Sixty Years of Feynman's Prophecy

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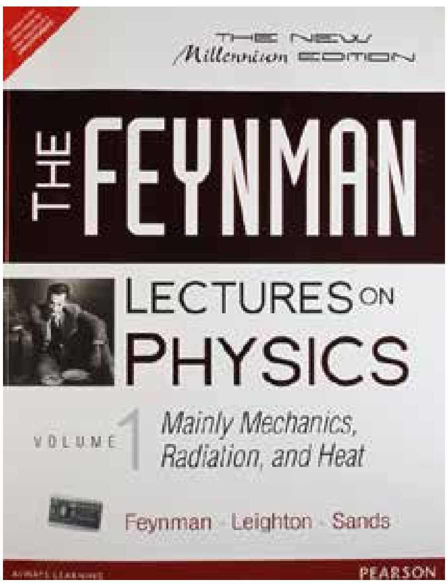
SCIENTISTS are able to see beyond times due to their great powers of imagination. Richard Feynman was one such scientist (Box 1) who delivered a prophetic talk describing a new field of nanotechnology on 29 December 1959. The completion of 60 years of this event this year provides us an occasion to pay tribute to the imagination of one of the greatest minds that led to the emergence of one of the most advanced fields of science and technology.

Feynman delivered the talk at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) and the title of his talk was 'There's Plenty of Room at the Bottom – An Invitation to Enter a New Field of Physics'. The new field of nanotechnology presaged by Feynman in this lecture grew very rapidly in the following decades not only translating Feynman's predictions into reality but also providing several new breakthroughs in this field.

Feynman described a new bottomless field in his talk – one of manipulating and controlling things on the scale of a nanometer (nm), which is a billionth part of a metre. Just for a quantitative feel, ten hydrogen atoms in a line make up 1 nm, a DNA double-helix is about 2 nm across, the smallest cellular life forms are around 200 nm in length, the smallest thing that can be seen with an unaided human eye is about 10,000 nm across and a human hair is about 50,000 nm thick.



Feynman predicted that matter would have many surprises to offer at the nanoscale and that would have an enormous number of technical applications. Both these predictions are very aptly proved by the wealth of scientific knowledge and its applications to engineering and technology that has accrued over last 60 years. Nanomaterials behave far differently than bulk materials because of the nature of the interactions among the atoms of the material at nanoscale. Much of the fascination with nanotechnology stems from such behavioural changes.

The novel behaviour of matter at the nanoscale attracted a tremendous amount of attention from scientists and technologists from several domains of knowledge over a relatively short span of time. Sensing a huge promise, governments as well as big commercial establishments allocated large finances for research and developments in this field catapulting it onto a steep upward journey.

Feynman began his talk by citing his predecessors, Kamerlingh Onnes and Percy Bridgman, who pioneered the bottomless fields of low temperatures and higher pressures, respectively, before proposing his new bottomless field. Kamerlingh Onnes, a Dutch physicist, developed a large cryogenics laboratory in 1904 and could go down to the coldest temperatures achieved on the earth at the time – a temperature of 4.2 K by liquefying helium and further down to near 1.5 K by reducing the pressure of liquid helium. The bottomless field of high pressure was pioneered by Percy Bridgman, an American physicist. With the devices that existed during his time pressures up to 0.3 GPa could be achieved. Bridgman made many improvements in these devices and could achieve pressures exceeding 10 GPa.

Feynman introduced his new field by posing a motivating question, "Why cannot we write the entire 24 volumes of the *Encyclopaedia Britannica* on the head of a pin?" He then explained how this can be made possible by working at the nano level. He also explained how this could be read with an electron microscope

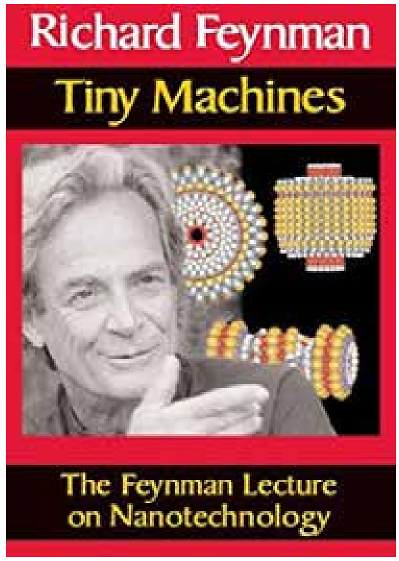
Richard Feynman

Richard Feynman (11 May, 1918–15 February, 1988) was born in Queens, New York and made pioneering contributions to research in fields such as quantum electrodynamics, superfluidity and particle physics. He also took keen interest in popularising physics through his books and lectures. He was awarded Nobel Prize in Physics in 1965 along with Julian Schwinger and Shin'ichirō Tomonaga for his contributions to the development of quantum electrodynamics. In his last days he was diagnosed with cancer. His last words were: "I'd hate to die twice. It's so boring."

and tried to impress upon the importance of improving the electron microscope. He was convinced that the fundamental questions in biology could be solved if atoms could be seen directly. He asked, "What good would it be to see individual atoms distinctly?"

The science and technology of reading (seeing) small, i.e., microscopy and of writing small, i.e., lithography advanced rapidly in the following years and today we are not only able to see individual atoms but we can also manipulate and guide them to achieve many tasks including writing. Interestingly, the inventions that enabled us to read small could also be used to write small.

This was made possible by different types of microscopes such as electron microscopes, followed by Tunnelling Electron Microscope (TEM), Reflection Electron Microscope, Scanning Transmission Electron Microscope (STEM), High-Resolution TEM (HRTEM), and the Scanning Tunneling Microscope (STM).



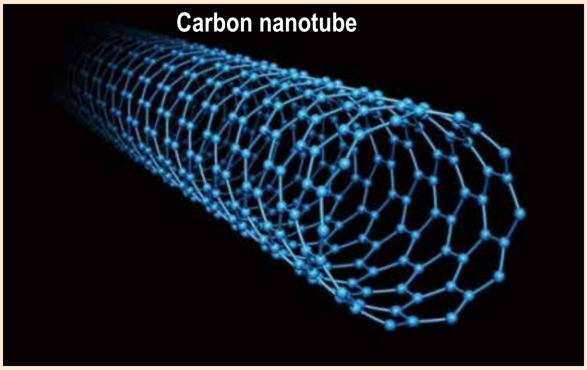
Feynman mentioned how the marvellous biological system inspired him, "A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvellous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that maneuvers at that level!"

There has been a lot of progress in developing objects and machines that maneuver at nano level during the last 60 years. These efforts embody the confluence of the smallest of human-made devices and the largest molecules of living things. Bionanotechnology emerged through these efforts as a science that uses biomolecules for applications in nanotechnology. For example, proteins are the machines of biology and thus understanding of processes such as protein synthesis provided insights into the natural world of nanoscience and nanotechnology and helped in the development of bionanotechnology.

A discipline based on nanoscale machines operating on the molecular scale is known as molecular nanotechnology. It uses the concept of a molecular assembler, a machine that can produce a desired structure or device atom-by-atom. An experiment indicating this possibility was performed by Wilson Ho and Hyojune Lee at Cornell University in 1999 in which they used STM to move an individual carbon monoxide molecule

Applications Based on Nanotechnology

- Carbon nanotubes are used in products ranging from paints and textiles to medical diagnostic tools and components of a future quantum computer because they have remarkable properties such as very high elastic strength alongside low mass density or very high current densities with no heat loss.


Carbon nanotube

- Graphene is used in transparent electrodes for solar cells, LCD, robust non-volatile atomic switches, chemical and biological sensors and in spintronic devices.
- Semiconducting nanowires are highly versatile optoelectronic components for a wide variety of applications such as polarisation-sensitive photodetectors and arrays with subwavelength resolution; optical modulators and nano-waveguides, nano-LEDs and nano-lasers, solar cells and biomedical sensors.
- Nanowhiskers on clothes create a cushion of air around the fabric so that liquids cannot stain them.
- Nanoparticles of silver embedded into fibres have anti-microbial action.
- Silver nanoparticles are incorporated in apparel, footwear, paints, wound dressings, appliances, cosmetics and plastics for their antibacterial properties.
- New and cheap solar cells use nanoparticles of titanium oxide coated with dye molecules to capture the energy of visible light and convert it into electricity.
- Special filters using nanomaterials can remove objects as tiny as viruses from water.
- Nanoenhanced paints can reduce emission of nitrogen oxides, hydrocarbons, and carbon monoxide in the atmosphere; addition of nanoparticles makes paint scratchproof, easy cleaning, air purifying, UV resistant, water repellent, flame resistant and anti-bacterial.

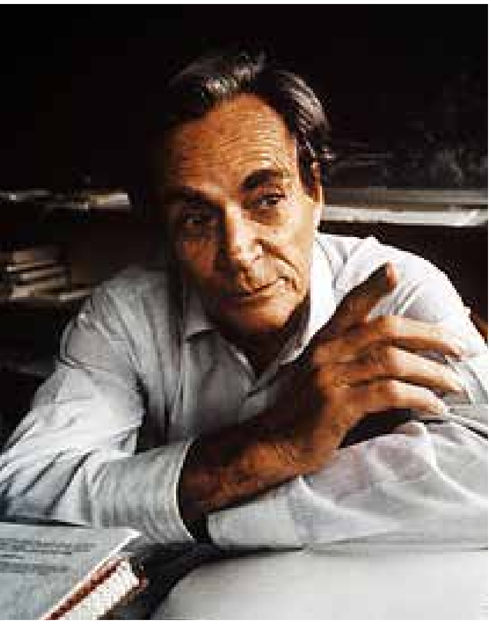

Nano enhanced paints

- A novel catalytic nanosheet form of a nickel molybdenum-nitride, a thousand times cheaper than traditional platinum, is the new model for harvesting hydrogen from water for use as fuel.
- Adding a little boron to carbon while creating nanotubes produces solid, spongy, reusable blocks that can absorb large quantities of oil spilled in water.
- Nanoenhanced construction ceramics such as floor and wall tiles and sanitary ware have self-cleaning, anti-bacterial, hygienic and scratch resistant features.
- Nanoenhanced cement obtained by addition of nanoparticles like nano silica (silica fume), nanostructured metals, CNTs and carbon nanofibres gives stronger, more durable, self-healing, air purifying, fire resistant, easy to clean and quick compacting concrete.
- Nanotechnology based smart windows have energy-saving, easy cleaning, UV controlling and photovoltaic properties.


Smart windows

- Addition of fumed silica nanoparticles makes glasses fire resistant.
- Nanotechnology can facilitate different forms of insulation solutions like coatings, vacuum insulation glazing, and nanofoams.

(Source: Engineering Physics by Jain and Sahasrabudhe, Universities Press, Second Edition)



(CO) to an individual iron atom (Fe) sitting on a flat silver crystal, and chemically bound the CO to the Fe by applying a voltage.

Feynman's imagination of making any infinitesimal machines, for example, an automobile, could be seen translating into reality through the progress and state of art in devices known as nanoelectromechanical systems or NEMS. These are a class of devices that integrate electrical and mechanical functionality on a nanoscale. They typically integrate transistor-like nanoelectronics with mechanical actuators, pumps, or motors, and may thereby form physical, biological, and chemical sensors. The first VLSI (very-large-scale integration) NEMS device was demonstrated by researchers at IBM in 2000. DNA and proteins are examples of Bio-nanoelectromechanical Systems (BioNEMS).

Feynman also discussed about miniaturising the computer, "Why can't we make them very small, make them of little wires, little elements. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now."

Today, progress in nanoelectronics has made possible such miniaturised computers. Nanoelectronics deals with building electronic devices at the atomic level to harness the quantum properties of materials at nano level. Commercial fabrication of nanoelectronic semiconductor devices and nanoelectronic semiconductor memory began in the 2010s.

The pathbreaking advances in nanoelectronic devices have aptly proved Feynman's prediction that the field of nanotechnology will offer completely new opportunities for design. Said Feynman, "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. Another thing we will notice is that, if we go down far enough, all of our devices can be mass produced so that they are absolutely perfect copies of one another." He also emphasised, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

Feynman also put forth his imagination of building sub-microscopic computers that would have capabilities such as face recognition. The progress in Artificial Intelligence (AI) and Machine Learning (ML) via convolutional neural networks (CNNs) has led to the development of computing machines with advanced capabilities such as understanding human speech, competing in games such as chess, operating cars, and military simulations. Face recognition as foreseen by Feynman, has been realised to near human accuracy by CNNs.

Feynman mentioned an interesting possibility, suggested by his friend, Albert R. Hibbs, "…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." The progress in nanomedicine and nanosurgery bear testimony to how the suggestion of Hibbs had been transformed into reality.

Developments in nanomedicine have provided the possibility of delivering drugs to specific cells using nanoparticles. This has several benefits such as reduction in the side effects of drugs and in the treatment expenses. Nanoscale devices are less invasive, faster and more sensitive than typical drug delivery. Nanotubes made of magnetic materials and carrying drugs inside them can be used to deliver them to desired areas in the body. Mechanised nano-based drug synthesis and delivery using MEMS have been demonstrated. Nanotechnology is helping to advance the use of arthroscopes, which are pencil-sized devices that are helping surgeons to do the surgeries with smaller incisions. It may be useful in tissue engineering to help repair or reshape damaged tissue using suitable nanomaterial-based scaffolds.

Nanotechnology continues to grow rapidly with new products based on the applications of this knowledge hitting the market very frequently. The revolutionary growth of nanotechnology was rightly predicted by Feynman 60 years back. The intense research and developments that are taking place in this field even today convince us that there is still plenty of room at the bottom and the field continues to be bottomless.

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