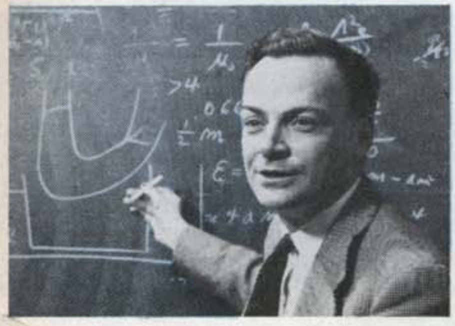
There's plenty of room at the bottom, says noted scientist as he reveals—

How to Build an Automobile



At 42, Richard Phillips Feynman, Ph.D., enjoys world renown as a theoretical physicist, local fame as a "marvelous" performer on the bongo drums, and campus admiration as a man with a pixyish humor that turns a lecture on quantum electrodynamics into a ball. You'll see why when you read his impassioned and witty plea to think small.

This tall, slim, dark-haired scholar helped importantly in developing the atomic bomb and watched its first test explosion. In 1954 he won the $15,000 Albert Einstein Award, one of the nation's highest scientific honors.

He is capable both of exuberant fellowship and of rather stern withdrawal, especially when pondering intricate problems. Even his heavy thinking has a light touch, however. In deepest thought, while pacing the floor, he slowly flips a silver dollar back and forth across the fingers of his right hand by carefully controlled movements of the knuckles. It's no easy trick even when you have nothing else to think about.

Born in New York City in 1918, he graduated from MIT in 1939 and got his Ph.D. at Princeton in 1942. He was a member of the Laboratory of Nuclear Studies at Cornell from 1945 to 1950. In 1950, he began his present job as professor of theoretical physics at Caltech.

Dr. Feynman loves music, children, camping in the wilds, and unpremeditated jaunts to faraway places. He boned up on Portuguese to become a visiting lecturer for two seasons in Brazil, and learned Spanish under forced draft to go to Peru and poke around Inca ruins.

The accompanying article is condensed from a speech (addressed to an American Physical Society meeting, not the Pasadena Rotary luncheon). The full transcript appeared in "Engineering and Science Magazine," published at the California Institute of Technology.

Exploring the fantastic possibilities of the very small should pay off handsomely—and provide a lot of fun, too

By Richard P. Feynman

Professor of Theoretical Physics, California Institute of Technology

PEOPLE tell me about miniaturization, about electric motors the size of the nail on your small finger. There is a device on the market 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.

Why not write the entire 24 volumes of the "Encyclopaedia Britannica" on the head of a pin?

Let's see what would be involved. The head of a pin is a sixteenth of an inch across. If you magnify it 25,000 diameters, the area of the head of the pin is equal to the area of all pages of the encyclopedia. All it is necessary to do is to reduce the writing in the encyclopedia 25,000 times. Is that possible? One of the little dots on the fine halftone reproductions in the encyclopedia, when you demagnify it by 25,000 times, still would contain in its area 1,000 atoms. So, each dot can easily be adjusted in size as required, and there is no question that there is enough room on the head of a pin to put all of the "Encyclopaedia Britannica."

IMAGINE that it is written in raised letters of metal that are 1/25,000 ordinary size. How would we read it?

We would press the metal into plastic and make a mold; peel the plastic off very carefully; evaporate silica into the plastic to get a very thin film; then shadow it by evaporating gold at an angle against the silica so that all the little letters appear clearly; dissolve the plastic away from the silica film; and then look through it with an electron microscope.

Smaller Than This Dot ▶ ·

How do we write it? Reverse the lenses of the electron microscope to demagnify. Ions, sent through the lenses in reverse, could be focused to a very small spot. We could write with that spot as we write in TV, by going across in lines, and having an adjustment that determines the amount of material that is deposited.

Don't tell me about microfilm!

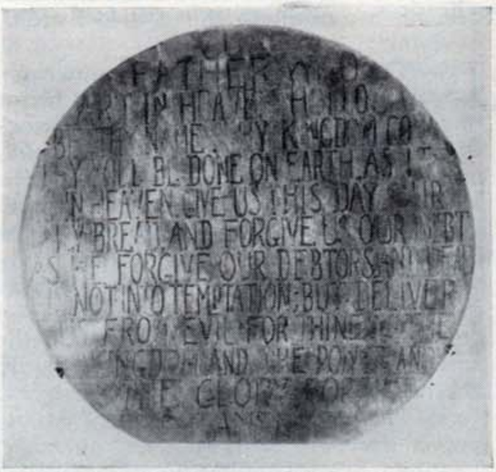
THERE is *plenty* of room at the bottom—not just room at the bottom. I want to show what is possible according to the laws of physics. I am not inventing antigravity, which is possible only if the laws are not what we think. I am telling you what could be done if the laws *are* what we think; we are not doing it simply because we haven't yet gotten around to it.

How many times when you are working on something frustratingly tiny, like your wife's wrist watch, have you said, "If I could only train an ant to do this!" I suggest training an ant to train a mite to do this. What are the possibilities of small but movable machines? They may or may not be useful, but they surely would be fun to make.

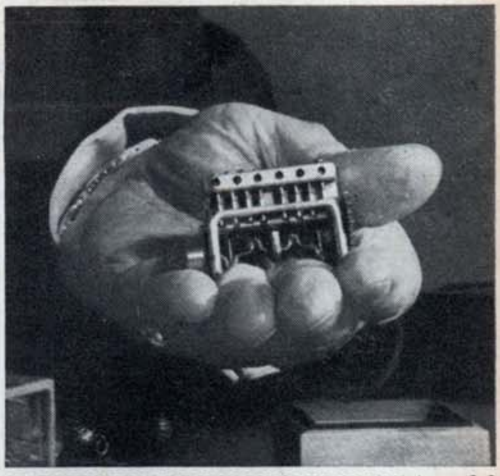
CONSIDER an automobile. Suppose we need an accuracy of 4/10,000 of an inch. If things are more inaccurate than that in the shape of the cylinder and so on, it isn't going to work very well. If I make the thing too small, I have to worry about the size of the atoms; I can't make a circle out of "balls" if the circle is too small.

So, let's say I make the error, corresponding to 4/10,000 of an inch, correspond to an error of 10 atoms. I can reduce the dimensions of an automobile 4,000 times, approximately—so that it is 1/25 inch across.

In such small machines the forces go as the area you are reducing, so that weight and inertia are of relatively no importance. The strength of material is very much greater in proportion. The stresses and expansion of the flywheel from centrifugal force, for example,



THIS IS TOO EASY, says Professor Feynman of Lord's Prayer written on pinhead (above). He shows how 24-volume encyclopedia could be reproduced—in letters and pictures—on pinhead with standard tools and techniques. If coding system were used, every book ever written could be copied into a barely visible speck of dust.



IS THIS THE SMALLEST ENGINE YET BUILT? A model of a Ford four-cylinder, it is one of 33,000 miniatures in collection of San Francisco art expert Jules Charbneau. It is an exact copy with moving parts—but a long way from Professor Feynman's proposal for a complete, operating automobile measuring 1/25 inch.

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would be the same proportion only if the rotational speed is increased as we decrease the size. On the other hand, metals have a grain structure and this would be very annoying at small scale. Plastics and glass are very much more homogeneous, and so we would have to make our machines out of such materials.

THERE are problems associated with the electrical system—copper wires and magnetic parts. The magnetic properties on a very small scale are not the same as on a large scale. The electrical equipment won't simply be scaled down. It has to be redesigned to work again.

Lubrication involves some interesting points. The viscosity of oil would be higher and higher as we went down. If we change from oil to kerosene or some other fluid, the problem is not so bad.

But 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.

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

SMALLEST MACHINES made commercially are pivot bearings—two fit on pinhead—for jet fuel meters, product of Miniature Precision Bearings.

What would be the utility of such machines? Who knows? A small automobile would only be useful for the mites to drive around in, and I suppose our Christian interests don't go that far. However, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and "looks" around. It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be incorporated in the body to assist some inadequately functioning organ.

HOW do we make such a tiny mechanism? In atomic-energy plants they have materials they can't handle directly because they have become radioactive. To unscrew nuts and put on bolts, they have a set of master and slave hands. By operating a set of levers here, you control the "hands" there, and can turn them this way and that so you can handle things quite nicely.

Most of these devices are made rather simply. A cable, like a marionnette string, goes directly from the controls to the "hands." But things also have been made using servo motors, so that the connection is electrical rather than mechanical. When you turn the levers, they turn a servo motor, and reposition a motor at the other end.

I want slaves to be made one-fourth the scale of the "hands" that you ordinarily maneuver. So you can do things at one-quarter scale—the little servo motors with little hands play with little nuts and bolts; they drill little holes; they are four times smaller. Aha!

I 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! This is $\frac{1}{16}$ size, from my point of view. And after I finish doing this I wire directly from my large-scale system to the $\frac{1}{16}$ servo motors. Thus I can now manipulate the $\frac{1}{16}$-size hands.

IF YOU work through a pantograph, you can get much more than a factor of four in one step. But you can't work directly through a pantograph that makes a smaller pantograph—because of the looseness of the holes and the irregularities of construction. The end of the pantograph wiggles with a relatively greater irregularity than the irregularity with which you move your hands. In going down this scale, I would find the end of the pantograph shaking so badly it wouldn't be doing anything sensible.

At each stage, it is necessary to improve the precision of the apparatus. Having made a small lathe with a pantograph, we may find its lead screw irregular—more irregular than the large-scale one. We could lap the lead screw against breakable nuts that you reverse in the

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usual way, until this lead screw was, at its scale, as accurate as our original lead screws, at our scale.

We can make flats by rubbing unflat surfaces together in three pairs—and the flats then become flatter than the thing you started with. So we improve the equipment by working awhile down there, making accurate lead screws, Johansson blocks, and all the other materials that we use in accurate machine work at the higher level.

WHEN I make my first set of slave "hands" at one-fourth scale, I am going to make 10 sets. I wire them to my original levers so they each do exactly the same thing at the same time in parallel. Now, when I am making my new devices one-quarter again as small, I let each one manufacture 10 copies, so that I have 100 "hands" at the $\frac{1}{16}$ size.

Where am I going to put the million lathes that I am going to have? There is nothing to it; the volume is much less than that of even one full-scale lathe. If I made a billion little lathes, each 1/4,000 the scale of a regular lathe, there would be plenty of materials and space available. In the billion little ones there is less than two percent of the materials in one big lathe.

There is the problem that materials stick together by the molecular attractions. After you unscrew the nut from a bolt, it isn't going to fall down, because the gravity isn't appreciable; it would even be hard to get it 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 ultimately we can arrange atoms, the very *atoms,* all the way down!

Up to now, we have dug in the ground to find minerals. We heat them and we hope to get a substance with just so much impurity. But we must always accept some atomic arrangement that nature gives us. We haven't got anything, say, with a "checkerboard" arrangement.

WHEN we have some control of arrangement we will get an enormously greater range of properties that substances can have, and of things that we can do.

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How to Build an Auto Smaller Than a Dot

Consider, little coils and condensers (1/30,000 inch or smaller), one right next to the other, over a large area, with little antennas sticking out.

Is it possible to get a whole set of antennas to emit light as an organized set of antennas emits radio waves to beam the radio programs to Europe?

If we go down far enough, all our devices can be mass-produced so that they are absolutely perfect copies of one another. We cannot build two large machines exactly the same. But if your machine is only 100 atoms high, you only have to get it correct to one-half of one percent to make sure the other machine is exactly the same size—100 atoms high!

We can do chemical synthesis: A chemist says, "Look, I want a molecule that has the atoms arranged thus and so; make me that molecule." He mixes this and that, and he shakes it, and he fiddles around. And, at the end of a difficult process, he usually does succeed in synthesizing what he wants. By the time I get my devices working, so that we can do it by physics, he will have figured out how to synthesize absolutely anything, so that my devices will really be useless.

But it would be possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Put the atoms down where the chemist says, and so you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things, on an atomic level, is developed.

You might ask, "Who should do this, and why should they do it?" I pointed out a few of the economic applications, but I know that the reason that you would do it might be just for fun.

Let's have a competition between laboratories. Let one laboratory make a tiny motor and send it to another lab which sends it back with a thing that fits inside the shaft of the first motor.

To get kids interested, I propose some kind of high-school competition. Even the kids can write smaller than has ever been written before. The Los Angeles high school could send to the Venice high school a pin which says on it, "How's this?"

When they get the pin back, in the dot of the "i" it says, "Not so hot."