IN-DEPTH REVIEW

Nanotechnology—what is it? Should we be worried?

Roger W. Whatmore

Abstract

This paper describes the origins of nanoscience from theoretical reasoning to its realization in terms of mechanical manipulation of atoms. The ability to visualize and manipulate matter at the nanoscale has led to a diverse technology that ranges from better and faster electronics and more efficient fuel usage to sensing, drug discovery and stronger, more resistant materials. It has the prospect of affecting the lives of all of us and already a number of applications are in the market-place. But in our development of these technologies, we need to take care to reduce the risks of the adverse consequences that usually attend new applications of science.

Key words

Hazards; materials science; nanoparticles; nanoscience; nanotechnology.

Origins of nanotechnology

What is nanotechnology? This is not as easy to answer as one might think because the term encompasses a huge range of activities. Nanotechnology has received enormous attention in the last 15 years—some commentators and financial observers—such as the finance house Merrill Lynch [1]—have even gone so far as to suggest that the impact of nanotechnology will be so great that the term will be used to describe a new era of world economic growth. The prefix ‘nano’ comes from the Greek word ‘nanos’ meaning ‘a dwarf’. Hence, ‘nanotechnology’ might well simply mean a technology to do with ‘small’ things. However, nano has also long been used as a prefix in scientific circles to mean 1 billionth (using billion in its American sense of a one followed by nine zeros). So we have the term ‘nanometre’ meaning 1 billionth of a metre. A nanometre is exceedingly small—only ~10 atoms across. On that score, we might expect nanotechnology to have something to do with technologies that are working at the nanometre level, and this is the general sense in which the term is used today. It is important to distinguish here between ‘nanoscience’, which is the study of phenomena at the very small scale, and ‘nanotechnology’, which implies an aim to achieve an end that is in some way useful. In 1994, the Royal Society/Royal Academy of Engineering Working Group on the subject adopted the following definitions [2]:

Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at larger scale.

Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometre scale.

The scale of dimensions adopted for the applicability of nanotechnology is usually <100 nm. Nanoscience, arguably, has been around since the early part of the 20th century, but the idea that there might be some technological advantages to be gained by working at the very small scale came much later. It was first put forward by the physicist Richard Feynman, when he gave a lecture in 1959 to the American Physical Society entitled ‘There’s plenty of room at the bottom—an invitation to enter a new field of physics’ [3]. In this lecture—which actually had almost no physics in it but is mainly concerned with the technology of making things—he explored the benefits that might accrue to us if we started manufacturing things on the very small scale. The ideas he put forward were remarkably prescient. For example, he foresaw the techniques that could be used to make large-scale integrated circuits and the revolutionary effects that the use of these circuits would have upon computing. He talked about making machines for sequencing genes by reading DNA molecules. He foresaw the use of electron microscopes for writing massive amounts of information in very small areas. He also talked about using mechanical machines to make other machines with increasing precision. He talked about exploiting the interactions of quantized spins, a kind of ‘spin logic’, which is now only being studied. Many of his predictions in that
The first use of the term nanotechnology was by Norio Taniguchi, who, in 1974, gave a talk describing how the dimensional accuracy with which we make things had improved over time [4,5]. He studied the developments in machining techniques over the period from 1940 until the early 1970s and predicted (correctly) that by the late 1980s techniques would have evolved to a degree that dimensional accuracies of better than 100 nm would be achievable. He applied the term nanotechnology to this.

All the early running in the field of nanotechnology was made by physicists and engineers, who mainly thought in terms of using one machine, made from components manufactured to a certain level of precision, to make objects, or components for another machine, to a greater precision. We now call this 'top-down' nanotechnology. It has led directly to the hugely successful semiconductor and information and communications technology industries, with a world market size in excess of $2 trillion, currently growing at 4.8% per annum. We all use advanced microprocessors in our portable computers. The current generation of chips, which have just gone into production in 2006, have metal lines written on them that are only 65 billionths of a metre wide and have >100 million transistors on a single piece of silicon a few millimetres across.

The march of decreasing dimensions in this field is inexorable, with linear dimensions reducing by a factor of \sqrt{2} every 18 months. Hence, the critical dimensions on a chip will be down to 45 nm by late 2007 and to 22 nm by the end of the decade. The technologies established by the semiconductor industry are also now being applied to the manufacture of tiny micromechanical machines for sensing and actuation. These ‘micro-electromechanical systems’ are finding their way into a host of applications, particularly in the automotive and medical fields, where cost and size-based functionality are key factors. We can start to see here the enormous effects that working at the very small scale is having on our world.

Feynman put forward two other themes in his lecture. First, he had envisaged the possibility of making machines that could pick up and place single atoms to make chemical compounds. In 1981, Binnig and Rohrer, at IBM in Zurich, invented the scanning probe microscope. This uses a very sharp metal point scanned over a surface to ‘see’ the atoms in the surface. They won the Nobel Prize for this work in 1986. In 1989, Eigler used the scanning probe microscope to ‘nudge’ atoms of xenon on a copper surface held at a temperature close to absolute zero to spell out the letters ‘IBM’. Eigler and his group have done some remarkable work, mainly using the technique to explore basic physical and quantum mechanical phenomena [6]. Gimzewski at IBM has used similar techniques, but at room temperature, to push single molecules around on surfaces. This kind of work with single atoms and molecules is called ‘extreme nanotechnology’.

Feynman’s second vision in 1959 was of a factory in which billions of very small machine tools were drilling and stamping myriad tiny mechanical parts, which would then be assembled into larger products. In the late 1980s, another scientist in California, Drexler, combined these ‘small manufacturing’ ideas of Feynman with another ‘thought experiment’ that had been put forward by von Neumann in the late 1940s. This was the idea of a mechanical machine—called a ‘clanking replicator’—that could be programmed to make replicas of itself. All it would need was a supply of raw materials and a source of energy. Those replicas would make more replicas, and the result would be an exponential growth in the number of the machines—until either the source of raw materials or the energy was exhausted.

Drexler’s combination of the clanking replicator idea with Feynman’s factory of tiny machines produced his concept of the ‘universal assembler’, first put forward in his book ‘Engines of Creation’ [7,8]. The clanking replicator concept is reduced to very small size through the use of mechanical components that are made on the molecular scale. The first ‘assembler’ would be programmed to make copies of itself by atomic and molecular manipulation. The exponential growth would lead to billions of assemblers that would be programmed to work in concert with each other to build virtually anything required. Clearly, such a technology would have enormous economic implications, in terms of material and energy use, effects on employment, etc. Drexler also first raised the alarm bells about the possibility of the assemblers reproducing out of control and reducing all around them to a ‘grey-goo’ of tiny machines. Actually, there is now a new variant on this vision, which postulates the fusion of nanotechnology with biotechnology to create an assembler that is at least partly biologically based. In this case, the problem becomes one of ‘green-goo’ rather than grey-goo, but the outcome is essentially the same. The potential feasibility of these ideas will be discussed in more detail below.

Development of the technologies

Some remarkable developments in materials science and chemistry have occurred over the last 15 years or so, particularly where small size plays a big role in determining basic properties. In this field, size matters! If we take a piece of a semiconductor less than a few tens of nanometres in size, then the electrons in it behave differently from those in the ‘bulk’. For example, the colours of light absorption and emission change. Very small particles (nanoparticles) of materials like cadmium telluride are being used in applications such as the labelling of biological molecules and in new types of displays. These can be made with amazing precision in
size—within a couple of nanometres—using reasonably standard wet chemical processes.

Very small particles (less than a few hundred nanometres in size) do not scatter visible light. Good absorbers of ultraviolet (UV) light such as titanium dioxide are now being made in nanoparticulate form for sunscreens. The fact that the particles are so small means that they are invisible on the skin, while still being highly effective as UV blockers. Very small particles also possess high surface areas per unit of mass. Oxonica, a start-up company from Oxford University, has found that nanoparticles of cerium oxide when introduced into diesel fuel act as oxidation catalysts during combustion. This provides improvements in fuel efficiency of up to 10% and reduces the emissions of carbon soot from the engine exhaust.

If we look at other areas of materials science, we see that new forms of carbon have been discovered. Harry Kroto from the University of Sussex, together with Richard Smalley and Robert Curl, discovered the carbon-60 molecule in 1985 and won the Nobel Prize for chemistry in 1996. This molecule is a sphere 0.7 nm across, which looks like a soccer ball, or the geodesic dome structure pioneered by the 1930s architect Buckminster Fuller, so they called it Buckminsterfullerene. It is amusing to note that if you could blow up the carbon-60 molecule to the size of a soccer ball, the soccer ball, if blown up by the same factor, would be about half the size of the planet Jupiter!

The ‘fullerenes’ form a whole family of related structures that possess remarkable physical and chemical properties. When fully fluorinated, the molecules (which can then be thought of as tiny ‘Teflon’ balls) form one of the best lubricants known. In 1991, Iijima discovered carbon nanotubes. These are like sheets of graphite rolled into long tubes, each one being terminated with a fullerene group. They also have remarkable properties. They can be either metallic or semiconducting, depending on the precise way in which the carbon atoms are assembled in the tube. The metallic forms have electrical conductivities 1000 times that of copper and are now being mixed with polymers to make conducting composite materials for applications such as electromagnetic shielding in mobile phones and static electricity reduction in cars. They possess mechanical properties that are many times those of steel, bringing the promise of replacing carbon fibres in a new generation of high-strength composite materials. They have been demonstrated in applications as diverse as super-capacitors for energy storage, field emission devices for flat-panel displays and nanometre-sized transistors. Clearly, these nanomaterials hold huge promise for the future.

So, what is nanotechnology? Firstly, it is very diverse. It employs all the conventional scientific and engineering subjects in order to achieve new applications through the exploitation of phenomena in which small size is the key to obtaining an exploitable property. Secondly, it is an area of endeavour where there are real and remarkable properties that we can seek to exploit. Thirdly, and increasingly, we are starting to see synthesis between different areas of nanotechnology. The size range of interest between a few nanometres and 100 nm is one where many interesting things happen. All sorts of physical properties change and many biological systems function in this length scale. Hence, we are starting to see the use of processes such as electron beam lithography, originally developed for writing very fine scale features on silicon for electronics, now being applied for the modification of surfaces on which biological species can be grown in a controlled way. The self-assembling properties of biological systems, such as DNA molecules, can be used to control the organization of species such as carbon nanotubes, which may ultimately lead to the ability to ‘grow’ parts of an integrated circuit, rather than having to rely upon expensive top-down techniques. This type of self-assembly is called ‘bottom-up’ nanotechnology. The convergence between the top-down and bottom-up routes to the exploitation of nanoscale phenomena is illustrated in Figure 1.

We are thus seeing an area that is providing real potential in its applications. Some people have predicted a world market for nanotechnology-related products that could reach trillions of dollars by the end of the decade. There is no doubt that the technology associated with our ability to manipulate matter on the very small scale is having major impacts on our lives and this impact will only increase. Hence, we should now ask the question: ‘Should we be worried?’ Could the introduction of nanotechnology have unforeseen consequences?

**Possible problems from nanotechnologies**

First, consider the Drexlerian dystopia in which a rogue ‘molecular assembler’ ostensibly created for the
betterment of mankind goes out of control and reduces everything to a ‘grey (or green)-goo’. Many highly rated, first-class scientific minds have stated that the assembler is not possible for many reasons. These include the ‘sticky fingers’ problem, whereby atoms picked up by an assembler would bond to the manipulator, making it impossible to place them where intended; problems with the storage and transmission of the huge amount of information needed and the vast complexity of the design required to make anything of this type, which would be far greater than the complexity of a modern microprocessor.

The assembler concept needs to stay where it belongs, firmly in the realms of science fiction. There are very real ‘self-assemblers’ all around us in the form of viruses and bacteria that owe nothing to nanotechnology but which pose a substantial threat, which is increasing, due to our farming practices, profligate use of antibiotics and cheap international air travel. The creation of this hazard cannot be laid at the door of nanotechnology, although some of the nanoscale techniques evolved for nanotechnology may well be able to help with combating it.

What about the less spectacular aspects of nanotechnology? Are there aspects of these materials that we need to be careful about? There is no doubt that the properties that give nanomaterials their technological exploitability might also give us cause for concern. We have already seen in the last 100 years how a single material with hugely beneficial properties can bring big problems.

Asbestos was very widely used in the period between the late 19th and late 20th centuries. It has extraordinarily useful insulating and fireproofing properties. The high-pressure, high-efficiency engines used in ocean-going liners and steam locomotives would have been impossible without it. However, we all know now how lethal asbestos fibres can be if inhaled in sufficient quantity.

Is there any risk that any of the materials that are emerging from our nanotechnology laboratories might be building up a similar problem for the future? There are certainly enough physical similarities between the dimensional characteristics of asbestos fibres and carbon nanotubes to cause some concern. At the moment, we just do not know if carbon nanotubes are hazardous or not. There has not been sufficient research. It is important to note that in many applications for carbon nanotubes, such as in composite materials or in electronic displays, the tubes would be very firmly tied up in a stable structure and would therefore be unlikely to pose a threat, although we should still ask questions about how the product would ultimately be disposed of. Would there be a chance of carbon nanotubes being released into the environment? We should also question how the products would be manufactured and what the exposure might be for manufacturing workers (or, indeed, researchers using the materials). A full life cycle analysis is essential for these new materials.

What about nanoparticles? Should we be concerned about inhaling these, or indeed rubbing them onto our skins? There is good evidence that we have been exposed to certain types of nanoparticles in the atmosphere for millennia. Wood-based camp-fires are an excellent source of nanoparticulate soot, for example. There is little cause for alarm, in the sense that nanoparticles, *per se*, do not constitute a new hazard at low levels of exposure. However, there is evidence that exposure to nanoparticulate matter from sources such as vehicle exhausts and welding fume is associated with increased risks to health. There is also evidence that, should nanoparticles lodge in the lungs, they may not stay there, but can cross the barrier into the blood stream and possibly migrate to other parts of the body. There is, at least to date, very little evidence to tell us what damage nanoparticles might cause.

On the specific issue of sunscreens, it is known that the main oxides of interest are inert when at the larger scale, but again there is a dearth of evidence about how these particles might behave when at the nanoscale. There is no evidence to suggest that they can penetrate healthy skin, but the fact that nanoparticles are known to have different properties from those exhibited at the larger scale must give us some cause for concern should they be ingested. There is a need for much more research in this area. We should consider treating size as a property when dealing with chemicals in, for example, assessments of chemical or disposal hazards, just as we would deal with any other chemical property. There is also a need for companies to put into the public domain the results of research on nanoparticle-based products. The uncontrolled environmental release of nanoparticles is another cause for concern. Nanoparticles that are not bound to other materials may become widely dispersed in the environment and turn up in unexpected places.

However, we must also keep a sense of proportion and take the ‘wide view’. We have little evidence at the moment that oxide nanoparticles form a general hazard and there may be benefits to their use. If a nanoparticulate oxide fuel additive can reduce nanoparticulate carbon emissions, then that may have significant benefits for the health of the general population. An improvement in fuel efficiency would make a positive contribution through reductions in carbon dioxide emissions and thereby a reduction in global warming. Similarly, if the availability of nanoparticulate sunscreens was to increase their general acceptability and thereby their use, then this might contribute to a reduction in skin cancer. It is certain that we need to understand more about all the health and environmental issues associated with nanoparticulate materials use.

Are there other areas for concern about nanotechnology? Nanotechnology, like virtually all technologies, is being considered for the contributions it can make to military defence. These include obvious developments such as improved electronic systems for communications,
improved sensors and, especially, improved materials. Examples include composites using carbon nanotubes and novel body armour that uses oxide nanoparticles dispersed in a fluid and held between two flexible Kevlar sheets. Metallic nanopowders can be expected to deliver more powerful conventional explosives. These developments would certainly give the armies using them a military ‘edge’ but this is no different in principle from other new technologies that have been pressed into military service.

One clear area of concern for the nanotechnologist is the perception of the subject by the general public. We certainly want to avoid the problems that have beset the GM area, largely through the attempt by large companies to impose GM crops and foodstuffs on the general public, without first entering into a dialogue with civil society representatives or attempting to engage people in debate. The approach backfired badly, especially in Europe. The study conducted early in 2004 under the auspices of the Royal Society and Royal Academy of Engineering showed that few people had any preconceived ideas about nanotechnology [2]. Those that had heard of the topic were more or less equally balanced between those who generally thought of it in terms of a beneficial high technology (better computers and mobile phones) and those who vaguely perceived it as slightly threatening or menacing. We are certainly not (yet) in the GM position. This is not to say we should be complacent. Nor is it correct to say ‘If only the general public understood more about our subject, then they would warmly embrace it.’ This ‘deficit model’ of the public understanding of science is pretty controversial. However, we as scientists and engineers certainly need to work harder to get the public, and especially our children, more engaged with the subject. This is a real area for concern, but again it is a general one and not simply to do with nanotechnology.

Conclusions

This article has tried to show how nanotechnology—the exploitation of matter when it is deliberately structured on the very small scale—has the potential to provide huge benefits, just as any useful technology should. It is a real, very broadly based and multidisciplinary area of human endeavour and not just a token epithet that can be applied to the latest research proposal or business venture in an attempt to get it funded, although admittedly it is frequently used that way. Certainly, there are issues that should concern us. These can be specific. We need, for example, to understand more about the health and environmental impacts of our uses of nanoparticles. There are also more general concerns. Nanotechnology could provide us with a broad range of capabilities and these should be applied in a thoughtful and responsible manner. However, these are similar to the concerns that might have been applied to any significant technology in the past. The only difference is that we are now in a position to learn from history and try to take action before mistakes are made but the action should be both proportionate and based on a realistic analysis of the likely risks and benefits of using nanotechnology.

Conflicts of interest

None declared.

References