There's Plenty of Room at the Bottom

An Invitation to Enter a New Field of Physics

*by Richard P. Feynman*

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For an account of the talk and how people reacted to it, see chapter4 of *Nano!* by Ed Regis, Little/Brown 1995. An excellent technicalintroduction to nanotechnology is*Nanosystems:molecular machinery, manufacturing, and computation* by K. EricDrexler, Wiley 1992.

I imagine experimental physicists must often look with envy at menlike Kamerlingh Onnes, who discovered a field like low temperature, whichseems to be bottomless and in which one can go down and down. Such a manis then a leader and has some temporary monopoly in a scientific adventure.Percy Bridgman, in designing a way to obtain higher pressures, opened upanother new field and was able to move into it and to lead us all along.The development of ever higher vacuum was a continuing development of thesame kind.

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

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

As soon as I mention this, people tell me about miniaturization, andhow far it has progressed today. They tell me about electric motors thatare the size of the nail on your small finger. And there is a device onthe market, they tell me, by which you can write the Lord's Prayer on thehead of a pin. But that's nothing; that's the most primitive, halting stepin the direction I intend to discuss. It is a staggeringly small worldthat is below. In the year 2000, when they look back at this age, theywill wonder why it was not until the year 1960 that anybody began seriouslyto move in this direction.

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanicaon the head of a pin?

Let's see what would be involved. The head of a pin is a sixteenth ofan inch across. If you magnify it by 25,000 diameters, the area of thehead of the pin is then equal to the area of all the pages of the EncyclopaediaBrittanica. Therefore, all it is necessary to do is to reduce in size allthe writing in the Encyclopaedia by 25,000 times. Is that possible? Theresolving power of the eye is about 1/120 of an inch---that is roughlythe diameter of one of the little dots on the fine half-tone reproductionsin the Encyclopaedia. This, when you demagnify it by 25,000 times, is still80 angstroms in diameter---32 atoms across, in an ordinary metal. In otherwords, one of those dots still would contain in its area 1,000 atoms. So,each dot can easily be adjusted in size as required by the photoengraving,and there is no question that there is enough room on the head of a pinto put all of the Encyclopaedia Brittanica.

Furthermore, it can be read if it is so written. Let's imagine thatit is written in raised letters of metal; that is, where the black is inthe Encyclopedia, we have raised letters of metal that are actually 1/25,000of their ordinary size. How would we read it?

If we had something written in such a way, we could read it using techniquesin common use today. (They will undoubtedly find a better way when we doactually have it written, but to make my point conservatively I shall justtake techniques we know today.) We would press the metal into a plasticmaterial and make a mold of it, then peel the plastic off very carefully,evaporate silica into the plastic to get a very thin film, then shadowit by evaporating gold at an angle against the silica so that all the littleletters will appear clearly, dissolve the plastic away from the silicafilm, and then look through it with an electron microscope!

There is no question that if the thing were reduced by 25,000 timesin the form of raised letters on the pin, it would be easy for us to readit today. Furthermore; there is no question that we would find it easyto make copies of the master; we would just need to press the same metalplate again into plastic and we would have another copy.

How do we write small?

The next question is: How do we *write* it? We have no standard techniqueto do this now. But let me argue that it is not as difficult as it firstappears to be. We can reverse the lenses of the electron microscope inorder to demagnify as well as magnify. A source of ions, sent through themicroscope lenses in reverse, could be focused to a very small spot. Wecould write with that spot like we write in a TV cathode ray oscilloscope,by going across in lines, and having an adjustment which determines theamount of material which is going to be deposited as we scan in lines.

This method might be very slow because of space charge limitations.There will be more rapid methods. We could first make, perhaps by somephoto process, a screen which has holes in it in the form of the letters.Then we would strike an arc behind the holes and draw metallic ions throughthe holes; then we could again use our system of lenses and make a smallimage in the form of ions, which would deposit the metal on the pin.

A simpler way might be this (though I am not sure it would work): Wetake light and, through an optical microscope running backwards, we focusit onto a very small photoelectric screen. Then electrons come away fromthe screen where the light is shining. These electrons are focused downin size by the electron microscope lenses to impinge directly upon thesurface of the metal. Will such a beam etch away the metal if it is runlong enough? I don't know. If it doesn't work for a metal surface, it mustbe possible to find some surface with which to coat the original pin sothat, where the electrons bombard, a change is made which we could recognizelater.

There is no intensity problem in these devices---not what you are usedto in magnification, where you have to take a few electrons and spreadthem over a bigger and bigger screen; it is just the opposite. The lightwhich we get from a page is concentrated onto a very small area so it isvery intense. The few electrons which come from the photoelectric screenare demagnified down to a very tiny area so that, again, they are veryintense. I don't know why this hasn't been done yet!

That's the Encyclopaedia Brittanica on the head of a pin, but let'sconsider all the books in the world. The Library of Congress has approximately9 million volumes; the British Museum Library has 5 million volumes; thereare also 5 million volumes in the National Library in France. Undoubtedlythere are duplications, so let us say that there are some 24 million volumesof interest in the world.

What would happen if I print all this down at the scale we have beendiscussing? How much space would it take? It would take, of course, thearea of about a million pinheads because, instead of there being just the24 volumes of the Encyclopaedia, there are 24 million volumes. The millionpinheads can be put in a square of a thousand pins on a side, or an areaof about 3 square yards. That is to say, the silica replica with the paper-thinbacking of plastic, with which we have made the copies, with all this information,is on an area of approximately the size of 35 pages of the Encyclopaedia.That is about half as many pages as there are in this magazine. All ofthe information which all of mankind has every recorded in books can becarried around in a pamphlet in your hand---and not written in code, buta simple reproduction of the original pictures, engravings, and everythingelse on a small scale without loss of resolution.

What would our librarian at Caltech say, as she runs all over from onebuilding to another, if I tell her that, ten years from now, all of theinformation that she is struggling to keep track of--- 120,000 volumes,stacked from the floor to the ceiling, drawers full of cards, storage roomsfull of the older books---can be kept on just one library card! When theUniversity of Brazil, for example, finds that their library is burned,we can send them a copy of every book in our library by striking off acopy from the master plate in a few hours and mailing it in an envelopeno bigger or heavier than any other ordinary air mail letter.

Now, the name of this talk is ``There is *Plenty* of Room at theBottom''---not just ``There is Room at the Bottom.'' What I have demonstratedis that there *is* room---that you can decrease the size of thingsin a practical way. I now want to show that there is *plenty* of room.I will not now discuss how we are going to do it, but only what is possiblein principle---in other words, what is possible according to the laws ofphysics. I am not inventing anti-gravity, which is possible someday onlyif the laws are not what we think. I am telling you what could be doneif the laws *are* what we think; we are not doing it simply becausewe haven't yet gotten around to it.

Information on a small scale

Suppose that, instead of trying to reproduce the pictures and all the informationdirectly in its present form, we write only the information content ina code of dots and dashes, or something like that, to represent the variousletters. Each letter represents six or seven ``bits'' of information; thatis, you need only about six or seven dots or dashes for each letter. Now,instead of writing everything, as I did before, on the *surface* ofthe head of a pin, I am going to use the interior of the material as well.

Let us represent a dot by a small spot of one metal, the next 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 5times 5 times 5---that is 125 atoms. Perhaps we need a hundred and someodd atoms to make sure that the information is not lost through diffusion,or through some other process.

I have estimated how many letters there are in the Encyclopaedia, andI have assumed that each of my 24 million books is as big as an Encyclopaediavolume, and have calculated, then, how many bits of information there are(10^15). For each bit I allow 100 atoms. And it turns out that all of theinformation that man has carefully accumulated in all the books in theworld can be written in this form in a cube of material one two-hundredthof an inch wide--- which is the barest piece of dust that can be made outby the human eye. So there is *plenty* of room at the bottom! Don'ttell me about microfilm!

This fact---that enormous amounts of information can be carried in anexceedingly small space---is, of course, well known to the biologists,and resolves the mystery which existed before we understood all this clearly,of how it could be that, in the tiniest cell, all of the information forthe organization of a complex creature such as ourselves can be stored.All this information---whether we have brown eyes, or whether we thinkat all, or that in the embryo the jawbone should first develop with a littlehole in the side so that later a nerve can grow through it---all this informationis contained in a very tiny fraction of the cell in the form of long-chainDNA molecules in which approximately 50 atoms are used for one bit of informationabout the cell.

Better electron microscopes

If I have written in a code, with 5 times 5 times 5 atoms to a bit, thequestion is: How could I read it today? The electron microscope is notquite good enough, with the greatest care and effort, it can only resolveabout 10 angstroms. I would like to try and impress upon you while I amtalking about all of these things on a small scale, the importance of improvingthe electron microscope by a hundred times. It is not impossible; it isnot against the laws of diffraction of the electron. The wave length ofthe electron in such a microscope is only 1/20 of an angstrom. So it shouldbe possible to see the individual atoms. What good would it be to see individualatoms distinctly?

We have friends in other fields---in biology, for instance. We physicistsoften look at them and say, ``You know the reason you fellows are makingso little progress?'' (Actually I don't know any field where they are makingmore rapid progress than they are in biology today.) ``You should use moremathematics, like we do.'' They could answer us---but they're polite, soI'll answer for them: ``What *you* should do in order for *us*to make more rapid progress is to make the electron microscope 100 timesbetter.''

What are the most central and fundamental problems of biology today?They are questions like: What is the sequence of bases in the DNA? Whathappens when you have a mutation? How is the base order in the DNA connectedto the order of amino acids in the protein? What is the structure of theRNA; is it single-chain or double-chain, and how is it related in its orderof bases to the DNA? What is the organization of the microsomes? How areproteins synthesized? Where does the RNA go? How does it sit? Where dothe proteins sit? Where do the amino acids go in? In photosynthesis, whereis the chlorophyll; how is it arranged; where are the carotenoids involvedin this thing? What is the system of the conversion of light into chemicalenergy?

It is very easy to answer many of these fundamental biological questions;you just *look at the thing!* You will see the order of bases in thechain; you will see the structure of the microsome. Unfortunately, thepresent microscope sees at a scale which is just a bit too crude. Makethe microscope one hundred times more powerful, and many problems of biologywould be made very much easier. I exaggerate, of course, but the biologistswould surely be very thankful to you---and they would prefer that to thecriticism that they should use more mathematics.

The theory of chemical processes today is based on theoretical physics.In this sense, physics supplies the foundation of chemistry. But chemistryalso has analysis. If you have a strange substance and you want to knowwhat it is, you go through a long and complicated process of chemical analysis.You can analyze almost anything today, so I am a little late with my idea.But if the physicists wanted to, they could also dig under the chemistsin the problem of chemical analysis. It would be very easy to make an analysisof any complicated chemical substance; all one would have to do would beto look at it and see where the atoms are. The only trouble is that theelectron microscope is one hundred times too poor. (Later, I would liketo ask the question: Can the physicists do something about the third problemof chemistry---namely, synthesis? Is there a *physical* way to synthesizeany chemical substance?

The reason the electron microscope is so poor is that the f- value ofthe lenses is only 1 part to 1,000; you don't have a big enough numericalaperture. And I know that there are theorems which prove that it is impossible,with axially symmetrical stationary field lenses, to produce an f-valueany bigger than so and so; and therefore the resolving power at the presenttime is at its theoretical maximum. But in every theorem there are assumptions.Why must the field be symmetrical? I put this out as a challenge: Is thereno way to make the electron microscope more powerful?

The marvelous biological system

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

There may even be an economic point to this business of making thingsvery small. Let me remind you of some of the problems of computing machines.In computers we have to store an enormous amount of information. The kindof writing that I was mentioning before, in which I had everything downas a distribution of metal, is permanent. Much more interesting to a computeris a way of writing, erasing, and writing something else. (This is usuallybecause we don't want to waste the material on which we have just written.Yet if we could write it in a very small space, it wouldn't make any difference;it could just be thrown away after it was read. It doesn't cost very muchfor the material).

Miniaturizing the computer

I don't know how to do this on a small scale in a practical way, but Ido know that computing machines are very large; they fill rooms. Why can'twe make them very small, make them of little wires, little elements---andby little, I mean *little*. For instance, the wires should be 10 or100 atoms in diameter, and the circuits should be a few thousand angstromsacross. Everybody who has analyzed the logical theory of computers hascome to the conclusion that the possibilities of computers are very interesting---ifthey 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.They would have time to calculate what is the best way to make the calculationthat they are about to make. They could select the method of analysis which,from their experience, is better than the one that we would give to them.And in many other ways, they would have new qualitative features.

If I look at your face I immediately recognize that I have seen it before.(Actually, my friends will say I have chosen an unfortunate example herefor the subject of this illustration. At least I recognize that it is a*man* and not an *apple*.) Yet there is no machine which, withthat 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---unlessit is exactly the same picture. If the face is changed; if I am closerto the face; if I am further from the face; if the light changes---I recognizeit anyway. Now, this little computer I carry in my head is easily ableto do that. The computers that we build are not able to do that. The numberof elements in this bone box of mine are enormously greater than the numberof elements in our ``wonderful'' computers. But our mechanical computersare too big; the elements in this box are microscopic. I want to make somethat are *sub*microscopic.

If we wanted to make a computer that had all these marvelous extra qualitativeabilities, we would have to make it, perhaps, the size of the Pentagon.This has several disadvantages. First, it requires too much material; theremay not be enough germanium in the world for all the transistors whichwould have to be put into this enormous thing. There is also the problemof heat generation and power consumption; TVA would be needed to run thecomputer. But an even more practical difficulty is that the computer wouldbe limited to a certain speed. Because of its large size, there is finitetime required to get the information from one place to another. The informationcannot go any faster than the speed of light---so, ultimately, when ourcomputers get faster and faster and more and more elaborate, we will haveto make them smaller and smaller.

But there is plenty of room to make them smaller. There is nothing thatI can see in the physical laws that says the computer elements cannot bemade enormously smaller than they are now. In fact, there may be certainadvantages.

Miniaturization by evaporation

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

But I would like to discuss, just for amusement, that there are otherpossibilities. Why can't we manufacture these small computers somewhatlike we manufacture the big ones? Why can't we drill holes, cut things,solder things, stamp things out, mold different shapes all at an infinitesimallevel? What are the limitations as to how small a thing has to be beforeyou can no longer mold it? How many times when you are working on somethingfrustratingly tiny like your wife's wrist watch, have you said to yourself,``If I could only train an ant to do this!" What I would like to suggestis the possibility of training an ant to train a mite to do this. Whatare the possibilities of small but movable machines? They may or may notbe useful, but they surely would be fun to make.

Consider any machine---for example, an automobile---and ask about theproblems of making an infinitesimal machine like it. Suppose, in the particulardesign of the automobile, we need a certain precision of the parts; weneed an accuracy, let's suppose, of 4/10,000 of an inch. If things aremore inaccurate than that in the shape of the cylinder and so on, it isn'tgoing to work very well. If I make the thing too small, I have to worryabout the size of the atoms; I can't make a circle of ``balls" so to speak,if the circle is too small. So, if I make the error, corresponding to 4/10,000of an inch, correspond to an error of 10 atoms, it turns out that I canreduce the dimensions of an automobile 4,000 times, approximately---sothat it is 1 mm. across. Obviously, if you redesign the car so that itwould work with a much larger tolerance, which is not at all impossible,then you could make a much smaller device.

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 areayou are reducing, so that things like weight and inertia are of relativelyno importance. The strength of material, in other words, is very much greaterin proportion. The stresses and expansion of the flywheel from centrifugalforce, for example, would be the same proportion only if the rotationalspeed is increased in the same proportion as we decrease the size. On theother hand, the metals that we use have a grain structure, and this wouldbe very annoying at small scale because the material is not homogeneous.Plastics and glass and things of this amorphous nature are very much morehomogeneous, and so we would have to make our machines out of such materials.

There are problems associated with the electrical part of the system---withthe copper wires and the magnetic parts. The magnetic properties on a verysmall 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 bemade on a small scale with one domain. The electrical equipment won't simplybe scaled down; it has to be redesigned. But I can see no reason why itcan't be redesigned to work again.

Problems of lubrication

Lubrication involves some interesting points. The effective viscosity ofoil would be higher and higher in proportion as we went down (and if weincrease the speed as much as we can). If we don't increase the speed somuch, and change from oil to kerosene or some other fluid, the problemis not so bad. But actually we may not have to lubricate at all! We havea lot of extra force. Let the bearings run dry; they won't run hot becausethe heat escapes away from such a small device very, very rapidly.

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

Probably an external supply of electricalpower would be most convenient for such small machines.

What would be the utility of such machines? Who knows? Of course, asmall automobile would only be useful for the mites to drive around in,and I suppose our Christian interests don't go that far. However, we didnote the possibility of the manufacture of small elements for computersin completely automatic factories, containing lathes and other machinetools at the very small level. The small lathe would not have to be exactlylike our big lathe. I leave to your imagination the improvement of thedesign to take full advantage of the properties of things on a small scale,and in such a way that the fully automatic aspect would be easiest to manage.

A friend of mine (Albert R. Hibbs) suggests a very interesting possibilityfor relatively small machines. He says that, although it is a very wildidea, it would be interesting in surgery if you could swallow the surgeon.You put the mechanical surgeon inside the blood vessel and it goes intothe heart and ``looks'' around. (Of course the information has to be fedout.) It finds out which valve is the faulty one and takes a little knifeand slices it out. Other small machines might be permanently incorporatedin the body to assist some inadequately-functioning organ.

Now comes the interesting question: How do we make such a tiny mechanism?I leave that to you. However, let me suggest one weird possibility. Youknow, in the atomic energy plants they have materials and machines thatthey can't handle directly because they have become radioactive. To unscrewnuts and put on bolts and so on, they have a set of master and slave hands,so that 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 actually made rather simply, in that thereis a particular cable, like a marionette string, that goes directly fromthe controls to the ``hands.'' But, of course, things also have been madeusing servo motors, so that the connection between the one thing and theother is electrical rather than mechanical. When you turn the levers, theyturn a servo motor, and it changes the electrical currents in the wires,which repositions a motor at the other end.

Now, I want to build much the same device---a master-slave system whichoperates electrically. But I want the slaves to be made especially carefullyby modern large-scale machinists so that they are one-fourth the scaleof the ``hands'' that you ordinarily maneuver. So you have a scheme bywhich you can do things at one- quarter scale anyway---the little servomotors with little hands play with little nuts and bolts; they drill littleholes; they are four times smaller. Aha! So I manufacture a quarter-sizelathe; I manufacture quarter-size tools; and I make, at the one-quarterscale, still another set of hands again relatively one-quarter size! Thisis one-sixteenth size, from my point of view. And after I finish doingthis I wire directly from my large-scale system, through transformers perhaps,to the one-sixteenth-size servo motors. Thus I can now manipulate the one-sixteenthsize hands.

Well, you get the principle from there on. It is rather a difficultprogram, but it is a possibility. You might say that one can go much fartherin one step than from one to four. Of course, this has all to be designedvery carefully and it is not necessary simply to make it like hands. Ifyou thought of it very carefully, you could probably arrive at a much bettersystem for doing such things.

If you work through a pantograph, even today, you can get much morethan a factor of four in even one step. But you can't work directly througha pantograph which makes a smaller pantograph which then makes a smallerpantograph---because of the looseness of the holes and the irregularitiesof construction. The end of the pantograph wiggles with a relatively greaterirregularity than the irregularity with which you move your hands. In goingdown this scale, I would find the end of the pantograph on the end of thepantograph on the end of the pantograph shaking so badly that it wasn'tdoing anything sensible at all.

At each stage, it is necessary to improve the precision of the apparatus.If, for instance, having made a small lathe with a pantograph, we findits lead screw irregular---more irregular than the large-scale one---wecould lap the lead screw against breakable nuts that you can reverse inthe usual way back and forth until this lead screw is, at its scale, asaccurate as our original lead screws, at our scale.

We can make flats by rubbing unflat surfaces in triplicates together---inthree pairs---and the flats then become flatter than the thing you startedwith. Thus, it is not impossible to improve precision on a small scaleby the correct operations. So, when we build this stuff, it is necessaryat each step to improve the accuracy of the equipment by working for awhiledown there, making accurate lead screws, Johansen blocks, and all the othermaterials which we use in accurate machine work at the higher level. Wehave to stop at each level and manufacture all the stuff to go to the nextlevel---a very long and very difficult program. Perhaps you can figurea better way than that to get down to small scale more rapidly.

Yet, after all this, you have just got one little baby lathe four thousandtimes smaller than usual. But we were thinking of making an enormous computer,which we were going to build by drilling holes on this lathe to make littlewashers for the computer. How many washers can you manufacture on thisone lathe?

A hundred tiny hands

When I make my first set of slave ``hands'' at one-fourth scale, I am goingto make ten sets. I make ten sets of ``hands,'' and I wire them to my originallevers 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 leteach one manufacture ten copies, so that I would have a hundred ``hands''at the 1/16th size.

Where am I going to put the million lathes that I am going to have?Why, there is nothing to it; the volume is much less than that of evenone full-scale lathe. For instance, if I made a billion little lathes,each 1/4000 of the scale of a regular lathe, there are plenty of materialsand space available because in the billion little ones there is less than2 percent of the materials in one big lathe.

It doesn't cost anything for materials, you see. So I want to builda billion tiny factories, models of each other, which are manufacturingsimultaneously, drilling holes, stamping parts, and so on.

As we go down in size, there are a number of interesting problems thatarise. All things do not simply scale down in proportion. There is theproblem that materials stick together by the molecular (Van der Waals)attractions. It would be like this: After you have made a part and youunscrew the nut from a bolt, it isn't going to fall down because the gravityisn't appreciable; it would even be hard to get it off the bolt. It wouldbe like those old movies of a man with his hands full of molasses, tryingto get rid of a glass of water. There will be several problems of thisnature that we will have to be ready to design for.

Rearranging the atoms

But I am not afraid to consider the final question as to whether, ultimately---inthe 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 byone the way we want them (within reason, of course; you can't put themso that they are chemically unstable, for example).

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 toget a pure substance with just so much impurity, and so on. But we mustalways accept some atomic arrangement that nature gives us. We haven'tgot anything, say, with a ``checkerboard'' arrangement, with the impurityatoms exactly arranged 1,000 angstroms apart, or in some other particularpattern.

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

Consider, for example, a piece of material in which we make little coilsand condensers (or their solid state analogs) 1,000 or 10,000 angstromsin a circuit, one right next to the other, over a large area, with littleantennas sticking out at the other end---a whole series of circuits. Isit possible, for example, to emit light from a whole set of antennas, likewe emit radio waves from an organized set of antennas to beam the radioprograms to Europe? The same thing would be to *beam* the light outin a definite direction with very high intensity. (Perhaps such a beamis not very useful technically or economically.)

I have thought about some of the problems of building electric circuitson a small scale, and the problem of resistance is serious. If you builda corresponding circuit on a small scale, its natural frequency goes up,since the wave length goes down as the scale; but the skin depth only decreaseswith the square root of the scale ratio, and so resistive problems areof increasing difficulty. Possibly we can beat resistance through the useof superconductivity if the frequency is not too high, or by other tricks.

Atoms in a small world

When we get to the very, very small world---say circuits of seven atoms---wehave a lot of new things that would happen that represent completely newopportunities for design. Atoms on a small scale behave like *nothing*on a large scale, for they satisfy the laws of quantum mechanics. So, aswe go down and fiddle around with the atoms down there, we are workingwith different laws, and we can expect to do different things. We can manufacturein different ways. We can use, not just circuits, but some system involvingthe quantized energy levels, or the interactions of quantized spins, etc.

Another thing we will notice is that, if we go down far enough, allof our devices can be mass produced so that they are absolutely perfectcopies of one another. We cannot build two large machines so that the dimensionsare exactly the same. But if your machine is only 100 atoms high, you onlyhave to get it correct to one-half of one percent to make sure the othermachine is exactly the same size---namely, 100 atoms high!

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 materialswill be quite different. I am, as I said, inspired by the biological phenomenain which chemical forces are used in repetitious fashion to produce allkinds of weird effects (one of which is the author).

The principles of physics, as far as I can see, do not speak againstthe possibility of maneuvering things atom by atom. It is not an attemptto violate any laws; it is something, in principle, that can be done; butin practice, it has not been done because we are too big.

Ultimately, we can do chemical synthesis. A chemist comes to us andsays, ``Look, I want a molecule that has the atoms arranged thus and so;make me that molecule." The chemist does a mysterious thing when he wantsto make a molecule. He sees that it has got that ring, so he mixes thisand that, and he shakes it, and he fiddles around. And, at the end of adifficult 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 thatthis will really be useless.

But it is interesting that it would be, in principle, possible (I think)for a physicist to synthesize any chemical substance that the chemist writesdown. Give the orders and the physicist synthesizes it. How? Put the atomsdown where the chemist says, and so you make the substance. The problemsof chemistry and biology can be greatly helped if our ability to see whatwe are doing, and to do things on an atomic level, is ultimately developed---adevelopment which I think cannot be avoided.

Now, you might say, ``Who should do this and why should they do it?"Well, I pointed out a few of the economic applications, but I know thatthe reason that you would do it might be just for fun. But have some fun!Let's have a competition between laboratories. Let one laboratory makea tiny motor which it sends to another lab which sends it back with a thingthat fits inside the shaft of the first motor.

High school competition

Just for the fun of it, and in order to get kids interested in this field,I would propose that someone who has some contact with the high schoolsthink of making some kind of high school competition. After all, we haven'teven started in this field, and even the kids can write smaller than hasever been written before. They could have competition in high schools.The Los Angeles high school could send a pin to the Venice high schoolon which it says, ``How's this?" They get the pin back, and in the dotof the ``i" it says, ``Not so hot."

Perhaps this doesn't excite you to do it, and only economics will doso. Then I want to do something; but I can't do it at the present moment,because I haven't prepared the ground. It is my intention to offer a prizeof $1,000 to the first guy who can take the information on the page ofa book and put it on an area 1/25,000 smaller in linear scale in such mannerthat it can be read by an electron microscope.

And I want to offer another prize---if I can figure out how to phraseit so that I don't get into a mess of arguments about definitions---ofanother $1,000 to the first guy who makes an operating electric motor---arotating electric motor which can be controlled from the outside and, notcounting the lead-in wires, is only 1/64 inch cube.

I do not expect that such prizes will have to wait very long for claimants.