely possibilities next.
Who Were the RF Contemporaries of TPORATB?

Freeman Dyson mentioned that Tommy (Thomas) Gold "... was talking about nanotechnology as early as Feynman."
Who Were the RF Contemporaries of TPORATB? ...

• In “No Ordinary Genius: The Illustrated Richard Feynman”, there is this comment by Marvin Minsky relating a post-TPORATB meeting with RF and Ed Fredkin:

One day I was in Los Angeles for some meeting or other with my friend Ed Fredkin. We rented some Honda trail motorcycles, which I had never ridden before. They are wonderful things—very high torque, so you can go through all sorts of woods as though you were walking (but very destructive, of course).

We rode up towards Mount Wilson because we thought that would be a good place to visit, and then Fredkin said, “Why don’t we go and visit Pauling?” Linus Pauling had been one of Ed’s teachers when he was at Caltech. So we rang up Pauling, but he wasn’t home. Then we thought, why don’t we ring up Feynman, whom we had heard of, but never met. He was home. Ed and I were both interested in computers and small machines, so we said we would like to come and talk about that. Feynman said come over, and we did. He had offered a prize for anyone who could build a tiny electric motor—I forget the size, but maybe a cubic millimeter—and some fellow had built one! So we talked all about the future of small components. It was wonderful.
Who Were the RF Contemporaries of TPORATB? ...

- The paper “From an idea to a vision: There’s plenty of room at the bottom” mentions Phillip Morrison as a chief stimulus for TPORATB:

IV. FEYNMAN’S OBJECTIVES FOR THE NEW TECHNOLOGY

The aim of Feynman’s talk was to encourage the development of new techniques in the field of miniaturization. His motivation did not emerge from any technical developments or any of his Caltech projects, but was inspired by discussions with one of his old friends, Phillip Morrison (MIT). Morrison was also most enthusiastic about the ideas of data storage, but was in favor of using biological systems and DNA, whereas Feynman concentrated on physical mechanisms. DNA was the system that represented the scale to be reached. The construction of an atomic data carrier following Feynman’s model would still have taken too much space; the number of atoms that Feynman proposed for the storage of one byte exceeds a DNA basic strand, which is enough to produce a human. The human body and brain leave all of today’s computers far behind in storage capacity and calculation speed. Morrison and Feynman included the mathematical concepts of Shannon, Weiner, and Mandelbrot in their discussions, but were not able to match evolution, from which a vast variety of storage devices with non-reproducible control mechanisms have emerged, all of them adapted to the environment and capable of reproducing themselves.
Who Were the RF Contemporaries of TPORATB? ...

• In the 1970s, I had discovered the 1960’s era work of Ken Shoulders. Ken was one of the leading pioneers of {electron beam lithography and vacuum electronic devices}. Ken’s work was aimed towards nanotech scales.
• I later decided to try tracking Ken down.
• It turns out Ken had indeed known RF before TPORATB.

Who Were the RF Contemporaries of TPORATB? ...

• Ken Shoulders also knew a number of other people interested in TPORATB-era “proto-nanotech”.
  – Before Ken relocated to SRI in 1958, he had known Marvin Minsky at MIT (where Ken had also been pursuing ultra-miniaturization).
  – Ken was also familiar with Carver Mead’s early post-TPORATB attempts to fabricate solid state tunneling transistors with nano-scale barriers. Unfortunately {materials quality and instrumentation limitation} issues precluded success.
    • Ken’s vacuum-based point projection field emission approach had the electron microscopic advantage of “seeing” defects in action. Even so, the technical challenges were still enormous.
  – Importantly, besides being a great experimentalist, Ken also knew far-sighted funding sources. He credits the NSA for steering funding his way in the {late 1950s and early 1960s}. 
Nano-Related Thinking After TPORATB

• I’m going to briefly mention some highlights from the chapter I wrote for “The First Los Alamos Conference on Artificial Life”.

• Most of this chapter’s content is historical. One important insight is that TPORATB wasn’t an isolated appreciation of nano-related possibilities.

• Many people were surprised to find out how many supposedly new ideas weren’t new.

• Richer historical perspectives can help counter {cults of wildly unrealistic radical developments and naïve neglect of instrumental issues}, among other things.
Nano-Related Thinking After TPORATB ...

- More stuff from the 1960s and 1970s.
- Nano-miniaturization of robots.
- Molecular engineering.

**ETTINGER, WHITE, DARWIN, DONALDSON: MEDICAL NANOTECHNOLOGY**

Ettinger\(^{63,64}\) suggested using nanotechnology for life extension and artificial evolution, and “nano miniaturization” of robots was later suggested by Ettinger\(^{65}\), White\(^{239}\), Darwin\(^{36}\), and Donaldson\(^{48,49}\) envisioned the use of genetic engineering and other possibilities for making nanorobots that could function as cell repair machines. These possibilities are discussed in the appendix.

**VON HIPPEL, VON FOESTER, ZINGSHEIM, ELLIS, FULLER: MOLECULAR ENGINEERING**

Forrest\(^{88}\) notes, in connection with Von Hippel, that “…nanotechnology…will evolve from the integration of such diverse disciplines as genetic engineering, biophysics, robotics, artificial intelligence, computer-aided design and manufacture (CAD/CAM), biology, chemistry, physics, computer science, materials science, and many others. The concept of integrating these technologies is not new. Arthur von Hippel foresaw it at least as early as 1963, and others probably even before that.”

Von Hippel\(^{236}\) noted the fantastic possibilities that better materials technology holds for the world if only current science and engineering limitations could be conquered: “Suddenly all this is changing. ‘Molecular science’…has made a more powerful approach possible: ‘molecular engineering,’ the building of materials and devices to order.”
Nano-Related Thinking After TPORATB ...

• More stuff from the 1960s and 1970s.
• In the 1960s, Shoulders had proposed replicating systems, and noted the possibilities of nano-mechanical actuators.

We propose...a component based upon the quantum-mechanical tunneling of electrons into the vacuum...The transit time for electrons would be about $10^{-13}$ sec...

Ultimately, we would use a vacuum-tunnel effect cathode array for our electron source. The emission from discrete areas would be controlled by local grids...Thus we have components made by electronic micromachining responsible for the building of new systems by the same method. In the end, self-reproduction would be a distinct possibility without the use of a lens system, because all copies would be made on a one-to-one size basis.

As foreseen by Morrison,\textsuperscript{171} this technology clearly had potential for an artificial life form. Shoulders\textsuperscript{208} maps out an integrated circuit technology based on field-

Shoulder’s proposed electrostatic relays could also incorporate wear-free, non-contacting, subnanometer, vacuum-tunneling gaps, incorporating just a few atoms in the limiting case.\textsuperscript{203,204} These could also be used for electrostatic nano-actuators and mechanical power sources. Shoulders\textsuperscript{209} later reports testing of prototype devices and structures.
Nano-Related Thinking After TPORATB ...

- Still more stuff from the 1960s and 1970s.
- Molecular engineering.
- Assembly tools for molecular-level structures.
- Fractal meta-materials, spanning the atomic-to-macro level.

Von Foester\textsuperscript{235} commented that von Hippel’s anticipation of “engineering of molecules according to specification” may “also show us some novel manifestations of life.” Von Foester derived some mathematical constraints for the molecules needed for such a “molecular bionics” modeled on chemical modifications to a particular macromolecular structure called a macromolecular sequence computer.

Zingsheim\textsuperscript{252,253} was interested in molecular engineering using nanometer surface microstructures. He noted that “The aim of molecular engineering is the design and construction of man-made complex supramolecular systems from building blocks of molecular dimension.” He further noted that it concerns the “development of molecular components and assembly tools allowing manipulations at molecular dimensions.”

In a paper on microteleoperators, Ellis\textsuperscript{86} reports:

Electrolytically operated micromanipulators add automatic high-speed movement to normal manual control...

In addition to their use in biological investigations, piezoelectric micromanipulators may find important new uses in the development of semiconductor devices and microcircuits. For example, semiconductor junctions could be formed by microetching and electroplating with microelectrodes. Complex circuit paths could be formed by etching through a conducting layer deposited on an insulating substrate... With these techniques, complex circuits of unprecedentedly small size could be fabricated automatically.

Buckminster (“Doing More With Less”) Fuller proposed a nanoarchitecture having an interesting recursive or fractal structure (Fuller and Applewhite\textsuperscript{89}). Its macro level structure is simply a tensegrity mast, which is a rigid structure constructed from an ingenious configuration of interconnected tension (cable) and compression (strut) members, with the unique feature that the struts are isolated from each other. In one version of the macro-tensegrity mast, each individual solid strut and cable may be replaced by a miniaturized version of the macro-tensegrity mast. And then each one of the miniature solid struts may itself be replaced by a still smaller subminiature tensegrity mast. And so on recursively, down to the atomic level. The end result is an extremely light, mostly empty, yet rigid structure. This same idea may be applied to a large variety of other structures.
Nano-Related Thinking After TPORATB ...

- Still more stuff from the 1960s and 1970s.
- Molecular machines.
- Molecular devices.

**CHANGEUX AND KUHN: MOLECULAR MACHINES AND DEVICES**

The feasibility of artificial molecular machines is implied by the view that biology is based on molecular machines. Changeux notes that,

> The analogy between a living organism and a *machine* holds true to a remarkable extent *at all levels* at which it is investigated ... An organism can be compared to an *automatic factory* ...

> [The] cell is a mechanical microcosm: a mechanical machine in which the various structures are interdependent and controlled by feedback systems quite similar to the systems devised by engineers who specialize in control theory ...

> Regulating the production lines are control circuits that themselves require very little energy ... The elementary machines of the cellular factory are the biological catalysts known as *enzymes* ... Built into [their] structure, as into a computer, is the capacity to recognize and integrate various signals.

Langmuir-Blodgett films are one molecule thick films that are made by spreading fatty acid molecules across an air-water interface. These films may have guest molecules inserted into them, and a simple dipping process may be used to stack up such film into multilayer structures. Kuhn describes his pioneering work (starting in the 1960's) in applying Langmuir-Blodgett films to molecular scale devices:

> The construction of an artificial system acting as a complex machinery with cooperating components of molecular dimensions is a great challenge. First attempts in the early 1960's to approach this aim were governed by the idea that the Langmuir-Blodgett technique ... might be suitably modified and could then offer a way to arrange appropriate functional molecules of different species in an adequate fixed structure where the molecules could cooperate in a complex and purpose-oriented manner. Many different techniques to reach that goal have been developed and are summarized: methods to control monolayer formation and transfer and to study monolayer absorption, reflection and fluorescence spectra; special techniques to check the architecture of monolayer organizes by combining energy and electron transfer; synthesis of sterically interlocking and functionally cooperating molecules ...

> [It] should be mentioned that the search for the basic mechanisms in the origin of life can be strongly stimulated by studying possibilities of the formation of artificial machineries of molecular size and that quite unorthodox views are obtained from such studies. Conversely, the study of these mechanisms should indicate new ways of obtaining artificial devices of molecular size ...
Nano-Related Thinking After TPORATB ...

• Arranging molecules with electron beams.

• And still more stuff from the 1960s and 1970s.

• And still more stuff from the 1960s and 1970s.

• And still more stuff from the 1960s and 1970s.

• Once again, the theme of replicators....

Kuhn\textsuperscript{142} adds, “To our knowledge, the first demonstration of arranging molecules by means of an electron beam using a STEM (not STM) was realized in Kuhn’s group by H. P. Zingsheim.”\textsuperscript{252} Nature provides us with a wealth of prototypical molecular machines; some basic mechanisms of some of these machines are examined by Mitchell\textsuperscript{167} and McClaire.\textsuperscript{162}

**LAING: ARTIFICIAL NANOREPLICATORS**

In a series of papers with direct relevance to artificial life, Laing\textsuperscript{144–148} wrote about artificial replicators. In particular, his 1974 and 1975 papers are motivated by considerations of artificial molecular replicating machines, constrained to be “biologically reasonable” (including future biological possibilities and, hence by implication, artificial life). These papers have direct relevance to artificial nanoreplicators and microreplicators. While Von Neumann\textsuperscript{237} formulated a general theory of replicating automata in abstract form, Laing has considered some important design possibilities for molecular realizations of such automata. One form of these nanoreplicators described by Laing\textsuperscript{148} utilized molecular (data) tapes (based on the idea of universal Turing machines) to implement replicators (based on Von Neumann’s generalization of self-replicating Universal Turing machines). He then showed three ways that such molecular machines might replicate themselves. His exploration of “artificial organisms” was “a vehicle for the exploration of broad biological possibilities.”

Laing’s\textsuperscript{146} studies of kinematic replicators results in a new self-inspecting design that leads to the interesting conclusion that “contrary to von Neumann’s surmise, a prior description is not essential to the nondegenerative machine self-reproductive process.” Among other interesting features, this new replicator design has interesting self-repairing capabilities as well.
Nano-Related Thinking After TPORATB ...

- And still more stuff from the 1960s and 1970s.
- Molecular nanocomputing.

ROTHSTEIN, AVIRAM, RATTNER, CONRAD, CARTER, LIEBERMAN: MOLECULAR NANOCOMPUTING

Scientists extrapolating the development of electronic devices in the 1950's and 1960's noted that the next century should see the development of electronic devices the size of individual molecules and much faster than neurons. Rothstein\textsuperscript{194} examined some fundamental limits on chemical information storage systems. In 1974, Aviram and Ratner\textsuperscript{4} presented one of the earliest specific proposals for a molecular nanocomputer searching for means to assemble entire computers from molecular devices. Lieberman\textsuperscript{153} examined some of the possibilities for “molecular computers,” including their phenomenal memory capacities, noting that while on a modern computer there are about “$10^{10}$ simple memory elements,” that on the other hand, “on an excellent machine of the distant future…there might be $10^{30}$ elements.”
Nano-Related Thinking After TPORATB ...

- More stuff from the 1960s and 1970s.
- Nano-precision nano-scanners.

YOUNG, WARD, SCIRE, TEAGUE: PROTO-STM

The STM was very nearly invented 10 years earlier, but success was prevented by equipment vibrations and other problems. Young, Ward and Scire\textsuperscript{249} reported metal-vacuum-metal tunneling experiments and described a machine they had developed\textsuperscript{250} for these experiments at the National Bureau of Standards:

A noncontacting instrument for measuring the microtopography of metallic surfaces has been developed to the point where the feasibility of constructing a prototype instrument has been demonstrated... In the MVM [metal-vacuum-metal] mode, the instrument is capable of performing a noncontacting measurement of the position of a surface to within about 3 Å. The instrument can be used in certain scientific experiments to study the density of single and multiple atoms steps on single crystal surfaces, absorption of gases, and processes involving electronic excitations at the surfaces.

And, as in most current STMs, piezo scanning systems were used in their system. They were so very close to constructing a full STM—just before their funding was cut in 1972 (Gadzuk\textsuperscript{92})!
Nano-Related Thinking After TPORATB ...

- More stuff from the 1960s and 1970s.
- The artificially-synthesized life route to nanotech — ultimately growing airplanes.

Nemes\textsuperscript{174} discussion of self-reproducing machines includes the description of how to construct “an automatic lathe able to reproduce itself,” a concept developed before Von Neumann’s work on replication. The same principle could be applied to Feynman’s\textsuperscript{78} suggested nano-lathes.

In 1972, Danielli\textsuperscript{37} described an array of possibilities for generating new life forms via “life-synthesis” and genetic engineering. He also noted that “macromolecular engineering” might enable the development of very powerful and compact macromolecular computer systems. In his Nobel lecture, Lehn\textsuperscript{150} summarizes the wide range of advances in supramolecular design and engineering that have occurred since then and which “open perspectives toward the realization of molecular photonic, electronic, and ionic devices that would perform highly selective recognition, reaction, and transfer operations for signal and information processing at the molecular level.”

In 1974, Halacy\textsuperscript{106} noted “some rather inglorious ways” to use “the miracle of artificial life,” including potential capabilities for growing diverse items ranging from computers to airplanes. Halacy also noted that “Leonard Engel wrote in 1962 that ‘cold-war-minded scientists have in fact urged a crash program to guarantee a U.S. first’ in creating living matter in the laboratory.”

In 1974, Morowitz\textsuperscript{170} suggested cooling cells to cryogenic temperatures in order to analyze and determine their structure. Artificial cells would likewise be constructed at such temperatures and then set in motion by thawing. He further reported that microsurgery experiments on amoebas “have been most dramatic. Cell
Nano-Related Thinking After TPORATB ...

- Arranging molecules with electron beams.
- And still more stuff from the 1960s and 1970s.
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Nano-Related Thinking After TPORATB ...

• That’s about enough examples from the 1960s and 1970s.
• We’ll wind up this overview with Pat Gunkel’s encyclopedic Hudson Institute study on “The Future of Space”. In 1975, Pat generically anticipated the awesome potential of extremely advanced nanotech.

behind after their departure, to reduce mission costs, &c. Tremendous, progressive miniaturization of sensors, computers, operators, experiments, vehicles, power sources, engines, memories, laboratories (diverse instruments), & even certain payloads should be possible and occur over the future, miniaturization so exquisite and so many orders of magnitude beyond present degrees and past progress as to seem to us miraculous and impossible. So much information and mechanical versatility seems ultimately possible in a 1-centimeter, 1-gram, and $10^{24}$-atom cube of matter—whatever its shape and form—that is hard to think of things not precisely or equivalently achievable simultaneously in an ultimate cube of such insignificant dimensions as a teleological condensate or quintessence. This is not only because of the micromanipulative, microscopical, ultrasensitive, microcosmical (otherworldly), elegant, &c powers possible for such micromachines, nor their computational capabilities (e.g. $10^{24}$-bit memory, $10^{-10} - 10^{-18}$ sec operations, &r arbitrarily great intelligence). Cellular automata and general ontological micromachines could and probably will eventually—even before 2050—acquire theurgic infinite and superinfinite powers to fulfill assignments to an infinite degree, reform the universe, create a universe, maximize natural evolution, destroy the universe, &c, or perform any intermediate thing within the finite or infinite realms of possibility (such supreme devices might be called "omnipotent atoms"). That a 1-gram
Nano-Related Thinking After TPORATB ...

- RF’s Cal Tech colleague, Carver Mead, was inspired by TPORATB.
  - Both Carver and RF encouraged my enthusiasm for STMs.
  - Carver is notable for correctly deducing that IC transistors could be scaled down much further than commonly believed, and then working to realize his visionary insights.
  - Carver launched a whole series of related {technical initiatives and high-tech startups} to help make such developments happen. Carver thus helped lead the long-distance charge to the realm of nanoelectronics, which is why his work was much more frequently cited than TPORATB.
- However, TPORATB was cited by Carver. In my view, that’s worth dozens of citations. In “Collective Electrodynamics: Quantum Foundations of Electromagnetism”, Carver says:

> Back in 1959, Feynman gave a lecture entitled “There’s Plenty of Room at the Bottom,” in which he discussed how much smaller things can be made than we ordinarily imagine. That talk had made a big impression on me; I thought about it often, and it would sometimes come up in our discussions on the tunneling work. When I told him about the scaling law for electronic devices, Feynman got jazzed. He came to my seminars on the sub-
Nano-Related Thinking After TPORATB ...

• So what can we learn from TPORATB and somewhat related examples from the 1960s and 1970s?
  – The history of nano-related thinking is {deeper and richer} than generally recognized.
    • Much of this sort of {thinking and discussion} that is “in the air” {isn’t well-reported or isn’t cross-referenced} in the literature.
    • RF fortunately {was well-positioned and had a semi-ideal form} to present TPORATB.
  – Nanotech developments most often seem to naturally result from working to pushing the development of present technology forward.
    • The corollary of this is that visionary ideas often don’t do much to drive progress.
    • Many visionary ideas turn out to be practically-inferior to the subsequent “organic trajectory” of technological development. To its credit, TPORATB was alert to this possibility.
The Little Motor That Could

• Just for fun.
STMs (Scanning Tunneling Microscopes)

- When I had first talked to RF about STMs, I was surprised to find out he didn’t know about them. Naturally RF was {delighted and intrigued}.
- I initiated a project to build an STM at the University of Arizona in the mid-1980s, with the aim of imaging bovine microtubules. Here is the first result of that collaboration.
RF’s STM-Inspired Nanotech Suggestions

• This was one of the results of our earlier discussions.

During a recent talk on his quantum computing ideas, Feynman briefly speculated on a simple possibility for making nanocomputer components: use a STM tip to make tiny holes in very thin metal sheets, thus forming grids for tunneling “nano-vacuum tubes,” perhaps around 3 to 10 nm in size. Even more compact and potentially faster experimental configurations using several ultrasharp STM tips were mentioned in further speculations by Feynman. Unfortunately, no one...
RF’s STM-Inspired Nanotech Suggestions ...

- Continuing on the same theme....

![Diagram of a nano-vacuum tube](image)

FIGURE 8. A schematic drawing illustrating the concept of a “nano-vacuum tube.” This is the near-minimum-scale case of the submicron triodes proposed by Shoulders, but using an STM tip as suggested by Feynman. A perfect monoatomic STM tip, similar to one later invented by Fink, is shown here.

has followed up on his ideas with either calculations or experiments. Analogous, but much larger (down to 100 nm scale) devices with calculated, *subpicosecond*-range, switching speeds have been proposed by Shoulders. Although he considered even smaller, faster devices, limitations of electron beam micromachining technology at that time prevented further size reduction.

Computing in general and quantum computing in particular was Feynman’s “Holy Grail” of nanotechnology; when I told him about STMs, his first thoughts about it involved computing devices. Computing components each consisting of a few atoms might use quantized energy levels or quantum-mechanical spin effects. Feynman analyzes quantum computing and concludes that, “At any rate, it seems
TPORATB Reprint Permission from RF

• Support for using TPORATB {to explain key nano-tech ideas, to further the cause of STMs, and to counter misleading cultish nano-hype}.

CALIFORNIA INSTITUTE OF TECHNOLOGY
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August 19, 1986

Dr. Conrad Schneiker
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Tucson, AZ 85721

Dear Dr. Schneiker:

You have my permission to reprint "Plenty of Room at the Bottom," as an appendix to your book.

Sincerely,

Richard P. Feynman

Richard P. Feynman

RPF;ht
The item for challenge (2a) is now called graphene, which looks like it may be hugely valuable for nanoelectronics.
“From Idea to Vision: There’s Plenty of Room at the Bottom”

- This paper has lots of good-to-know historical information.
- It helps identify some of the contemporaries that Feynman previously told me about.

From an idea to a vision: There’s plenty of room at the bottom

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(Received 7 November 2005; accepted 19 May 2006)

Many workers in nanotechnology cite Richard Feynman’s after-dinner speech, “There’s plenty of room at the bottom,” which was given by him on December 29, 1959, to be the birthday of theoretical nanotechnology. This attribution is misleading because there is no direct link from Feynman’s talk to today’s micromachines. We discuss the historical background of Feynman’s talk, the state of the art in 1959, and Feynman’s motivation. We conclude that Feynman was not interested in building miniaturized versions of existing macroscopic machines, but wished to construct microbiological machines and tools that would enable scientists to mimic microbiological materials. © 2006 American Association of Physics Teachers.  
[DOI: 10.1119/1.2213634]
“From Idea to Vision: There’s Plenty of Room at the Bottom” ...

• However, while many of this paper’s insightful critiques are on target, it also makes a number of unwarranted inferences:
  – It conflates Feynman’s initial {inspiration and point of departure} for TPORATB with his broader {interests and aims}. Having talked with RF about TPORATB, I think the authors’ claim concerning RF’s predominantly (versus inclusively) biological focus is mistaken. However, they are right to object to those who spin TPORATB in exclusively micro-machine terms.
  – The discussion of {STMs, TPORATB, and Feynman} is somewhat off-base. Unfortunately the authors didn’t see my chapter on nanotech, which would have corrected some mistaken presumptions.
  – There are excellent reasons to cite {historical and conceptual} versus {causal and developmental} precursors (such as TPORATB). In my case, TPORATB was indeed a major influence for {pursuing and publishing} STM-related work.
“Recent Ancient History”

• A brief aside:
  – I like to think of TPORATB as “recent ancient history”.
  – Sam Cohen (the inventor of the neutron bomb) likes using this phrase, and he says it was a favorite expression of John von Neumann.
  – Incidentally, Sam mentioned that RF taught him how to pick locks at Los Alamos. Previously, I’d only recalled hearing of RF’s safe-cracking skills.
Conclusion — The Most Important Suggestion of TPORATB

• Instrumentation advances are extremely important for opening new technological frontiers. RF appreciated this. Quoting TPORATB:
  – “I would like to try and impress upon you, while I am talking about all of these things on a small scale, the importance of improving the electron microscope by a hundred times. It is not impossible; it is not against the laws of diffraction of the electron. The wave length of the electron in such a microscope is only 1/20 of an angstrom. So it should be possible to see the individual atoms. ... I put this out as a challenge: Is there no way to make the electron microscope more powerful?”

• Of course we would like such atomic-resolution scanning electron microscopes to be {micro-to-nano scale, relatively inexpensive, and mass-producible} as well. There are some interesting nanotech-related prospects for achieving this.

• (A comparable atomic-resolution scanning inert ion microscope is also an extremely desirable objective.)
Thank You, RF!
Any Questions?