Excursions into Diverse Fields

Jagdish Mehra

A ‘graduate student’ in biology

To Feynman, biology was a very interesting field; as a boy, his father had encouraged him to take interest in science in general and, when he was at Princeton, he had taken a course from Newton Harvey on cell physiology. Thus he was not entirely ignorant of problems in biology, which he actually found fascinating. However, all he thought he would be able to do would be to go into the laboratory, clean up, wash bottles, and hear the biologists talk among themselves about their problems, just as he had done as a younger in the chemistry laboratory at Far Rockaway High School.

At Caltech, Feynman’s interest in biology arose because he frequently used to visit Max Delbrück and other members of the biology department. On occasion he would attend biology seminars given by visitors. So, when it occurred to Feynman that he might wish to do some work in biology, he mentioned it to Delbrück, who sent him to see Robert S. Edgar, who, at that time, was a postdoctoral fellow, responsible for bacteriophage research that was still going on in Delbrück’s laboratory. Delbrück himself was increasingly losing interest in bacteriophages as his work on the mechanism of phototropism in the fungus Phycomyces accelerated.

Feynman proposed to Edgar that he would like to hang around his laboratory and do odd things. Edgar told him that what he had to do was act like a graduate student who would do some research.

The late Prof. Jagdish Mehra wrote a fascinating biography of Richard Feynman titled, The Beat of a Different Drum (Oxford University Press, 1994). It provides a comprehensive perspective of the range of Feynman’s interests in physics and matters that related to other areas of science and education. The excerpt that is reprinted here, from Jagdish Mehra’s 1994 biography of Richard Feynman, The Beat of a Different Drum (Courtesy of Special Collections, University of Houston Libraries), illustrates Feynman’s brilliance as he delved into fundamental questions in biology and nanotechnology.
He would first have to go through the phages course, learn to handle phages, and Edgar would give him a research project and a room in the laboratory—like a graduate student, only better. That’s what they did and Feynman learned how to handle the phages.

Feynman was given a special problem. It had to do with back-mutations. A mutation had been discovered in which a virus lost its ability to attack a certain kind of bacteria. Then another mutation would gain this ability back, but it was not exactly the opposite mutation, because when it got back it would do something different. For example, it would attack faster or slower; it wasn’t exactly the same. And the question was to investigate what these back-mutations were.

Mutations are structural changes in the genes. Feynman’s project dealt with the characterization of back-mutations, that is, mutations which appear to restore a mutant gene to its normal state. The mutant that he started with, r43, is a representative of a mutation at one site within the rIIB gene that occurs at an abnormally high frequency, a mutational ‘hot spot’. The notion was to explore this unusual behavior.

Using a variety of bacterial hosts, Feynman was able to distinguish various types of back-mutations (revertants); not all were identical to the normal, or wild-type, strain. He examined further some of the unusual back-mutants that were clearly not completely normal. His studies revealed that these unusual back-mutants still retained the original r43 mutation and had a second mutation that somehow ameliorated the effects of r43 mutation. These ‘suppressor’ mutations were, by themselves, typical mutations producing a strong mutant effect, similar to r43. Nevertheless, when combined with r43, these suppressor mutations produced a near normal effect on the phage.

Feynman went on to show that when these suppressors are combined with one another they do not show mutual suppression, that is, reduction in the mutant effect on the phage, nor do they do...
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so with a wide variety of other rII mutations tested—the effect appeared to be specific for the r43 mutation. Feynman also showed that these suppressor mutations were located in close proximity to the r43 mutation.

Feynman carried this study further by showing that when one started with one of these ‘suppressor’ mutations and looked at their back-mutations, some were found to be due to new suppressor mutations similar in characteristics to the r43 mutation. Thus there exist two types of mutations which we could call plus and minus. Either a plus or a minus mutation by itself produced a mutant effect on the phage. However, a plus mutation combined with a minus mutation returned the phage to almost its normal unmuted state. Feynman speculated about the possible nature of these mutations. In a conversation with Edgar, he suggested that one class caused a positively charged amino acid to be introduced in the gene product protein, while the other caused a negatively charged amino acid to be introduced; in the double mutant the original charge state of the protein could be restored. (When one refers to the mutant or nonmutant ‘state’ of the phage, one is referring to the functional activity of the rII gene, i.e. the gene-specific protein product, when it contains no mutation, one mutation, or two mutations.)

The paper on the ‘General nature of the genetic code for proteins’ by F. H. C. Crick et al. is widely regarded as one of the most important and elegant studies in the history of genetic research. In this work the authors showed that in a small region of the rII gene (the region which Feynman was studying) one can find two special classes of mutations that show mutual suppression: Feynman’s plus and minus classes.

Given their notion that these mutations were additions and deletions of nucleotides, Crick and collaborators correctly speculated that this remarkable finding must be due to the fact that the gene is translated, starting from one fixed point, and that the sequence of nucleotides within the gene is read and translated by the translation machinery of the cell three nucleotides at a time. A
single mutation of the addition–deletion type will have a severe effect on the translation process because the reading will be thrown ‘out of phase’. Phase will be restored only in case where an addition is combined with a deletion or if three additions or three deletions are combined. Feynman had independently discovered some of the characteristics of addition–deletion, or as one now calls them ‘frame-shift’ mutations. However, he did not realize that they were actually addition and deletion mutations, and did not discover that ‘3’ was a magic number. Crick and his colleagues took note of Feynman’s work in their paper.

Feynman continued his biological research during his sabbatical year (1959–60), and worked with Matt Meselson on ribosomes. The ribosome work did not go very well, because Feynman was not able to reproduce his results. By the time he realized where the trouble was coming from he had to return to physics. However, he was invited to give a seminar on his work at Harvard, and during his biology sabbatical year he got to know James Watson, Francis Crick, and other well-known biologists and became friends with them.

The experience of his year in the biology department that pleased Feynman the most was the response to him as a ‘graduate teaching assistant’! In biology they put the students through a wide range of things, different kinds of techniques, and one of them was phages. So, for a week, Feynman taught them how to handle phages carefully by sucking them up the tubes containing cyanide—‘you have to be damn careful!’ He taught them about calculating statistics and probability. These were first year students and they did not know who Feynman really was; on their evaluation sheet they ranked him ‘the best teaching assistant’ they had, one ‘who is excellent at explaining things’. ‘I got a tremendous boost by obtaining the best score of all teaching assistants; even in biology, not my field, I could explain things clearly, and I was rather proud of it. It was great fun to be in another world and act like somebody else—a graduate student and teaching assistant!’

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There’s plenty of room at the bottom

On 29 December 1959, at the Annual Meeting of the American Physical Society, held at Caltech, Richard Feynman gave a talk entitled ‘There’s plenty of room at the bottom.’ In this talk, Feynman sought to describe a field, ‘in which little has been done, but in which an enormous amount can be done in principle.’ This field is not quite the same as others in that it wouldn’t tell us much of fundamental physics (in the sense of ‘What are the strange particles?’), but 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 more important is that it would have an enormous number of technical applications. What Feynman wanted to talk about ‘is the problem of manipulating and controlling things on a small scale.’

Feynman recalled that, whenever he mentioned this problem to people, they would tell him about miniaturization, and how far it had 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.’

Feynman discussed what would be involved. The head of a pin is a sixteenth of an inch across. If we magnify it by 25 000 diameters, the area of the pinhead is then equal to all the pages of the Encyclopaedia Britannica. Therefore, what is necessary is to reduce in size all the writing in the Encyclopaedia by 25 000 times. Is that possible? The resolving power of the eye is about 1/120 of an inch, which is roughly the diameter of one of the little dots on the fine half-tone reproductions in the Encyclopaedia. If the little dot is demagnified by 25 000 times, it is still 80 angstroms across in diameter, or thirty-two atoms across in an ordinary metal. Thus, each dot can be adjusted in size as required by photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia.
Britannica... There is no question that if things were reduced by 25,000 times in the form of raised letters on the pin it would be easy for us to read it today.

The question that then arises is this: How do we write it? One way to do this might be to take light and, through an optical microscope running backwards, focus it on to 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 could be recognized later.’

That would take care of putting the entire Encyclopaedia Britannica on the head of a pin. Now let’s consider all the books in the world. Consider three great libraries: the Library of Congress (approximately nine million volumes); the British Museum Library (about five million volumes); the Bibliothèque Nationale of Paris (another five million volumes). Discounting the duplications, let us say that there are about twenty-four million volumes of interest in the world. What would happen if we were to print all these volumes at the scale we have mentioned? That is, instead of the twenty-four volumes of the Encyclopaedia, we now have twenty-four million volumes. The million pinheads required for this can be put in a square of a thousand pins on a side, or an area about three square yards. That is to say, the silicon replica with the paper-thin backing of plastic, with which we have made the copies, with all this information, would occupy an area approximately the size of thirty-five pages of the Encyclopaedia. ‘All of the information which all mankind has ever recorded in books can be carried around in a pamphlet in your hand—not written in code, but as simple reproduction of the original pictures, engravings, and everything else on a small scale without loss of resolution.’
Suppose that, instead of trying to reproduce the pictures and all the information directly in its present form, we write only the information content in a code of dots and dashes to represent the various letters. Each letter represents six or seven ‘bits’ of information; that is, we need only about six or seven dots or dashes for each letter. Now, instead of writing everything, as we did before, on the surface of the head of a pin, let us 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 $5 \times 5 \times 5$, that is, 125 atoms. Let’s say, we need a hundred or some more atoms to make sure that the information is not lost through diffusion or some other means.

Now, estimating the number of letters in the Encyclopaedia’s twenty-four volumes, and assuming that each of our twenty-four million books is as big as an Encyclopaedia volume, then how many bits of information do we need? 10. For each bit let us allow 100 atoms. It turns out that all the information that man has accumulated in all the books in the world can be written in this form in a cube of material $1/200$ of an inch wide, which is the barest particle of dust that can be made out by the human eye. ‘So there is plenty of room at the bottom! Don’t tell me about microfilm!’

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The fact that enormous amounts of information can be carried in an exceedingly small space is, of course, known to biologists. It resolves the mystery that existed, before it was understood clearly, of how it could be, in the tiniest cell, all of the information for organization of a complex structure such as ourselves can be stored.

The biological example of storing information on a small scale inspired Feynman to imagine what should be possible. Biology is concerned not simply with writing information; it does something about it. A biological system can be very small. All the information—whether we have brown eyes, or whether we think at all, or 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—is
contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately fifty atoms are used for one bit of information about the cell. 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 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!

Feynman surmized the economic possibilities of making things very small. Consider some of the problems of computing machines. It was not evident how to build computing machines—which in 1959 were very large and occupied much space—on a very small scale in a practical way. Feynman thought that we should be able to make them very small, make them of little wires and little elements—and by ‘little’ Feynman meant really little: for instance, wires should be ten or a hundred 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... If I look at your face I immediately recognize that I have seen it before. (At least I 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 the light changes—I recognize it anyway. Now, this little computer I carry in my head is easily able to do that. The computers that we build are not 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. But our mechanical computers are too big; the elements in this box are microscopic. I want to make some that are submicroscopic.’
Ultimately, when our computers get faster and faster and more and more elaborate, we will have to make them smaller and smaller. But there’s plenty of room (at the bottom) to make them smaller. There is nothing 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 devices? What kind of processes would we use to make them? One possibility would be to consider (as in 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 on. So, one simply keeps on evaporating until one has a block of material that has the elements—coils and condensers, transistors, and so on—of exceedingly fine dimensions.

We should not be afraid, to consider the final question as to whether, ultimately (‘in the great future’), we can arrange the atoms that 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 (within reason, of course; you can’t put them so that they are chemically unstable, for example)?’

Up to now, we have been content to dig in the ground to find materials. We do all kinds of things with them on a large scale to get a pure substance with just so much impurity, and so on. But we must accept some atomic arrangement that nature gives us. ‘We haven’t got anything, say, with a “checkerboard” arrangement, or with impurity atoms arranged just exactly 1000 angstroms apart, or in some other peculiar 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 atoms the way we want them? That 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.’
When we get to the very, very small world—say, circuits of seven atoms—we will 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 obey the laws of quantum mechanics. So, as we go down, and ‘fiddle with the atoms down there’, we are working with different laws than the ones that operate at the macroscopic level, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving quantized energy levels, or interactions of quantized spins, etc.

At the atomic level, there are new kinds of forces, and there will be new kinds of possibilities and effects. The problems of manufacture and reproduction of materials will be quite different. ‘I am,’ said Feynman, ‘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 me [Richard Feynman]).’

Feynman then announced that he would ‘offer a prize of $1000 to the first guy who can take information on the page of a book and put it on an area 1/25 000 smaller on a linear scale in such a manner that it can be read by an electron microscope. And I want to offer another prize—if I can figure out how to phrase it so that I don’t get into a mess of arguments about definitions—of $1000 to the first guy who makes an operating motor—a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cubed. I do not expect that such prizes will have to wait long for claimants.’

After this announcement, which was published in the February 1960 issue of Caltech’s Engineering and Science magazine, Feynman was besieged by inventors of miniature motors; it was a rare day when Feynman was not interrupted in his office by someone eager to show him what usually turned to be a very large small motor.

In November 1960, William McLellan, a senior engineer at Electro-Optical systems in Pasadena, California, walked into Feynman’s office in the Biology Department with his small motor. It looked

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‘And I want to offer another prize—of $1,000 to the first guy who makes an operating motor...and is only 1/64 inch cubed.’
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like the same old story, because McLellan was carrying his invention in a big grocery carton. OK, said Feynman wearily, he would look at the thing—but there was no money in it for anybody; it had been his intention to set up the prize, but never got around to doing it.

This was all right with McLellan. It was a challenge that had set him to work on the problem anyway. Then he took a microscope out of the grocery carton and let Feynman look in to see the motor he had built. It had taken McLellan two and a half months of lunch hours to make it. The motor was 1/64 of an inch cubed, or about as big as a speck in one’s eye. It weighed 250 micrograms, had thirteen parts, was built with the aid of a microscope, a watchmaker’s lathe and a toothpick, and it could be controlled from the outside. As Feynman watched, McLellan set the motor going.

Feynman and McLellan spent the better part of the afternoon operating the motor. It was after he got home that night that Feynman’s conscience began to bother him. After all, the motor was exactly what he had asked for. ‘So, I sent the guy a check for a thousand bucks.’

Elated as he was over the little motor, Feynman was now worried about the prize: another $1000 ‘to the first guy who can take the information on the page of a book and put it in an area 1/25 000 smaller in linear scale in such a manner that it can be read by an electron microscope.’ Feynman expected any day to meet the man who had accomplished this particular feat. And daily, the thought would haunt him—because, in the meantime, Feynman got married (1960), bought a house, and, what with one thing and another, hadn’t ‘got another $1000.’ Engineering and Science announced a public appeal ‘to all inventors who are now at work trying to write small and collect the second Feynman Prize—TAKE YOUR TIME! WORK SLOWLY! RELAX!’

The general reaction to Feynman’s talk at the APS meeting was amusement. Most of the people who heard him thought that he was trying to be funny as usual; ‘it simply took everybody by surprise’. Actually, Feynman had always been interested in the
limits that physics puts on the things one would like to do. When he theoretically probed the possibilities of what kind of ‘room was there at the bottom’, he conceived of a realm that is rapidly being realized in laboratories thirty years later: 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. This is the new science of ‘nanotechnology’. Just as Feynman did, the nanotechnologists—who exploit the atomic scale for making new devices—credit their inspiration to molecular-scale processes and information systems of living things. Feynman’s talk ‘was so visionary that it didn’t really connect with people until the technology caught up with it.’ Many of those who manipulate atoms using the scanning tunneling microscope (STM) did not know about Feynman’s talk until after they got into the atom-moving business. As Don Eigler of the IBM Almaden Research Center in San Jose, California, who uses STM to manipulate atoms, recalled: ‘I felt the ghost of Feynman behind me while I was reading, saying, “Look, I thought of these things 30 years ago.”’

The tiny circuits, lasers, mirrors, and mechanical devices that take shape at laboratories like the National Nanofabrication Facility at Cornell University, Ithaca, New York, are built layer by layer, often using higher-resolution versions of the techniques now commonplace in the microelectronics industry. For each layer, engineers transfer a pattern to the surface—usually silicon, gallium arsenide, or some other semiconductor—through stencil-like masks. Then they etch out the patterned region, deposit new materials on it, or modify it with beams of ions. Several iterations of the process yield completed devices: tiny technoscopes sculpted in high relief and criss-crossed with metal connections of varying conductivity.

In 1990, researchers at IBM spelled ‘IBM’ by lifting and depositing individual, supercooled xenon atoms on to a nickel substrate with a scanning tunneling microscope (STM). Less than a year later, Shigeyuki Hosoki, an electronics researcher at Hitachi
Central Research Laboratory (HCRL) in Tokyo, carved ‘PEACE ’91 HCRL’ into a sulfur medium using an STM—but unlike the IBM team, he did it at room temperature, without the need of a massive cooling system. Soon afterward, several other Japanese electronic equipment manufacturers moved in with further improvements on the US technique, reducing from hours to seconds the time needed to etch lines just a few atoms wide in silicon, thus boldly realizing Feynman’s vision about there being ‘plenty of room at the bottom’.

The complete text of Feynman’s lecture is reproduced in the Classics Section on p.890 in this issue. Prof. Roddam Narasimha, then a student at Caltech, recollects his experience here below.

**Reminiscences of Feynman’s ‘Plenty of Room’ Lecture**

*R Narasimha*

When Feynman gave this talk in 1959 the hall was packed, and a fairly large part of the audience was actually young students, many of whom sat on the steps in the steeply raked auditorium. Feynman seemed to know instinctively how to speak to a young audience, and they came there to listen to their faculty star on campus, for he could show them how doing deep science was great fun. The atmosphere, as always with a Feynman talk, was crackling with expectation. Three things that Feynman said during that talk remain vivid in my mind – the rest are a bit hazy, as I see by reading the printed text of the talk. (By the way the text does not capture the mood of excitement that prevailed in the hall during the talk.) For me the major thing was the biological inspiration. If these strange things that are you and me are in some sense assembling themselves, atom by atom, and there is only physics and chemistry in what they are doing, surely we must be able to do something similar in the laboratory. Nothing in physics rules it out, so one of these days it should be – and will be – possible. This argument, set out with Feynman’s characteristic flair – he was a great showman – seemed simple and compelling, especially as it was bolstered by back-of the-envelope numbers. It made me, and I believe most others in the hall, wonder why we had not ourselves seen this apparently simple truth, and its astounding consequences. One of the things that got a huge roar of laughter was his story of the competing schools. The kids from one school send their friends in the other a message on a pinhead that says: ‘How is this?’ And they get the reply (now all packed into the dot on the i) ‘NOT SO HOT!’ (Feynman’s loud, dismissive words on behalf of the second school still ring in my ears). The third was Feynman’s challenge, to make the ‘world’s smallest motor’ on a pin-head (1/64 inch cube). He announced an award of US$ 1000 for the first person who makes it. This item in particular (if I can trust my memory) was carried prominently in the next day’s local newspapers. Some months later a man walked into Feynman’s office, with the pinhead motor and a microscope to let Feynman get a good look at it. He collected the award. Like lots of other people on the campus, I too went there the next day to take a peek at the motor through the microscope – both left there for anybody to see on a table outside Feynman’s office.