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Reith Lectures 2005: The Triumph of the Technology

Lecture 4: Nanotechnology and Nanoscience

Since time immemorial people have been entranced by structures of great size. From the Colossus of Rhodes and the Great Pyramid, themselves no mean technical achievements, to the mighty Cunard 'Queens' built here in Glasgow, and whichever is transiently the tallest building in the world, beholders have gaped at the gigantic. One simple attraction has been that of comparative scale, so many times the size of a man or a horse or of Nelson's column, as popular illustrations used to show. It was easy for the bystander immediately to apprehend the vast size of these objects.

In some of these instances, big was beautiful: the sole purpose of size was to inspire awe. But, increasingly, in other cases there was an important practical purpose, the superior functionality of a large steamship or aircraft, for instance, which would out-perform its smaller rivals. Starting with that greatest of engineers, I.K.Brunel, increase in size, whether of ships or railway locomotives, became an important technical aspiration.

We had to wait for the age of electronics, however, for miniaturization to become an important achievement in its own right - until the same kind of awe could be inspired by the very small. Over the centuries artisans painstakingly wrote prayers on the heads of pins, painted portraits so small that the detail is scarcely discernible, and carved ivory figures so tiny that one can but marvel at the dexterity of the sculptors. Collectors treasured these works as examples of remarkable human skill, but few if any practical applications were found for them and to most people they were, quite literally, invisible. Even in our great grandparents' day, the most advanced technology easily accessible to ordinary people was probably the pocket watch, in its day a triumph of miniaturization.

Electronics changed all of this. Electronics becomes better and more useful in almost every respect as it is miniaturized. Less than a lifetime ago, radio technology was awkward and cumbersome partly because it relied on vacuum valves to amplify the tiny radio signals. These 'valves' were not only bulky and fragile but they needed heat in order to work, so that a source for that heat was required, and the system had to be cooled. As I have already discussed in an earlier lecture, the development of the transistor after the Second World War changed all of that. Beginning with the original point-contact transistor, a family of devices was developed which superseded the thermionic valve, because they were faster, cheaper, and consumed less energy. Crucially, they were also smaller, so much so that eventually thousands of millions of them could be crowded on to a piece of silicon no larger than a postage stamp. When this vast assembly of electronic switches is brought into action, its computational power rivals that of the human brain. It is a technology that has changed the way we live.

In my view, this was the original thread in the tapestry that has become nanotechnology and nanoscience. There are now dozens of threads of many colours that have been woven in to this tapestry and in this fourth Reith lecture I explore their origins and articulate a view about this suddenly so fashionable branch of science and technology. As in the history of any human endeavour, the weaving of the tapestry has not been without diversions and distractions and some of the more extravagant and exaggerated threads have had to be unpicked. I will also use the relationship between nanotechnology and nanoscience to illustrate the more general relationship between science and technology. It is rich with examples of the different ways in which scientists and technologists are motivated and go about their professions.

As I have said, the founding thread was the electronic chip. The concept of the chip emerged in the late 1950s when it was first realised that it would be possible to integrate all the elements of an electronic circuit onto a single piece of silicon. As a result, it was no longer necessary slavishly to follow the route that been used with valve electronics, where circuits were built up with physically separated components, that were linked together with wires. Instead it became possible to fabricate all the elements simultaneously in a single piece of silicon using 'microlithography', a process that had its roots in the art of lithography. Microlithography is used first to fabricate the transistors in the silicon and then to pattern the multilayer maze of wires on top of the transistors that interconnect them. For the first two decades of this miniaturization revolution, the prefix 'micro' seemed adequate, but when we managed to make an 8 nm wire at IBM in 1976, and even wrote USA 1976 in 10 nm gold letters, we decided that it was time to replace 'micro', or one millionth, with 'nano' meaning one billionth. The electron beam method we used was derived from one that I had used in Cambridge in the early 1960s to make 50 nm metal structures. It would have taken about a hundred million of the 8 nm diameter wires to form a cable the size of a human hair and we decided that the term microlithography was no longer adequate, so we introduced the term nanolithography. This was the first technology to adopt the 'nano' prefix.

Initially we said that to be a 'nanostructure' the structure had to be smaller than10 nm, but over the years, because too few useful artificial structures of this size were made, the definition was relaxed to 100 nm. The early nanostructures were not used in integrated circuits because nobody knew how to design a transistor that small. In fact for many years it was thought that transistors would not operate properly when their dimensions were reduced below a micron, or 1000 nanometres, but these pessimists proved resoundingly wrong. In a modern transistor, the 'gate length', which is approximately the distance the electrons have to travel, is only about 40 nanometres.

Although the nanostructures were not immediately useful to integrated circuits, there was a surge of interest in them because they allowed quantum phenomena to be observed - they were so small that electrons passing through them behaved as waves as well as particles and it was hoped that this behaviour might be used in devices - and naturally the techniques used to make them were also used by those exploring the limits of transistor fabrication. One of the leading laboratories in the world in this field, especially in the fabrication of very fast transistors, is here at Glasgow University.

The wonderful progress that has been made in miniaturizing electronics, and which was accurately predicted by Gordon Moore forty years ago, has now reached the point where 'microelectronics' has become 'nanoelectronics', and electronic chips are now without doubt amongst the most useful of the nanotechnologies.

The second thread that makes up the nanotechnology tapestry had its origin in 1981 in the development of the scanning tunnelling microscope, known as the STM, a striking new scientific instrument that won its creators, Gerd Binnig and Heinrich Rohrer, a share in the 1986 Nobel Prize in Physics. The STM and a number of instruments that operate in a similar way, are simple in concept but have proved capable of producing immense quantities of original scientific data about surfaces and molecules, and a version of the STM was used in the late 1980s to produce the ultimate in nanofabrication - the placement of single atoms. The STM truly works at the nanoscale and the scientific information it produced comprises the oeuvre that became 'nanoscience'.

The scanning tunnelling microscope consists of a tiny metal wire that is scanned across the surface to form an image of the surface - in the same way that the spot scans across the screen to form a television image, but more slowly. The tip is brought so close to the surface that electrons tunnel across the gap, and the tip is raised and lowered to keep this tunneling current constant. The instrument is so sensitive that the tip has to be raised and lowered to pass over individual atoms, and as it moves up and down, the brightness or colour of the image changes. The microscope 'sees' atoms as arrays of adjacent spheres, rather like oranges packed in a crate.

Interestingly, it was another scanning instrument, the scanning electron microscope, that uses a tiny beam of electrons rather than a metal tip, that we used to fabricate the 8 nm wire in 1976, and Ernst Ruska, the designer of the first electron microscope, shared the Nobel prize with Binnig and Rohrer. In terms of ultimate capability the STM was able to place individual atoms, which are some forty times smaller than the 8 nm wire so it might be thought that the STM would be an ideal tool for fabricating electronic devices, and that it would immediately make it possible to make transistors with atomic proportions. Unfortunately, this is not the case; the process of placing atoms is far too slow to be economically practicable.

In contrast, the microlithography process that I described earlier is immensely fast. A modern microlithography camera exposes in one second a pattern that contains the elements of billions of transistors. The pattern has the complexity of a million high definition television images, so the camera has an effective exposure rate of about a trillion pixels per second. It is because billions of transistors are produced simultaneously that they become individually so cheap. The cost of a transistor has been reduced by a factor of more than ten million times since I was an undergraduate in Melbourne in the 1950s. To expose a pattern of this complexity using the same technique used to place single atoms in the STM would take tens of thousands of years. To overcome this constraint, researchers have been using arrays of thousands of tips to increase the speed of the process but so far the shortfall in writing speed remains immense. This is a classic example of the difficulty often encountered in bridging between science and technology. Technology by necessity must be practicable and economically sensible. With science, discovery is sufficient.

The next thread in the tapestry had its roots in mechanical engineering, in the ability to make precise components for a wide variety of products. It was in effect the skill underlying watch-making more than two centuries ago. In recent times the precision required in the components of jet engines, car engines, electric motors, cameras, telescopes, etcetera has reached the nanometre level. To meet this demand machines such as lathes and milling machines have themselves become examples of nanometre precision. Lathes have their cutting tools positioned with laser interferometers that are accurate to nanometres, and the cutting edges are made from diamond so that they do not wear. Laser controlled diamond machining in effect became a nanotechnology more than twenty years ago, and as such was one of the earlier of the new array of technologies to do so.

Another early example of the use of nanometre size elements was catalysis, where nanometre particles are used to 'catalyse' chemical processes. A well-known example is the catalytic converter used in car exhausts systems that has been so effective in reducing the pollution produced by vehicle engines. There are many other areas where the boundaries between chemistry, chemical engineering and nanotechnology become blurred.

The next series of threads arose from what had previously been known as thin film technology. It has long been possible to deposit, or grow, very thin films on surfaces to improve the properties of the surface for a variety of purposes, for example to increase resistance to corrosion and wear. Such films have been used extensively on the metal components of engines of all kinds producing great increases in lifetime and performance. Thin films on window glass reflect the suns rays and keep buildings cool in summer, or reject contaminants and keep the windows clean. Pilkington's self-cleaning glass is a striking example of what can be achieved. Thin film coatings have been used for almost a hundred years on the elements of lenses used in microscopes, telescopes, binoculars and cameras where they reduce scattered light by eliminating reflections and thereby increase the contrast in the image. Very often these thin layers are less than 1000 nanometres in thickness and hence their use can correctly be called a nanotechnology.

Another large group of threads arose from material science, especially composite materials. Composite materials have been around for decades, but recently the fibres and particles that are imbedded in these materials have become small enough to be classed as nanostructures and hence the whole subject becomes a nanotechnology. The outstanding examples in this category are the carbon fibre reinforced materials, especially those that use carbon nanotubes that are only few nanometres in diameter, and the sun screens that include nanometre particles to increase the absorption of ultra-violet radiation.

It is in the use of these nanoparticles and nanotubes that concern has most plausibly been expressed about the risks and dangers of nanotechnology. It is suggested that these particles may enter living cells more easily than larger particles and trigger unforeseen processes, and it is known that particles of this size may be more active chemically than larger particles of the same material. The air is full of nanometre-sized particles which we breathe in and out all the time but past experience teaches us to be cautious. Asbestos, cigarette smoke and carbon particles emitted by diesel engines come to mind. The two particular nanoparticles that have gained attention are titanium oxide nanoparticles that have been used in sun screens to filter out damaging ultra-violet radiation; and carbon nanotubes that may be used in composite materials to add strength, or as elements in electronic devices.

The recent report of the Royal Society and the Royal Academy of Engineering on Nanoscience and Nanotechnologies recommends that these nanoparticles should be carefully monitored, which would seem to be a very sensible precaution and I am pleased that it has gained wide support. The report does not see other areas as posing threats and even with nanoparticles there is no risk when the particles are embedded rather than discrete. It would seem wise to me to be cautious about the use of any new materials, whether of nanometre size or not, especially when they are to be brought in to contact with people and animals.

There is another aspect of nanotechnology that has gained a lot of attention as a potential threat but which is perhaps at most speculative and unproven. This is molecular manufacturing, which is the name given to the concept of using an 'assembler' to build up structures atom by atom to form molecular machines. It has been suggested by the proponent of this technology, Eric Drexler, that these machines could replicate in an uncontrollable manner to form what has been called 'grey goo'. But to date there has been no experimental verification that such machines could be built or that there are mechanisms by which they could replicate. There are not even proven ways to model such structures. As the report of the Royal Society and the Royal Academy of Engineering said "Our experience with chemistry and physics teaches us that we do not have any idea how to make an autonomous self-replicating machine at any scale."

There are of course biological systems that do replicate, and some of these, such as the bacterial viruses, are about 100 nm in size. However, they have to attach to a bacterium in order to replicate and we are far from understanding the details of the way in which they do this.

Which leads me to the group of threads that surprised me most when it became part of the nanotechnology tapestry; the group that has its roots in biochemistry and molecular biology. But having accepted that nanotechnologies were to do with structures and phenomena that have nanometre dimensions, as indeed we suggested more than thirty years ago, I should not have been surprised. DNA molecules and proteins have dimensions of nanometres and, as molecular biologists can manipulate the molecular structure of proteins and DNA, they can surely call themselves nanotechnologists, should they wish to do so.

But at this point I feel that the descriptive net may have been spread too far, and I have only had time this evening to mention a selection of threads that make up the tapestry of nanoscience and nanotechnology - others include the micro-electro-mechanical devices (MEMS), especially sensors, ceramics, light emitting diodes, nanofiltration membranes, drug discovery, compact disks, and on and on. Inclusion of molecular biology along with all of these means that nanotechnology covers almost all modern technologies, and the term becomes so unspecific that its usefulness is limited and it can be confusing to people. However, there are clearly advantages to the adoption of the labels 'nanotechnology' and 'nanoscience'. There is the excitement created by what is a new and exciting group of technologies, even if individually its members had perfectly satisfactory names, and those that take on the title gain the glamour of the most successful, and more importantly make themselves eligible for any funding that is allocated by government and private sources. On the other hand it is unfortunate for the majority of nanotechnologies that they should be linked with the potential dangers of the few that involve discrete nanoparticles, or with the unrealistic speculation that has accompanied nano-robots and self-replication.

Centuries ago, the watchmaker and instrument-maker with his eye-glass was working at the limit of then-available technology, in fabricating mechanisms which could hardly be seen by the naked eye. His was the technique which prefigured the almost infinitely-smaller technologies of today that have been enabled by the broad range of new microscopes and analytical tools.

But to go back to where I started this evening, I celebrate the fact that as the last century came to a close we saw the small catch up with the large in terms of practical significance to the human race. It would have been difficult to persuade Brunel that the ability to design and fabricate at the nanometre scale was going to have as much impact upon people as the ability to build bridges and railways, but I believe that this is now the case. Humankind stands to benefit as much - or more - from the brilliant array of nanotechnologies I have described as it did from the giant engineering achievements of a century or more ago.