'Plenty of room' – fifty years after the Feynman lecture

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'There's plenty of room at the bottom' was a lecture delivered in 1959 by Richard Feynman. Over a period of time, this lecture came to be looked upon as the starting point of nanoscience. In the talk, Feynman explored seemingly simple and elegant possibilities of working at the atomic scale – possibilities that would have startling results. He touched upon ideas such as miniature writing, seeing and moving atoms, the prospect of designing molecules one atom at a time and the challenges involved in developing miniature machines. Developments in electron microscopy were taking place even before Feynman's lecture. In fact, atoms were seen for the first time in 1955 – four years before 'Plenty of room'. Remarkable advances have been made on the nanoscale, such as developments in lithography, the discovery of fullerenes and improvements in microscopy that have made it possible to see, name and move atoms at will. Moreover, the concept of 'nano' can be traced back to ancient times – philosophers of various civilizations have contemplated the existence of 'the smallest indivisible particle' and have speculated about the properties that such a particle would have; and the artisans of yore have unconsciously incorporated nano-particles into their ware. Feynman did anticipate many things in nanoscience much before they happened. Yet, 'Who is the father of nanoscience?' is a question that gives plenty of room for thought.

Keywords: Atoms, Feynman, microscopy, nanoscience, plenty of room.

'GREAT scientists come in two varieties... foxes and hedgehogs. Foxes know many tricks, hedgehogs only one. Foxes are interested in everything, and move easily from one problem to another... Richard Feynman was a fox... When Feynman came onto the scene in the middle of the century, the foundations were firm and the universe was wide open for foxes to explore' says his student, Freeman Dyson. Feynman struggled 'to understand the workings of nature by rebuilding physics from the bottom up'[1].

It has been 50 years since the famous lecture 'There's plenty of room at the bottom'[2] by Richard Feynman (Figure 1). In his lecture, Feynman talked about 'the problem of manipulating and controlling things on a small scale'. One of the people who attended this after-dinner talk at the California Institute of Technology (Caltech) on 29 December 1959 says that Feynman's talk was greeted with 'amusement'[3]. However, Roddam Narasimha, who was probably one of the few, if not the only Indian who attended the talk, recollects that it was as always attractive and that it succeeded in impressing everybody in the packed auditorium (Box 1). As time passed by, this celebrated speech came to be regarded as the starting point of one of the most sought-after branches of science today – nanoscience. In this article, we look into the various ideas that Feynman presented in his talk, their development over time, important events that marked their growth, and how much they owe their existence to Feynman.

Figure 1. A sketch of Richard P. Feynman (courtesy: Subhankar Biswas).

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Box 1. Reminiscences of Feynman's 'Plenty of room' lecture*.

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.

*Based on an interview with Roddam Narasimha, 4 July 2010.

Writing small

'Why cannot we write the entire 24 volumes of the *Encyclopaedia Britannica* on the head of a pin?' was the first question that Feynman asked in his lecture. He then proceeded to make this feat sound remarkably simple: 'The head of a pin is a sixteenth of an inch across. If you magnify it by 25,000 diameters, the area of the head of the pin is then equal to the area of all the pages of the *Encyclopaedia Britannica*. Therefore, all it is necessary to do is to reduce in size all the writing in the *Encyclopaedia* by 25,000 times.' He then went about describing how this could be done in principle – microscopes could be used to demagnify the image of the pages, and the concentrated light (or electrons) could be used to etch the words on the metal of the pinhead. He calculated that the smallest dot in the *Encyclopaedia* would occupy 32 atoms across on the pinhead, and so there was 'plenty of room'[2].

A modern technique that would perhaps embody this vision of Feynman is lithography. Various forms of this technique, such as photolithography (that uses UV light), electron-beam lithography (that uses, as the name suggests, a beam of electrons) and soft lithography have been developed over time[4]. Reduction in size of the text using lithography probably started with developments in optical lithography. In the 1970s, a lens made by Carl Zeiss was used to print an image reduced 10 times in size[5]. The extent to which the image printed using photolithography can be reduced in size depends on the wavelength of light used. A technique called deep UV lithography uses light of wavelength 193 nm to achieve a resolution of about 50 nm. With the development in lithographic techniques such as the electron beam lithography, it became possible to attain much higher resolution – of the order of about 10 nm. This was initially done using a Scanning Electron Microscope (SEM)[6], and improvements in microscopy led to improvements in lithography.

Certain limitations in electron beam lithography, such as its immense cost, led to the development of other techniques in the 1990s such as soft lithography[7]. This technique has been defined as 'a form of contact printing that uses a high-resolution elastomeric stamp with a chemical ink capable of forming a self-assembled monolayer (SAM) on a target substrate, which can guide material deposition on or removal from the substrate to yield patterns of other materials'[6].

To what extent were these developments in 'writing small' influenced by Feynman's 1959 lecture? It is hard to say.

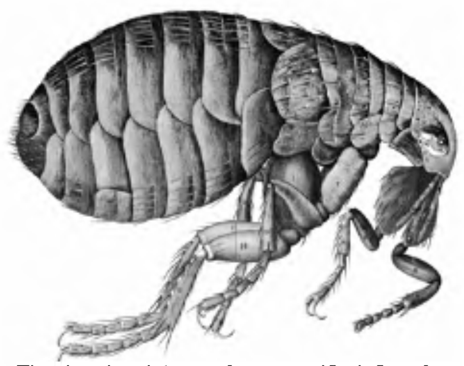
Seeing atoms

'If I have written in a code, with 5 times 5 times 5 atoms to a bit, the question is: How could I read it today? The electron microscope is not quite good enough... I would

Box 2. Evolution of microscopy – from glass lenses to 4D microscopy.

Henry Powers wrote in his poem, *In comendation of ye microscope* in 1664: 'Of all th' Inuentions none there is Surpasses the Noble Florentine's Dioptrick glasses. For what a better, fitter, guift Could bee in this world's Aged Luciosity. To Helpe our Blindnesse so as to deuize a paire of new and Artificiall eyes. By whose augmenting power wee now see more then all the world Has euer donn Before'. As this poem written in old English indicates, the human eye has some limitations. The spatial resolution of human eye is limited to 100 μm and the temporal resolution, to the fraction of a second[30].

Francis Collins once said, 'If you want to know the function, determine the structure'[30]. This requirement and the curiosity to see smaller objects has driven the development of microscopes, starting from a glass lens, to the use of artificial light, followed by the use of electrons for visualizing objects. It is believed that the Romans were the first to develop magnifying lenses. Alhazen (10th century CE) developed the *camera obscura* that ultimately led to the development of photography. The technique of grinding lenses was first developed in Italy in the 14th century (http://nobelprize.org/educational/physics/microscopes/timeline/index.html). This was put to use by Hans Jansen and Zacharias Jansen to make spectacles[31]. They also made the first compound microscope late in the 16th century[31]. The first book on microscopy, *Micrographia*, was published by Robert Hooke in 1665. Hooke was also the first to observe cork cells through a compound microscope[31]. Soon after this, in 1675, Anton van Leeuwenhoek developed a simple microscope and observed 'animalcules' in a drop of water (http://nobelprize.org/educational/physics/microscopes/timeline/index.html). In 1903, Richard Zsigmondy developed the ultramicroscope with which one could 'study objects below the wavelength of light'. Then the phase contrast microscope was developed by Frits Zernike, with which one could image colourless objects. Zernike won the Nobel Prize for this invention.



The iconic picture of a magnified flea from Hooke's *Micrographia*.

Another landmark in the history of microscopy is the development of the electron microscope by Ernst Ruska and Max Knoll in 1938. In 1986, the Nobel Prize in Physics was awarded to Ruska 'for his fundamental work in electron optics, and for the design of the first electron microscope', and to Gerd Binnig and Heinrich Rohrer 'for their design of the Scanning Tunnelling Microscope (STM)' (http://nobelprize.org/nobel_prizes/physics/laureates/1986/index.html). In 1955, Erwin Müller and Kanwar Bahadur developed the Field Ion Microscope. Later on, with the aid of the STM, one could get 3D images of atoms. Further progress in the field of microscopy has been signalled by the development of 4D microscopy. This technique of real-time imaging has been developed at Caltech and it allows for imaging changes in the structure and shape of nanoparticles by combining the time and spatial domains[30]. With the advent of 4D microscopy, we have indeed come a long way from Alhazen's *camera obscura*[32].

like to try and impress upon you the importance of improving the electron microscope by a hundred times', says Feynman[2]. Dependence on better microscopes for visualizing nano-size objects has been subsequently discussed by many, just as technological advances are being made at the other end of the spectrum to help us see galaxies and stars.

The desire to see smaller and smaller things and efforts to magnify objects, however, began much before 1959 (Box 2). Advances in microscopy made it possible to see microorganisms and cell organelles and ultimately, image atoms (Figure 2). Was this because Feynman said in his lecture, 'I put this out as a challenge: Is there no way to make the electron microscope more powerful?' According to S. Ranganathan (Indian Institute of Science and National Institute of Advanced Studies, Bangalore), 'Feynman was not aware of the fact that atoms had already been imaged before 1959; that is the story of Kanwar Bahadur. Atoms were imaged in 1955' (S. Ranganathan, pers. commun., 13 May 2010).

Erwin Müller and his student, Kanwar Bahadur, developed the Field Ion Microscope (FIM)[8] that made it possible to 'see atoms' for the first time. Melmed relates this thrilling story about the first time humans saw atoms[9]:

> 'The day of October 11, 1955 was a day long to be remembered by those of us who were in the laboratory. Bahadur had built the FIM to re-test the hypothesis that cooling the tip was worthwhile, and had gotten the experiment going. Now, he called Professor Müller into his laboratory room to show him the result. We waited outside quite anxiously . . . wondering what Müller's reaction would be to this long-awaited event. Inside, Bahadur has related to the author, when Müller saw the low temperature He image,

Figure 2. Evolution of the microscope – Anton van Leeuwenhoek's microscope, the compound microscope and the electron microscope. Source: http://en.wikipedia.org/wiki/File:Leeuwenhoek_Microscope.png, http://commons.wikimedia.org/wiki/File:MicroskopKremp_AG.JPG and http://commons.wikimedia.org/wiki/File:Transmission_electron_microscope_Kemira.jpg.

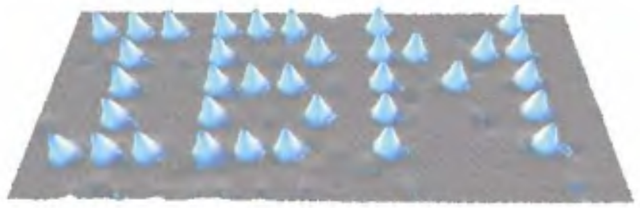


Figure 3. The iconic image of the IBM logo made by Donald Eigler by arranging 35 xenon atoms. Source: http://en.wikipedia.org/wiki/File:Ibm_nm.PNG.

> he said something like "This is it!". When Müller emerged from the room, he walked quickly across our lab to his office muttering simply, "Atoms, ja, atoms". For us, it was a time of unprecedented awe and joy; we thought that a Nobel Prize for Müller was shortly forthcoming. After all, Müller's microscope now made it possible to see atoms.'

This was such a remarkable breakthrough that it 'promised an understanding of all phenomena important in physical metallurgy in terms of the basic structural unit – the atom'[10].

Another student of Müller, John Panitz, developed the Atom Probe FIM in 1968, using which one could not only see atoms but also recognize them chemically. Müller, Panitz and others found that by coupling an FIM to a specially designed time-of-flight mass spectrometer, 'imaged atoms could be picked-off at will and identified – one at a time'[11]!

In 1983, much after Feynman's 'Plenty of room' talk (and the year in which Feynman delivered another talk, 'Infinitesimal machinery' or 'there's plenty of room at the bottom, revisited'), Gerd Binnig and Heinrich Rohrer of IBM Research Centre, Zurich, reached atomic resolutions using the Scanning Tunnelling Microscope (STM) that they had designed[12]. Talking about the development of STM, Ranganathan says, 'It was not because Feynman said "go and look at atoms"... they were developing the instruments independently. Once we could see individual atoms, the world was impressed. So some people credit Rohrer as being the father of nanoscience. But we can say, look Feynman anticipated the improvement in the electron microscope'. The power of STM was displayed in the most remarkable manner. In 1989, Donald M. Eigler moved and arranged 35 xenon atoms to form the IBM logo, 'dazzling Kings and Queens, Presidents and Prime Ministers' who 'released mega funds for research in nanoscience'[13] (Figure 3). Eigler won the Kavli Prize for Nanoscience in 2010 for the 'development of unprecedented methods to control matter on the nanoscale'.

After this, a number of new microscopic techniques such as Holographic Electron Microscopy and Scanning Probe Microscopy have been developed[14] and existing techniques have been improved to see atoms clearer and better, such as the technique to visualize the 'hidden' atom in graphite using the Atomic Force Microscope (AFM)[15]. Recently, the use of AFM in a controlled deposition of atoms to obtain the desired patterns was demonstrated in the Sn/Si system – a development that takes us still closer to 'the advent of future atomic level applications, even at room temperature'[16] (Figure 4). (This work won the Foresight Institute's Feynman Prize in Nanotechnology for the year 2009.)

Materials and manipulation – at the nanoscale

'The image of the buckyball, a beautiful C_{60}, was the reason why nanoscience was propelled into centre stage. For

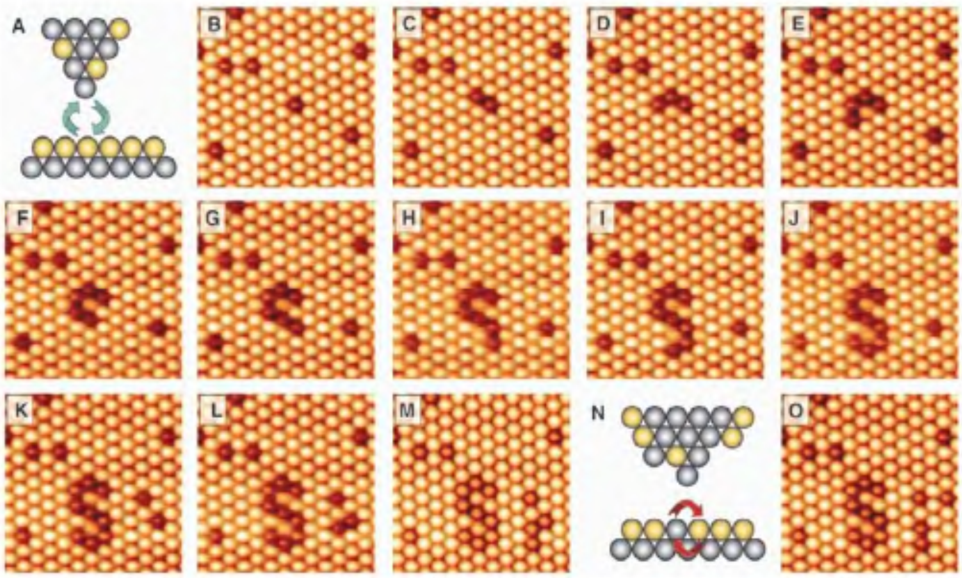


Figure 4. Series of topographic images showing the creation of atomic patterns. A and N, respectively, illustrate the concerted vertical and lateral interchange of atoms[16] (courtesy: Seizo Morita and Oscar Custance).

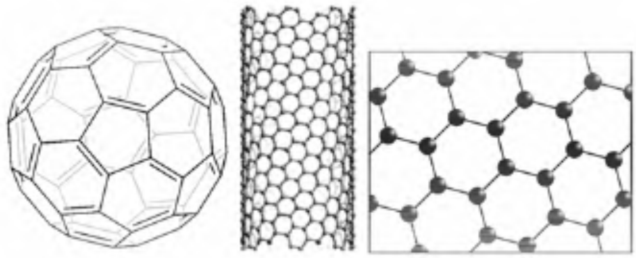


Figure 5. Fullerene, carbon nanotube and graphene. Source: http://commons.wikimedia.org/wiki/File:Buckminsterfullerene-2D-skeletal.png, http://commons.wikimedia.org/wiki/File:Nanotubos_enrolamento.PNG and http://commons.wikimedia.org/wiki/File:GraphenLayer.svg.

man to be impressed, there is nothing like seeing. He sees the beautiful images of atoms, he sees beautiful molecules, and feels it is wonderful', says Ranganathan. It is often said that the interest in nanoscience actually picked up only after the discovery of fullerenes, 25 years ago (Figure 5). An apparatus designed by R. E. Smalley, which used high-energy laser beams to vapourize materials, was employed to break carbon bonds in graphite. In an inert gas atmosphere, the carbons formed new bond arrangements and such spontaneously formed C_{60} was identified using mass spectroscopy[17,18]. R. E. Smalley, Harold Kroto and Robert F. Curl were awarded the Nobel Prize in 1996 for this discovery. But much earlier, in 1966, David Jones had suggested that 'if pentagonal disinclinations could be introduced among the hexagons in a graphene sheet, the sheet would close into a hollow balloon'. In 1970, Eiji Osawa had thought about the possibility of a stable C_{60} molecule, and had, with Yoshida, discussed the structure that such a molecule might possess[19].

The discovery of buckyballs fuelled great advances in the field of nanomaterials. In 1970, Morinobu Endo chanced upon carbon nanotubes (Figure 5) among carbon fibres (http://www.nanonet.go.jp/english/mailmag/2005/036a.html). S. Ijima, who is credited with the discovery of carbon nanotubes, identified them in 1991. Graphene, which had for long been the subject of theoretical studies, was isolated in 2004 by Andre Geim[20] (Figure 5). Today, a graphene sheet curling up into a fullerene can be observed using aberration-corrected transmission electron microscopy, in real time[21]!

Feynman had identified that 'seeing' atoms and chemical reactions would be one of the possible applications of improved electron microscopy. Another was to be able to 'arrange the atoms the way we want; the very *atoms*, all the way down!'[2]. This has, however, not been possible so far. 'In spite of intensive research we have still not been able to make carbon nanotubes in a reproducible form. We make all three forms of nanotubes – we don't even know how to separate them properly. If somebody can discover a way of manufacturing one type of tube by building it one atom at a time, we can build the chiral nanotube one atom of carbon at a time', says Ranganathan. The idea of the physicist synthesizing molecules by just 'putting the atoms where the chemist says' has not become a reality yet[22]. Feynman however did not specifically mention the importance of 'naming' or 'recognizing' atoms under the microscope, in his lecture. A step towards this end has been taken in an effort to identify individual atoms in a multi-element system using short-range atomic forces between the outermost atom of an AFM tip and individual surface atoms as a 'fingerprint'[23] (Figure 6). Now that seeing, recognizing and moving atoms have become possible, designing molecules under the microscope may not be a long way off.

Behaviour of molecules in the nano-domain is another area which is still only vaguely understood, though it is clear that 'atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things'[2]. Ranganathan illustrates this point: 'Gold, for example, melts at about 1064°C. But if you make 20 nm gold, it may melt at 600°. Fewer nanometres of gold will melt at room temperature. If you make it small enough, it will still be gold, but it will look green, white, or red'.

Miniature machines

Feynman, towards the end of his 'Plenty of room' lecture, discusses the possibility of manufacturing 'little' computers[2] (in 1959, computers occupied entire rooms). There was, apparently, some effort in this direction that was inspired by his speech. In 'Infinitesimal machines', Feynman describes one such miniature machine – a motor as big as a 'period at the end of a sentence' that one McLellan had devised[24]. Nanodevices are now used in computers, mobile phones and many other gadgets that we use on a daily basis.

How old is the concept of 'nano'?

Did nanotechnology really start with Feynman? Many people would say 'yes'. For instance, Drexler *et al.*[25] write in their book: 'Physicist Richard Feynman was a visionary of miniaturization who pointed toward something like molecular nanotechnology . . . he proposed that large machines could be used to make smaller machines, which could make still smaller ones, working in a top-down fashion from the macroscale to the microscale. At the end of his talk, he painted a vision of moving individual atoms. . . . He pictured making molecules, pointing clearly in the direction taken by the modern concept of nanotechnology'. However, many would say, 'not really', because there were people like Müller and Bahadur who had succeeded in seeing atoms before 1959, and others like Rohrer whose source of inspiration was not Feynman's speech. Chris Toumey asks, 'It *preceded* events like the invention of the scanning tunneling microscope, but did it inspire scientists to do things they would not have done otherwise? Did Feynman's paper directly influence important scientific developments in nanotechnology? Or is his paper being retroactively read into the history of nanotechnology?'[26] In fact, going by the citations to 'Plenty of room', the popularity of the talk went up only in the 1990s, about four decades after it was delivered[27] (Figure 7).

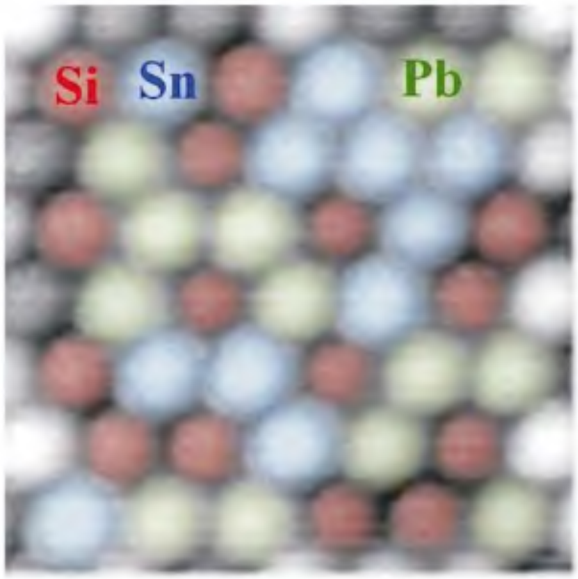


Figure 6. An AFM image indicating the chemical identity of atoms in a Si/Sn/Pb system (courtesy: Seizo Morita and Oscar Custance).

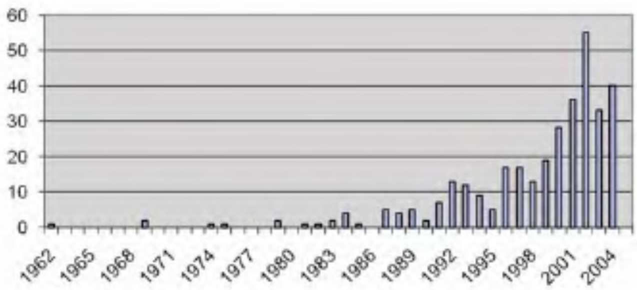


Figure 7. Graph showing citations to 'Plenty of room' (courtesy: Chris Toumey).

The concept of 'nano' itself is actually quite old. Ancient philosophers had contemplated about the nature of the 'smallest indestructible particle' that all matter is made of (Box 3). Besides, indigenous communities had unconsciously incorporated nanomaterials into products which, as a result, possessed unique properties. For instance, Wootz steel, once the pride of Indian sword-makers, was known for its strength and sharpness. TEM studies have now revealed that the strength is a due to the carbon nanotubes and cementite wires that the artisans had unknowingly incorporated into their ware[28]. The Mayan blue pigment that has not faded in centuries has white clay particles that are embedded in nano-sized surface grooves. Indigenous communities in Central America developed glass blades that measured 3 nm across, that are sharper than modern diamond scalpels[29].

The nature of nanotechnology seems to be as obscure as its origins. An editorial in this journal discussed this issue: 'Nanotechnology . . . "should let us (i) Get essentially every atom in the right place (ii) Make almost any structure consistent with the laws of physics that we can

Box 3. Origins of atomicity – the Indian and other concepts*.

The term *paramānu* that is featured in many Indian philosophical discussions is often translated as 'atom'. But this translation, or reference to discussion about the *paramānu* by ancient Indian philosophers as 'atomicity in India', is rather misleading. The *paramānu* was conceived as a concept representing the lower limit of size, much like infinity is used to denote the upper limit of measurement. Unlike the modern 'atom', the *paramānu* is not an entity that can be subject to experimental analysis, or something which we can strive to 'see' using state-of-the-art instruments, but is an entity whose existence can be deduced by logic alone. *Paramānu* can be defined as 'that than which nothing smaller exists'.

The term *paramānu* was coined by the Jain philosophers[33]. According to them, the *ajīva* or non-living component of existence is composed of *paramānus* that are all uniform in character[33]. Kanāda (approximately 600 BCE), the founder of the Vaisheshika School (one of the six Vedic schools of philosophy), discusses the *paramānu* in his work, *Vaisheshika Sūtra.* His proof for the existence of *paramānus* begins with the basic premise that physical objects are divisible. This property of matter leads to two possibilities – (i) the division goes on forever, yielding infinitely smaller and smaller particles, or (ii) the division stops when the 'smallest particle size' is reached. Infinite divisibility was negated and the particle size at which division stops was called the *paramānu.* According to Kanāda, the *paramānu* was partless, without beginning and eternal.

The Vaisheshika School, unlike the Jain school, recognized four types of *paramānu* – earth (*prithivī*), water (*ap*), fire (*tejas*) and air (*vāyu*), that move in the medium of vacuum (*ākāsha*), and aggregate to form matter. This aggregation follows a two-step process – two *paramānus* of the same type come together to form a dyad (*dvyanuka*). Three *dvyanukas* come together to form a *trasarenu.* These then combine with other *trasarenus* to form various objects.

Two of the four Buddhist schools too accepted the existence of the *paramanu*[34]*.* They however did not accept the *trasarenu* concept and suggested that the aggregation happens by the accretion of six *paramānus* around a central *paramānu.* This concept however was negated by Vasubandhu, a Buddhist philosopher who did not accept the *paramānu* concept, thus: 'The simultaneous accretion of six *paramānus* would mean that the central *paramānu* has six parts (which is not possible, as the *paramānu* is partless). On the other hand, if the *paramānus* touch each other at all points, there would be no increase in the size of the object (since all points on one *paramānu* would then belong to every other *paramānu*)'[33].

While the Indians were developing their concept of *paramānu*, atomicity was being discussed in other parts of the world too. Greek philosophers such as Thales and Leucippus have discussed the concept of the indivisible 'atom'. They too consider earth, water, air and fire to be the four basic 'elements'[33]. Islamic philosophers such as Abu al-Hudhayl considered the 'atom' to be indivisible, not of a material nature and indistinguishable from one another, and also suggested that atoms are finite in number and are separated by vacuum[35].

*Based on an interview with Arindam Chakrabarti, 27 May 2010.

specify in molecular detail (iii) Have manufacturing costs not greatly exceeding the cost of the required raw materials and energy". To me, all of this sounds very much like chemistry and chemical technology. Is nanotechnology really chemistry in disguise?'[22] Perhaps it is!

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