Feynman Revisited

Stephen D. Senturia
Massachusetts Institute of Technology
Cambridge, MA, USA

ABSTRACT

Richard Feynman on two occasions (in 1959 and 1983) addressed the problem of miniaturization of systems, including information storage, computers, and machines. This paper revisits those two speeches, and examines which of the various ideas suggested by Feynman have become realities.

INTRODUCTION

I never met Richard Feynman . However, I did become acquainted with him via video-tape when I edited his speech "Infinitesimal Machinery" for publication in JMEMS [1]. This speech, which was presented to a mixed professional audience at the Jet Propulsion Laboratory, was a sequel to his 1959 speech entitled "There's Plenty of Room at the Bottom," presented in December 1959, also reprinted in JMEMS [2].

In the process of converting the oral transcript of the "Infinitesimal Machinery" speech to publishable text, I had the opportunity to examine which of Feynman's various imaginative ideas have been converted to reality, and I made a few comments on that subject in the Editor's Preface to the published version. This, in turn, apparently led the MEMS '94 Program Committee to issue an eleventh-hour invitation for me to make a presentation at MEMS '94 called "Feynman Revisited". I accepted, with pleasure and trepidation -- pleasure, because it is so delightful to follow along with Feynman's enthusiastic quest for new ways of doing things, and trepidation, because the scope of Feynman's interest is so vast, and the number of areas he touched on which have now become active technological domains is so large, that I feel unequal to the task of accurate reporting. And because the invitation came relatively late, with only a few weeks before this manuscript had to be submitted, I was unable to do the kind of comprehensive referencing which we would normally expect from such a retrospective subject. By the time the talk is presented in January '94, more of the references will be compiled, and it is my plan eventually to prepare a full paper for publication in JMEMS which will repair the deficiencies of this very hasty summary.

In the discussion which follows, I will refer to "There's Plenty of Room at the Bottom" as "PRB", and "Infinitesimal Machinery" as "IM". In the hopes of capturing the boyish enthusiasm with which Feynman presented these ideas in real time, I have made liberal use of direct quotations from the two speeches, supplemented with comments of my own.

The Major Ideas

There is a common theme in PRB and IM. It is that the laws of physics provide a lot of room for miniaturization. We are limited by technology, not by fundamental physics. Feynman explores four major areas to develop this theme: *information storage*, *computers*, *manipulation of atoms*, and *machinery*. In PRB, presented at a time when integrated circuits had barely been invented, transistors were made of germanium, and computers with 4K core memories filled entire rooms, Feynman explores miniaturization by scaling familiar macroscopic structures to smaller sizes. In IM, with much of what had been hoped for in PRB already accomplished, Feynman turns to the implementation of miniaturization ideas, with emphasis on what we have come to know as *surface micromachining* to build freely moving parts (which was fully realized within a few years), and on low-power computation with registers made of atoms (which is still a futuristic idea).

MINIATURIZATION OF INFORMATION STORAGE

In both PRB and IM, Feynman addresses the idea of reducing the size of the unit of information. In PRB, he argues that it would take about 100 atoms to represent a unit of data, whether a printed letter in two dimensions, or as bits stacked into three dimensional arrays. In the case of printed letters, he suggests that reduction by a linear scale factor of 25,000 will allow the contents of all the books then in the world (estimated at 24 million volumes, each of a size of roughly 1000 pages) to be printed on 35 pages of a tabloid-size magazine. If the information is encoded in binary form and packed in three-dimensional arrays of 125-atom blocks, the estimated 10^{15} bits of information in the 24 million volumes could be packed into a speck of dust. This is why he emphasizes the idea that there is *plenty* of room at the bottom.

PRB then examines how to write and read such information. For two-dimensional storage, Feynman suggests *focused-ion-beam writing* or *electron-beam writing* into a suitable coatng, both of which are now well known, and for reading, suggests *replication with molding and metalization and reading via electron microscope*. Because of the key role played by electron microscopy, he identifies *improvements in the resolution of electron microscopes* as the most important thing to do. He was concerned that electron microscopes had only 10 Å resolution, far below the limit imposed by the electron wavelength. Now, of course, there have been improvements to where *atomic-scale resolution* is routinely achieved in modern transmission electron microscopes.

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MINIATURIZATION OF COMPUTERS

From PRB:

> "Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting -- if they could be made more complicated by several orders of magnitude. ... If I look at your face, I immediately recognize that ... it is a *man* and not an *apple*. Yet there is no machine which, with that speed, can take a picture of a face and say even that it is a man; and much less that it is the same man that you showed it before -- unless it is exactly the same picture. If the face is changed; if I am closer to the face; if I am further from the face: if the light changes -- I recognize it anyway. ... This little computer I carry in my head is easily able to do that. The number of elements in this "bone box" of mine are enormously greater than the number of elements in our "wonderful computers." ...
>
> "If we wanted to make a computer that had all these marvelous extra qualitative abilities, we would have to make it, perhaps, the size of the Pentagon. This has several disadvantages. First, it requires too much material; there may not be enough germanium in the world for all the transistors which would have to be put into this enormous thing. There is also the problem of heat generation and power consumption; the Tennessee Valley Authority (a major complex of hydroelectric dams in the US) would be needed to run the computer. But an even more practical difficulty is that the computer would be limited to a certain speed. Because of its large size, there is finite time required to get the information from one place to another. The information cannot go any faster than the speed of light -- so, ultimately, when our computers get faster and faster and more and more elaborate, we will have to make them smaller and smaller.
>
> "But there is plenty of room to make them smaller. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now."

That was in 1959. Everyone is now aware of the computer revolution, and how much of what is expressed here has come to pass in terms of speed, computing power, electric power management, and computer size. We are now able to do such complex tasks as *voice and handwriting recognition*, albeit with errors, and we can even do some of these tasks in portable hand-held computers called "Personal Digital Assistants."

Quantum Effects

In all this discussion of miniaturization of computing, though, I think Feynman overestimated the degree of miniaturization which would be required before quantum effects would set in. For example, in PRB, we find the following:

> "I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements -- and by little, I mean *little*. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across."

We now make such devices, but we do it for the purpose of examining *quantum transport, electron waveguides*, and the like. Feynman reserves his discussion of quantum effects until the scale reduces by another order of magnitude, as illustrated by this, also from PRB:

> "When we get to the very, very small world -- say circuits of seven atoms -- we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. ... We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc."

In IM, Feynman develops this theme further, discussing computing on the atomic scale. In this discussion, he uses a "row" of atoms with quantized spins as his register for holding results. This fascination with the idea of direct observation and manipulation of atoms is discussed below.

MANIPULATION OF ATOMS

Feynman was excited by the prospect of manipulating atoms for chemical synthesis and for creation of new substances and structures which are not found naturally. He did not anticipate the invention of the *scanning tunneling microscope* and the *atomic force microscope*, or our present ability to "see" DNA molecules when they are tagged with fluorescent substituents and suspended in *optical tweezers*. But consider the following, from PRB:

> "What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things we can do."

We are stimulated to think of *molecular beam epitaxy, heterojunction devices, modulation doping* to build *high-electron mobility transistors, quantum well devices*, and *strained-layer superlattices*, all in agreement with Feynman's vision.

MINIATURIZATION OF MACHINERY

In order to approach the subject of making small machines, Feynman (in PRB) used the example of making a small car. He argued that if an entire automobile, as we know it, were to be scaled as small as possible, assigning a macroscopic minimum tolerance of .0004 inch to a scaled tolerance of 10 atoms, then the scale factor for reducing the automobile is 4000, making the entire car about 1 mm across.

He then adds the following comments (from PRB):

> "It is interesting to consider what the problems are in such small machines. Firstly, with parts stressed to the same degree, the forces go as the area you are reducing, so that things like weight and inertia are of relatively no importance. The strength of material, in other words, is very much greater in proportion. The stresses and expansion of the flywheel from centrifugal

force, for example, would be the same proportion (as in a large car) only if the rotational speed is increased in the same proportion as we decreased the size. On the other hand, the metals that we use have a grain structure, and this would be very annoying at small scale because the material is not homogeneous. Plastics and glass and things of this amorphous nature are very much more homogeneous, and so we would have to make our machines out of such materials.

This anticipates the development of *fine-grained polysilicon* as a micromechanical material.

Continuing the discussion, Feynman observes that

> "There are (also) problems associated with the electrical part of the system. The magnetic properties on a very small scale are not the same as on a large scale; there is the "domain" problem involved. A big magnet made of millions of domains can only be made on a small scale with one domain. The electrical equipment won't simply be scaled down; it has to be redesigned."

At this time, we are just beginning to explore the magnetic structure of electroplated magnetic materials used in LIGA and other high-aspect-ratio metal structures.

And the discussion continues:

> "Lubrication involves some interesting points. The effective viscosity of oil would be higher and higher in proportion as we went down. ... But actually we may not have to lubricate at all! We have a lot of extra force. Let the bearings run dry; they won't run hot because the heat escapes away from such a small device, very, very rapidly."

Of course, those who work on micromotors and contend with its friction may not agree that "there is a lot of extra force". (Friction is discussed later.)

But first, an interesting observation on the engine which the microcar might use:

> "This rapid heat loss would prevent the gasoline from exploding, so an internal combustion engine is impossible. ... Probably an external supply of electrical power would be most convenient for such small machines."

And this leads Feynman to the idea of the small electric motor, needed as prime mover for small machines.

THE ELECTRIC MICROMOTOR

In PRB, Feynman offered his famous prize of $1000 for a functioning electric motor 1/64 inch on a side. As expressed in IM, he had hoped this would stimulate new ways of making machines. But as is well known, William McLellan claimed the prize within a year of its announcement, using a motor designed by conventional means.

In IM, Feynman once again addresses small motors. He first exhibits the McLellan motor (passing it around the audience), and then begins examining a new way to make small motors, as illustrated in the following quotation:

> "Let's say I'm talking about very small machines, with something like ten microns (that's a hundredth of a millimeter) for the size of the rotor. That's forty times smaller than the motor I passed around -- it's invisible, it's so small.
>
> "I would like to shock you by stating that I believe that with today's technology we can easily --I say *easily* -- construct motors on fortieth of this size on each dimension. That's sixty-four thousand times smaller than the size of McLellan's motor. And in fact, with our present technology, we can make thousands of these motors at a time, all separately controllable. ... I'll suggest how to do it -- it's very easy."

In what follows, Feynman refers to "evaporation" as a generic term for a photolithographic microelectronic thin-film process:

> "It's just like the way we put those evaporated layers down, and made all kinds of (microelectronic) structures. We keep making the structures a little thicker by adding a few more layers. We arrange the layers so that you can dissolve away a layer supporting some mechanical piece, and loosen the piece. The stuff that you evaporate would be such that it could be dissolved, or boiled away, or evaporated out. And it could be that you build this stuff up in a matrix, and build other things on it, and then other stuff over it. Let's call the material "soft wax," although it's not going to be wax. You put the wax down, and with a mask you put some silicon lumps that are not connected to anything, some more wax, some more wax, and then silicon dioxide or something. You melt out or evaporate the wax, and then you're left with loose pieces of silicon. The way I described it, that piece would fall somewhere, but you have other structures that hold it down. It does seem to me perfectly obvious that with today's technology, if you wanted to, you could make something one-fortieth the size of McLellan's motor."

To the best of my knowledge, no one from the Berkeley, MIT, or Bell Labs groups attended this lecture in 1983. But within a few years, all three groups had used sacrificial layers in photolithographically defined structures to created *freely moving microstructures* with bearings and supports.

Electrostatic actuation of the first silicon micromotors was also anticipated by Feynman. From IM:

> "Now how do you pull them along? That's not very hard -- I'll give you a design for pulling. If you had, for example, any object like a dielectric that could only move in a slot, and you wanted to move the object, then if you had electrodes arranged along the slot, and if you made one of them plus, and another one minus, the field that's generated pulls the dielectric along."

Also, Feynman did recognize what has proven to be a very difficult issue in microfabrication of released structures, namely, the *tendency of surfaces to stick together* (the following from IM):

> "One problem is that things stick together by molecular attraction. ... If you were to have two tungsten parts, perfectly clean, next to each other, they would bind and jam. The atoms simply pull together as if the two

parts were one piece. The friction is enormous, and you will never be able to move the parts. Therefore, you've go to have oxide layers or other layers in between the materials as a type of lubricant -- you will have to be very careful about that or everything will stick."

In the same issue of JMEMS in which IM appeared, there are two articles on adhesion of microstructures under the influence of capillary forces [3].

Scaled Teleoperation and Precision

In both PRB and IM, Feynman expressed the vision of using macro-machines to make smaller machines, and then using those smaller machines to make even smaller machines. This has not proved practical, at least not in any major way. Instead, we have discovered that even atomic-scale motions can be controlled in macro machines such as the scanning tunneling microscope.

Feynman was also concerned about how to make precise things from imprecise tools. He describes in both papers ways to establish mating concave and convex surfaces, and flat surfaces, by suitable mutual polishing. This, too, has not proved to be important in the micro-domain. Feynman also argues that if things get small enough, for example, with a dimension on the order of 100 atoms, then only 1% precision will result in perfect structures because the atom is a unit. *Self-assembling monolayers* on surfaces are examples of structures which implicitly have this precision.

How to Use Micromachines

Feynman expressed frustration in both PRB and IM because he couldn't think of a serious use for the micromachnes other than the scaled teleoperation, which has not proved practical so far. He suggested three things in IM -- a fast light shutter, a game (in which a self-propelled micromachine chases a paramecium), and a "swallowable surgeon" (a suggestion of his friend Al Hibbs). Of these, I can speak to the *fast light shutter*, because my colleagues and I at MIT have worked on such an application using polysilicon micromotors [4]. The most severe difficulty we have encountered is making good windows in the substrate (without allowing excessive reflections) and making opaque shutters on the rotor poles. When material dimensions are scaled down, they become more transparent, and when metals or silicides are used, adhesion and stress control can be difficult in the presence of the etch used to free the moving parts.

The free-swimming machine continues to be a dream. The game of "chase the paramecium" sounds like a good intermediate goal. I think that before any medical patient would allow an untethered device into his or her bloodstream or body, they would want to know for certain that the power and control problems for the small device were completely solved. Making a game sounds like a good test. And it sounds like the kind of fun Feynman would enjoy.

CONCLUSION

Feynman was clearly a visionary. He also understood the laws of physics deeply, and he had remarkable imagination and curiosity. Thus, he could define directions and opportunities very far in advance of actual technological developments. We will always need intellectual vision to define our path, and Feynman's contributions in this arena set the highest possible standards.

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