THE WONDERS THAT AWAIT A MICRO-MICROSCOPE

Including an Encyclopaedia Britannica on a Pinhead

By RICHARD P. FEYNMAN

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

As soon as I mention this, people tell me about miniaturization, and how far it has already progressed. They tell me about electric motors the size of the nail on my small finger. And there is a device on the market, they tell me, with which it is possible to write the Lord's Prayer on the head of a pin.

That device is the most primitive, halting step in the direction I intend to discuss. A staggeringly small world is below. In the year 2000, when people look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Why cannot we write the entire twenty-four volumes of the Encyclopaedia Britannica on the head of a pin?

Let's see what would be involved. The head of a pin is one-sixteenth of an inch across. If we magnify its diameter by 25,000 times, the area of the head of the pin is then equal to the area of all the pages of the Encyclopaedia Britannica. Therefore, all it is necessary to do is to reduce in size all the writing in the Encyclopaedia by 25,000 times. Is that possible?

The eye can distinguish images as small as about 1/120 of an inch, roughly the diameter of one of the little dots on the fine half-tone illustrations in the Encyclopaedia. This, demagnified by 25,000 times, is eighty angstroms (an angstrom is four-billionths of an inch, about half an atom, wide) in diameter—in an ordinary metal, thirty-two atoms across. In other words, one of those dots would contain within its surface between 800 and 1,000 atoms, depending on whether the dot were circular or square. So there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica.

Let's imagine it is written in raised letters of metal; that is, where the black is in the Encyclopaedia, we have raised letters that are 1/25,000 of their present size. How would we read it?

When it actually is written, they undoubtedly will find a better way than I am about to propose. But to make my point conservatively, I shall just take techniques we know today. We could press the metal of the pinhead into a plastic material and make a mold of it, then peel the plastic off very carefully, evaporate a thin film of silica onto the plastic and then evaporate a thin film of gold at an angle against the silica so that all the little letters will appear clearly, and finally dissolve the plastic away from the silica film in order to look through the film with an electron microscope!

In the electron microscope, great magnification is achieved by sending electrons instead of light through the lenses. The wave length of the electrons is so much smaller than that of visible light that we can see much smaller things.

There is no question that today's electron microscopes would make it easy for us to read a pinhead etched with letters 1/25,000 as big as the type now used in the Encyclopaedia.

The next question is: How do we *write* letters that tiny?

We have no standard technique to do this now. But let me argue that it is not as difficult as it first appears to be. We can reverse the lenses of the electron microscope in order to demagnify rather to magnify. Instead of electrons, we can send a beam of ions through the reversed lenses like a stream of metallic ink that draws finer lines the further it goes. The lines could be written as the lines of light and dark are written now on a TV screen.

Or we could first make, perhaps by some photo process, a screen with holes in it shaped like the letters of the alphabet. Then we would pour ions through these holes and let them deposit themselves on the pinhead.

A simpler way might be this (though I am not sure it would work): We run an optical microscope backwards, focusing the light onto a very small photoelectric screen. Electrons come away from the screen where the light is shining. The electrons are focused down in size by the reversed lenses of the electron microscope to impinge directly on the surface of the pinhead.

If such a beam of electrons is held in place long enough, will it etch away the metal of the pin?I don't know. If a metal surface can't be etched that way, there must be some other material with which to coat the pin so that electrons could make a change we would recognize later.

So much for the Encyclopaedia Britannica on the head of a pin. Now let's consider all the books in the world. The Library of Congress has approximately nine million volumes; the British Museum has five million volumes; there are also five million volumes in the National Library in France. There are many other collections, but duplications occur among them, so let us say there are some twenty-four million books of interest in the world.

IF I were to reduce all of these down to the scale we have been discussing, how much space would they occupy? With twenty-four volumes on one pinhead, we would need a million pinheads, and these can be put in a square of a thousand pins on a side, about three square yards altogether, approximately the area of thirty-five pages of the Encyclopaedia. That is to say, all the information in all the books of interest in the world could be carried around in a pamphlet in your hand—not in code, but as a simple reproduction of the original pictures, engravings, and printed text.

Suppose now, that instead of trying to reproduce the pictures and all the information directly in its present form, we write only the information content of all the world's books in a code of dots and dashes, or something like that, to represent the various letters. There are six or seven "bits" of information in each letter. That is, we need only about six or seven dots or dashes for each letter. Now, instead of writing everything, as I did before, on the *surface* of the head of a pin, I am going to use the interior of the pinhead as well.

Let us represent a dot by a small spot of one metal, a dash by an adjacent spot of another metal, and so on. Suppose, to be conservative, that a bit of information is going to require a little cube of atoms 5 x 5 x 5—that is, 125 atoms. If we round this off to 100 atoms for the sake of convenience in calculation, we can estimate how much information we can get *inside* the pinhead by first calculating how many letters there are in the Encyclopaedia and then assuming that each of the twenty-four million books of interest in the world is as big as a volume of the Encyclopaedia. I have figured this out (the total is 1,000,000,000,000,000 bits), and all these twenty-four million books can be written in code inside a cube of material 1/200th of an inch wide—which is the size of the barest piece of dust that can be distinguished by the human eye.

THIS fact—that enormous amounts of information can be carried in an exceedingly small space—is of course well known to biologists. It explains how it could be that, in the tiniest living cell, all of the information for the organization of a complex creature like yourself can be stored. All this information—that the eyes are to be brown, that the hair is to be curly, that there is to be an ability to think, that in the embryo the jawbone should first develop with a little hole in the side so that later a nerve can grow through it, and thousands of other such instructions—is contained in a very tiny fraction of the cell, in long-chain DNA molecules where one bit of data is crammed inside fifty atoms (inside our pinhead, we have room to give one bit two and a half times that much space).

If I were to write in a code, with 5 x 5 x 5 atoms to a bit, could I read it today? For the first time in this speculation of mine, the answer must be "no." The eye of the electron microscope is not quite keen enough. With the greatest care and effort, the smallest image it can make out is ten angstroms in size. We need to sharpen the seeing of the electron microscope by a hundred times. This 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 long. So it should be possible to see individual atoms.

What good would it be to see individual atoms distinctly?

What are the most central and fundamental problems of biology today? There are questions like: What happens when you have a mutation? How are proteins synthesized? In photosynthesis, where is the chlorophyll; how is it arranged? What is the relation of the structure of a gene to that of the enzyme it controls?

It would be very easy to answer many such questions if we could see the individual atoms involved.

Make the microscope a hundred times more powerful than it is today, and the atoms will become visible to us.

The practical limitation on the electron microscope's power at present is that the *f*-number of the lenses is only 0.001; we don't have a big enough aperture. I know there are theorems which prove that it is impossible, with axially symmetrical lenses in which the electrical and magnetic fields that focus the electrons are stationary, to produce a bigger *f*-number. Therefore the resolving power at the present time is at its theoretical maximum. But in every theorem there are assumptions. Why must the field be axially symmetrical? Why must the field be stationary? Can't we have pulsed electron beams in electrical and magnetic fields that move up along with the electrons just as the lenses in an optical microscope move with the light? Is there really no way to make the electron microscope more powerful? Or have we simply failed to use our imaginations enough?

The biological example of writing information on a small scale has inspired me to think of something else that should be possible. Biology is not simply writing information; it is *doing something* about it. In a biological system, many of the cells 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.

LET me remind you of some of the problems of computing machines. In computers we have to store an enormous amount of information. Computing machines are therefore very large; they fill rooms. But they cannot do some of the things that I can do in the bonebox of my head.

If I look at your face I immediately recognize that I have seen it before. There is no machine which, with that speed, can take a picture of a face and say that it is a picture of a man, much less that the man is the same man the machine saw before—unless the picture is exactly the same picture as before.

Everybody who has analyzed the logical theory of computers has come to the conclusion that if computers had millions of times as many computing elements as they now do, they could make such judgments. But with the present size of components, these computers would fill millions of rooms, cost impossible sums of money, and be too big to work anyhow.

Why can't we make smaller computers—and by small, I mean *small*? For instance, the wires should be ten or 100 atoms in diameter, and the circuits should be a few thousand angstroms across.

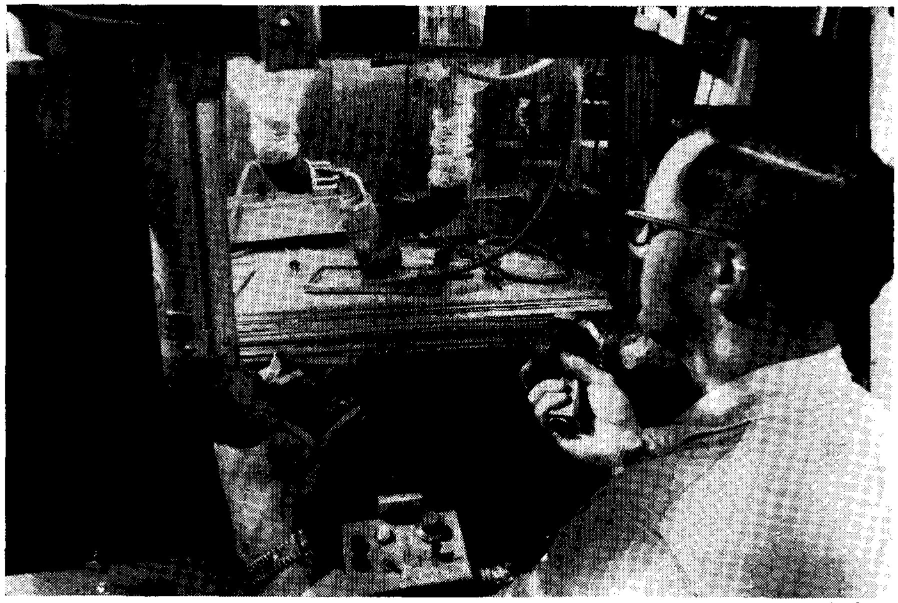
How can we make devices as small as that? What kind of manufacturing process would we use? One possibility we might consider, since we have talked about writing by putting atoms down in a certain arrangement, would be to evaporate metals or other materials in successive layers until we have a block of exceedingly fine dimensions.

JUST for amusement, I would like to discuss other possibilities. Why can't we manufacture these small computers somewhat like we manufacture the big ones? Why can't we drill holes, cut things, solder things, stamp things out, mold different shapes, all at an infinitesimal level? What are the limitations as to how small a thing has to be before we can no longer mold it? What are the possibilities of small but movable machines?

Consider, for example, an automobile. Ask about the problems of making an infinitesimal machine like it. Suppose, in the particular design of the automobile, we need a certain precision of the parts; we need an accuracy, let's suppose, of 4/10,000 of an inch. If we stay within ten atoms of error, we can reduce the dimensions of an automobile approximately 4,000 times—so that it is one millimeter across. Obviously, if we redesign the car so that it would work with a much larger tolerance, which is not at all impossible, then we could make an even smaller automobile.

In such small machines, the strength of materials is very much greater in proportion. On the other hand, the grain structure of metals would be very annoying at small scale because the material is not homogenous. Plastics and glass and things of an amorphous nature are very much more homogenous, and so we would have to make our machines out of such materials. There are problems associated with the electrical parts of the system. Magnetic properties on a very small scale are not the same as on a large scale. 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. But I can see no reason why it can't be redesigned to work again.

Lubrication might not be necessary. Bearings could run dry; they wouldn't run hot because heat escapes from such a small device very, very rapidly.



—*Union Carbide.*

In action above are "slave" hands that inspired Professor Feynman's imagination.

This rapid heat loss would prevent gasoline from exploding, however; so an internal combustion engine of that size is impossible. Other chemical reactions, liberating energy when cold, can be used instead.

What would be the utility of such machines? Who knows?

A friend of mine, Albert R. Hibbs, suggests a very interesting possibility. He says that, although it is a very wild idea, it would be interesting in surgery if we could swallow a surgeon. Inside the blood vessels this mechanical practitioner would go and from there into the heart to "look" around. (Of course the information has to be sent out.) The miniature surgeon finds out which heart valve is the faulty one and takes a little knife and slices that valve out. Other small machines might be permanently incorporated in the body to assist some inadequately functioning organ.

How do we make such a tiny mechanism? I leave that to you. However, let me suggest one weird possibility. In atomic energy plants there are materials and machines which can't be handled directly because of radioactivity. To unscrew nuts and put on bolts and so on, a set of master and slave hands is operated by a set of levers. Most of these devices are made rather simply in that they have a particular cable, like a marionette string, running directly from the controls to the hands. Others use servo motors, so that the connections are electrical rather than mechanical. When the levers are turned, they turn a servo motor, and it changes the electrical currents in the wires, which repositions a motor at the other end and this motor in turn moves the hands.

Now, I want to build much the same device, a master-slave system which operates electrically. But I want the slaves to be one-fourth the scale of the ordinary hand. Aha! So I use the quarter-size hands to manufacture a quarter-size lathe; I manufacture quarter-size tools; and I make, at the one-quarter scale, still another set of hands again relatively one-quarter size. I am now down to one-sixteenth size. You get the principle from there on. It is rather a difficult program, but it is a possibility.

As we go down in size, a number of interesting problems arise. All things do not simply scale down in proportion. Materials stick together by molecular attraction. It would be like this: after we have made a part and have unscrewed the nut from a bolt, the nut isn't going to fall down because the pull of gravity isn't appreciable; it would even be hard to get the nut off the bolt. It would be like those old movies of a man with his hands full of molasses, trying to get rid of a glass of water.

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, with the impure atoms exactly arranged 1,000 angstroms apart, or in some other particular pattern.

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.

WHEN we get down to the very, very small world—where, say, electrical circuits have only seven atoms—we encounter 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.

The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. To try to do this is not to attempt to violate any laws; in principle it is something that can be done; but, in practice, it has not been done because we are too big.

Ultimately, we can do chemical synthesis. A chemist comes to us and says, "Look, I want a molecule that has the atoms arranged thus and so; make me that molecule." The physicist synthesizes the molecule. How? By putting the atoms down where the chemist says. The problems of chemistry and biology can be brought much closer to solution if we develop the ability first to see what we are doing and then to do things on the atomic level—an eventuality which I think cannot be avoided.

In order to get kids interested in this, I propose that someone who has contact with the high schools think of starting a kind of high school competition. A school in Los Angeles could send a pin to a school in New York. On the head of the pin it says, "How's this?" Los Angeles gets the pin back, and in the dot of the "i" in the word "this" it says, "Not so hot."

Richard P. Feynman, professor of physics at California Institute of Technology, first advanced these provocative speculations in an after-dinner speech before the American Physical Society last December. The only record was a tape recording, which Caltech's journal, Engineering and Science, *has reproduced at greater length and in somewhat different phraseology.*

PERSONALITY PORTRAIT—XLIX

COMET BEHIND THE KITCHEN; STARS IN THE DINING ROOM

The History of Science Passes Through the House of Dr. C. Doris Hellman, Wife, Mother, Scholar

BETWEEN the dining room and the kitchen of Dr. C. Doris Hellman's apartment on the upper East Side of Manhattan runs a hard worn path that is common to every busy household. It is the road tramped by the woman of the house, bent on feeding her family. But the route at the Hellman place has an unaccustomed turning, with a fork that many of the guests who come to dinner never see. It leads around the kitchen into a small dim-lit grey room with a solitary window, a wash basin in the corner under the window, a battered desk with a low, flat top faced by a swivel chair in the corner opposite, three walls lined from top to bottom with shelves of books ordered in meticulous ranks according to size, and neat arrays of manila folders in cardboard cartons piled two deep at four points on the floor. "This used to be the maid's room when the children were little," she said as we stood in the midst of it. "Now that they've grown, I've made it into an office."

Her straight grey hair, cropped just below the ears, lent a quietly competent professional tone to the word "office." Pride was plain in her voice. It left me unready for her next words. "How the time has flown!" They came out like a sigh. Her big brown eyes were glowing. In them I could almost see her children, Alice and Carol, smiling back at her. "I miss them terribly," she said, and for the next few moments I could think of her only as a mother. I forgot completely that this hidden little room had become an office because this warm and vital woman had undertaken to lead a unique attempt to bring science back into society by way of the bridge of the history of science.

Many of the volumes on the shelves around us were science history classics. They were more than collector's items. They were source material for Dr. Hellman's researches. The cardboard boxes on the floor were filled with copies of documents pertinent to the life of Johannes Kepler (the great seventeenth century mathematician whose biography she recently translated from German into English) and with chronological notes of scores of historical observations that may in time become a book on the explosive "new star" of 1572.

"I like to spread my papers out on the top of the desk," she said, as though no other thought had interrupted our inspection of the office. "When the desk gets too small, I carry them into the dining room and spread them out on the table."

It was at this table, polished mirror-bright and glinting now with sun reflected by the silver candlesticks, that Dr. Hellman's lawyer-husband, Morton Pepper, at her instigation two years ago this month of April drew up letters of incorporation for the George Sarton Memorial Foundation.

The late George Sarton undoubtedly was the greatest historian of science of modern times. He spent his life in one long literary construction project to link science and the humanities. Before he died in 1956 he converted many disciples to his belief that this bridge is "the main cultural need" of the contemporary world. Two of the believers live under the Hellman roof. One is lawyer Pepper, who studied history at Harvard (where Sarton taught) and subsequently practiced in his own home Sarton's dictum that everyone who is not a scientist should have some interest in science just as every scientist should be an intelligently active citizen. The other believer is, of course, Mr. Pepper's wife, who was one of Sarton's proteges.

To say that Doris Hellman studied under Sarton would miss the point. She had a desk in his office at Harvard's Widener Library in 1930-31, and directly felt the pull of his demanding mind. He taught her to be precise, to read every available reference and footnote, to track down original documents, to learn foreign languages in order to use them in translation, and above all to be infinitely patient. He showed her how curiosity about one seemingly small point can illuminate a whole era of time, and, indeed, she spent twelve years in the pursuit of the answer to one of his questions: "Why are there so many more references to the comet of 1577 than to any other comet of that century?"

That comet, she ultimately discovered (and reported in a book, "The Comet of 1577") was one of the turning points in human thought. It helped to persuade reflective men that the heavens were not immutable—as had been supposed for 2,000 years—and that the Earth moved about the Sun instead of being itself the center of the Sun's life-giving ministrations.

For all his brilliance as a scholar, it was as a man that Sarton made the deepest impressions. Doris Hellman first went to see him while she was a Vassar senior. Already his name was a household word, especially in the household of her father, a gynecologist, Dr. Alfred Hellman, who had built up an impressive private library of books on the history of medicine. Given such a background, her teachers at Horace Mann High School (at that time coeducational) were not surprised to find her interested in mathematics, and they added their encouragement to her parents' gifts of first editions of Euclid in English and Italian. At Vassar, Doris branched out from mathematics into astronomy, and in one of her courses wrote such a pithy paper on the eighteenth century pendulum clock maker, George Graham, that it was quoted extensively in *Nature*.

IN HER last year at Vassar, Doris knew she wanted to go on into graduate study of the history of science. But where and how? Science was not yet a recognized specialty in the field of history. No path had been laid toward her objective. So she went to Sarton to ask his advice. "Girls didn't make trips to Cambridge in those days without their mothers," she recalls. Her mother was even more astonished than the daughter was when the famous man interceded for Doris at Radcliffe. On the strength of his endorsement, she was allowed to try for the first M.A. degree there in the history of science.

Long before then, Sarton had started the journal *Isis*. Now he opened its pages to his determined apprentice, who wrote several articles on Thomas Jefferson's introduction of science into the governmental machinery of the Thirteen Colonies, and on the unpublished diary of Edward Jenner, discoverer of smallpox vaccine. Even more