The Man Who Dared to Think Small

In a visionary lecture 32 years ago, Richard Feynman predicted many of the advances that are the subject of this special section of Science*—and foresaw their implications*

When Caltech physicist Richard Feynman stood to address the annual meeting of the American Physical Society on December 29, 1959, the world was still a big place. Electrical engineers were struggling with the challenge of fitting more than a few components on a chip, information storage didn't get much denser than microfilm, and atoms were far beyond the ken of the best microscopes. But that didn't stop Feynman from imagining what opportunities for technology might lurk on the scale of atoms and molecules. And the boldness and accuracy of his prognostications have made his talk, "There's Plenty of Room at the Bottom," a classic among the micro- and nanoengineers whose work is described in this 42-page special section of *Science*.

"Feynman had always been interested in the limits that physics put on the things you would like to do," recalls biophysicist John Hopfield, a colleague of Feynman's at Caltech until the Nobel Prize–winning physicist's death in 1988. What he found when he theoretically probed those limits was a realm of possibilities that look startlingly familiar to today's researchers—so much so that his talk serves as a catalogue of the themes sounded in this special section. Among his playful suggestions, which 30 years later are fast being realized: etching lines a few atoms wide with beams of electrons, building circuits on the scale of angstroms to make new kinds of computers, manipulating atoms to control the very properties of matter. And like many of the nanotechnologists of today, Feynman credited his inspiration to the molecular-scale machines and information systems of living things.

But the fact that many of Feynman's ideas have now become reality doesn't mean they caught on at the time. Paul Shlichta of Crystal Research in San Pedro, California, then a materials scientist at the Jet Propulsion Laboratory, heard the talk. "The general reaction was amusement. Most of the audience thought he was trying to be funny," he recalls. "It simply took everybody completely by surprise."

In retrospect, says Ralph Merkle of the Xerox Palo Alto Research Center, Feynman's talk "was so visionary that it didn't really connect with people until the technology caught up with it." That may be why many of today's researchers learned about the lecture only after they were already practicing exactly what Feynman had preached. Says Don Eigler of the IBM Almaden Research Center in San Jose, California, who manipulates atoms using the scanning tunneling microscope: "I didn't know about the talk until after I got into the atom-moving business."

But when he finally did see a transcript, Eigler recalls, "I felt the ghost of Feynman behind me while I was reading, saying, 'Look, I thought of these things 30 years ago.'" ■ Tim Appenzeller

A Special Section of SCIENCE

Engineering a Small World: From Atomic Manipulation to Microfabrication

For information about reprints of articles in this special section, see page 1414.

The following excerpts are reprinted with permission of Engineering and Science, *the Caltech alumni magazine, in which the text of the talk was originally published in February 1960.*

There's plenty of room at the bottom

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. The field is not quite the same as others in that it will not tell us much of fundamental physics (in the sense of, "What are the strange particles?"), but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications.

What I want to talk about is the problem of manipulating and controlling things on a small scale.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there's a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below.

How to write the *Encyclopaedia Britannica* on the head of a pin

One way might be this (though I am not sure it would work): We take light and, through an optical microscope running backwards, we focus it onto a very small photoelectric screen. Then electrons come away from the screen where the light is shining. These electrons are focused down in size by the electron microscope lenses to impinge directly upon the surface of the material. Will such a beam etch away the material if it is run long enough? I don't know. If it doesn't work for a metal surface, it must be possible to find some surface with which to coat the original pin so that, where the electrons bombard, a change is made which we could recognize later.

Getting even smaller

This fact—that enormous amounts of information can be carried in an exceedingly small space—is, of course, well known to the biologists, and resolves the mystery that existed before we understood all this clearly, of how it could be that, in the tiniest cell, all of the information for the organization of a complex creature such as ourselves can be stored...

The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not simply writing information; it is *doing something* about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things—all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small, which does what we want—that we can manufacture an object that maneuvers at that level!

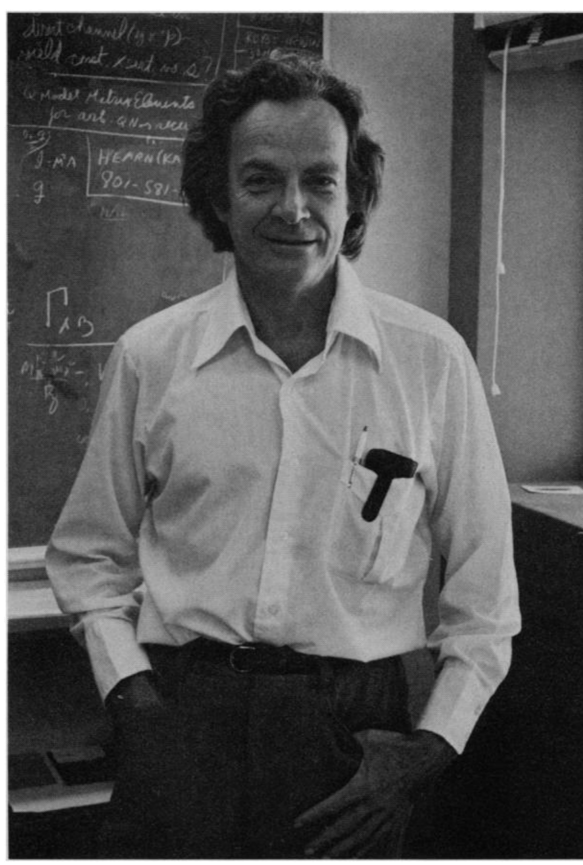
There may even be an economic point to this business of making things very small. Let me remind you of some of the problems of computing machines...

Miniaturizing the computer

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. 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 to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments...

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. In fact, there may be certain advantages.

How can we make such a device? What kind of manufacturing processes would we use? One possibility we might consider, since we have talked about writing by putting atoms down in a certain arrangement, would be to evaporate the material, then evaporate the insulator next to it. Then, for the next layer, evaporate another position of a wire, another insulator, and so. So, you simply evaporate until you have a block of stuff that has the elements—coils and condensers, transistors and so on—of exceedingly fine dimensions.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Richard Feynman in a 1974 photograph.

Rearranging atoms

But I am not afraid to consider the final question as to whether, ultimately—in the great future—we can arrange the atoms the way we want; the very *atoms*, all the way down! What would happen if we could arrange the atoms one by one the way we want them?

Up to now, we have been content to dig in the ground to find minerals. We heat them and we do things on a large scale with them, and we hope to get a pure substance with just so much impurity, and so on. But we must always accept some atomic arrangement that nature gives us. We haven't got anything, say, with a "checkerboard" arrangement, or with the impurity atoms arranged exactly 1000 angstroms apart.

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 that we can do.

Atoms in a small world

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. So as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc....

At the atomic level, we have new kinds of forces and new kinds of possibilities, new kinds of effects. The problems of manufacture and reproduction of materials will be quite different. I am, as I said, inspired by the biological phenomena in which chemical forces are used in a repetitious fashion to produce all kinds of weird effects (one of which is the author). ■