

Nanotechnology

Planning for the Future Now

22 May 2003

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Nanotechnology - the manipulation of matter and fabrication of devices at the atomic and molecular level - is currently one of the most intellectually exciting and potentially rewarding fields of scientific endeavour. The developed world is investing heavily in this commercially significant area. Nevertheless, visions of human progress through nanotechnology have recently been clouded by fears expressed by a few that it could release self-replicating nano robots that would transform the world into 'grey goo'. While most experts agree that this doomsday scenario remains firmly in the province of science fiction, it has prompted researchers, policy-makers and industry to consider more deeply the application of nanotechnology in society and how it should be regulated.

This seminar, chaired by Professor David Wallace President of the Institute of Physics, discussed what nanotechnology is *really* about with examples from research in electronics, materials and biology. Professor Mark Welland, Director of the Interdisciplinary Research Centre (IRC) in Nanotechnology, University of Cambridge, discussed the evolution of nanotechnological concepts and described progress in engineering at the atomic and molecular level to make new material structures and devices. Professor John Ryan, Director of the IRC in Bio-nanotechnology at the University of Oxford, showed how Nature depends on biological machines that work at the nano-scale, and considered how the principles on which they are based could be exploited.

The seminar also explored how the UK should organise and develop its investment in nanotechnology to best exploit the many applications.

The nanoworld

Nano has become a prefix familiar to everyone. It comes from the greek word for 'dwarf', *nanos*, and formally refers to the scale of 10^9 , or one-billionth of a unit. A nanometre is therefore one-millionth of a millimetre - and to give some idea of scale, a human hair is about a one-tenth of a millimetre, or 100,000 nanometres across. A nanometre is also about the width of five atoms, which is why nanotechnology operates at the scale of atoms and molecules, including many biological structures. The famous football-shaped carbon molecule, C_{60} , is about a nanometre across.

Engineering at the smallest scale

Professor Welland described how the concept of making ultra-small devices could be traced back to a lecture to the American Physical Society in 1959 called 'There's plenty of room at the bottom' given by the famous physicist Richard Feynman. This remarkable thinker envisaged assembling minute machines and circuits atom by atom. He realised, of course, that friction, or 'stickiness' between atoms would be an issue, and also anticipated that at this scale it would be possible to harness the sometimes-strange laws of quantum mechanics, which must apply at this level. In particular, Feynman suggested that devices based on quantum transitions in single atoms would offer an entirely new type of computing process (see IoP *Visions* paper 'Quantum information'). Indeed today, researchers are trying to turn that idea into reality.

Since Feynman's vision, electronic devices used in computers, such as transistors, have become ever smaller thanks to the development of some remarkable fabrication techniques which can lay down layers of atoms in a material in a pre-determined way. The Japanese scientist Norio Taniguchi, who was interested in making thin films of exact dimensions, first defined the word 'nanotechnology' in 1971 as the production technology that aims to achieve precision and fineness of structure on the scale of a nanometre. Today, it is possible to make ultrathin films only a few atoms thick and sculpt crystalline surfaces at the atomic level using a variety of tools such as lasers, beams of particles, gases and plasmas (electrically charged gases). In this way, physicists can create minute devices that allow even single electrons to be manipulated. At this scale quantum

laws rule, producing new electronic effects to exploit. The next generation of CD players will probably employ lasers based on 'quantum dots' - nanoscale semiconductor structures which behave like artificial atoms with analogous quantum energy levels. The wavelength of light they emit is governed by their size and the semiconductor used to construct them.

One of the most powerful tools underpinning nanotechnology is the family of scanning probe microscopes first developed in the 1980s. These microscopes rely on various physical interactions - mechanical or magnetic force, electric current, and so on - between an ultrafine tip and atoms on a surface so that an image of the nanostructure or device can be constructed by scanning the tip over the surface. In fact in 1990, Feynman's concept of manipulating atoms one by one was realised by Don Eigler at IBM when he famously used a scanning tunnelling microscope (STM) to create the word 'IBM' out of atoms.

From top-down to bottom-up

At about the same time, futurologist Eric Drexler, then at the Massachusetts Institute of Technology (MIT), suggested a completely different approach. He thought it would eventually be possible to design minute machines with functionalities built of molecular components that could self-assemble and replicate. He imagined that such nanomachines could be programmed, for example, to go into diseased cells in the body and repair them, or even autonomously manufacture spaceships outside the Earth's atmosphere. It is Drexler's (potentially over enthusiastic) 'assemblers' that has led to the imagined grey goo apocalypse.

Although the idea of such machines is farfetched, and attracts heated controversy about the practicality of their realisation, the underlying concept of self-assembly is important. This is very much the province of the chemist. Over the past three decades, chemists have been designing simple molecular assemblies, held together by directed supramolecular forces, which might function as electronic switches or light sensors, for instance.

One example that has caught the imagination of many are the fullerenes such as C_{60} . These spherical structures, which won Harry Kroto (a UK chemist) and Rick Smalley the Nobel Chemistry Prize in 1996, can harbour atoms in their interiors which endow them with interesting electronic properties such as superconductivity. Even more intriguing are nanotubes - tiny rolled-up sheets of graphitic carbon - which look set to have a variety of potential applications. A company called Babolat is already selling tennis rackets using carbon

nanotubes as a material with superior mechanical properties. Researchers in the Netherlands recently demonstrated logic gates (the basis of computers) using transistors based in single carbon nanotubes, while Malcolm Green's research group at the University of Oxford, has synthesised nanotubes containing various molecular species including crystals of potassium chloride and even proteins.

Ultimate nanotechnology

Nanotubes are just one manifestation of the principle of 'bottom-up' fabrication as opposed to the 'top-down' approach as traditionally employed in miniaturising electronic devices. In fact, biological evolution offers a definitive example of nanoscale self-assembly (the resulting humans could even be regarded as the ultimate assembler systems turning the world into grey goo!). Professor Ryan noted that in biological systems, large, complex molecules such as proteins form spontaneously under the right conditions, eventually being integrated into a larger microsystem - the cell.

Researchers in nanotechnology are increasingly studying a whole series of cellular components, from proteins to microtubules, in order to understand the design rules of Nature and then apply them. A potentially important area of applications is biomolecular mechanics. Jason Davis and colleagues at the University of Oxford have been interested in studying electron transfer in proteins, for example, metallothioneins which contain zinc or copper atoms. Amazingly, using scanning tunnelling microscopy, they could image the zinc atoms within the protein in its natural watery environment. This was a prelude to studies of another electrically active protein, cytochrome c. In one experiment, cytochrome c molecules were attached to a carbon nanotube to create a transistor.

Perhaps the most obvious molecular motors in biology are the nano-sized building blocks of muscle - filaments of the proteins myosin and actin. The action of muscles comes from the sliding of these filaments over each other. This process has been observed at the single molecule level by Claudia Veigel and Justin Molloy at the National Institute for Medical Research (a partner in the Bionanotechnology IRC) using the technique of optical 'tweezers', in which the force exerted by light from a laser beam can imprison very small objects. The ends of an actin filament were attached to two glass beads held in position by lasers. When the myosin molecule begins to 'walk' along the actin filament, it pulls on the actin and displaces the attached beads. This technique measures the forces generated and the efficiency

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of the motor, and allows the step-size to be measured with nanometre precision.

Another set of protein assemblies of great interest are ion channels. These form pore-like structures in the cell membrane which allow the passage of ions such as those of calcium, potassium, sodium and chloride in and out of cells. The pores are less than a nanometre in diameter and are highly ion-selective. They behave like transistors in which a tiny voltage across the cell membrane causes channels to open and close thus regulating the ion current. Such voltage-gated ion channels control electrical activity in nerve, muscle and many other kinds of cells. The voltage changes are very small compared with those in a standard silicon transistor, and physicists are trying to understand exactly how they work at the atomic level. Not only are these channels potentially interesting as models for developing devices, they are also implicated in a number of diseases such as cystic fibrosis and diabetes. Just recently, researchers at the University of Oxford have unravelled the behaviour of a potassium ion channel implicated in controlling the release of insulin.

An interdisciplinary field

Nanotechnology thus brings together the fields of physics, engineering, chemistry, molecular biology and medicine to offer a huge variety of applications. Here are just a few:

- Minute electronic devices working in new ways;
- Quantum information processing;
- Increased data storage using nano-sized-magnetic particles;
- Biosensors making use of individual molecules for instant medical diagnosis;
- Smart materials with new properties for construction, aerospace and transport;
- Novel, cheaper manufacturing processes such as inkjet technology to print nanometre-sized electronic elements;
- Complex liquids of minute particles and micelles containing active ingredients for use in cosmetics and domestic products;
- A better understanding of disease through the study of molecular assemblies in cells;
- Application of nano-scale biologically-based structures in electronics and engineering; and
- Precise delivery of medicines to tissues in the body.

The UK's future

The US is investing \$800 million in nanotechnology in this year alone. Germany and Japan are also investing heavily. So far, the UK has funded two

nanotechnology IRCs, a nanotechnology Research & Technology Centre at the University of Newcastle and related IRCs in tissue engineering and quantum information. Professor Welland put the scale of the UK investment into perspective: "The total budget we have for the IRC based at Cambridge (includes the University of Bristol and University College London) is £20 million over 5 years, while Californian universities are planning to spend around \$380 million on an equivalent facility."

Because of the limited funding available in the UK, Professor Ryan pointed out that coherent strategy for investment was vital. "We really ought to be developing a road map with applications in the forefront of our minds," he said. "We need an integrated approach to funding between the various Government agencies to build on the centres we already have." He also emphasised that international collaboration was essential, supported by the appropriate interdisciplinary training of doctoral students. The centres must also provide easy access for industry.

Finally, the seminar participants stressed the importance of good public communication with further debate about regulation issues. Although the grey goo scenario is highly unlikely, the nanoparticles used, for example, in cosmetics may need to be tested for potential toxicological effects. Because nanotechnology covers a very wide range of scientific fields, from lasers to drugs, any regulatory law will have to be appropriate to a specific area.

Further reading

1. Richard Feynman's lecture 'There's plenty of room at the bottom', [<http://www.its.caltech.edu/~nano>].
2. *Engines of Creation: The Coming Era of Nanotechnology*, K. Eric Drexler, Fourth Estate, London, 1990.
3. *Scientific American*, special issue 'Nanotech', September 2001.
4. *New dimensions for Manufacturing: A UK Strategy for Nanotechnology*, DTI/OST, June 2002.
5. *Nanotechnology*, Institute of Physics Publishing's monthly journal, [<http://www.iop.org/EJ/journal/Nano>].

Written for the Institute of Physics by Nina Hall, Freelance Science Writer, Tel: ++44 (0) 20 8248 8565, Email: ninah@ealing.demon.co.uk

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The Institute of Physics
76 Portland Place, London W1B 1NT
Tel: +44 (0) 20 7470 4800 Fax: +44 (0) 20 7470 4848
Email: physics@iop.org WWW: <http://www.iop.org>
Registered Charity No. 293851