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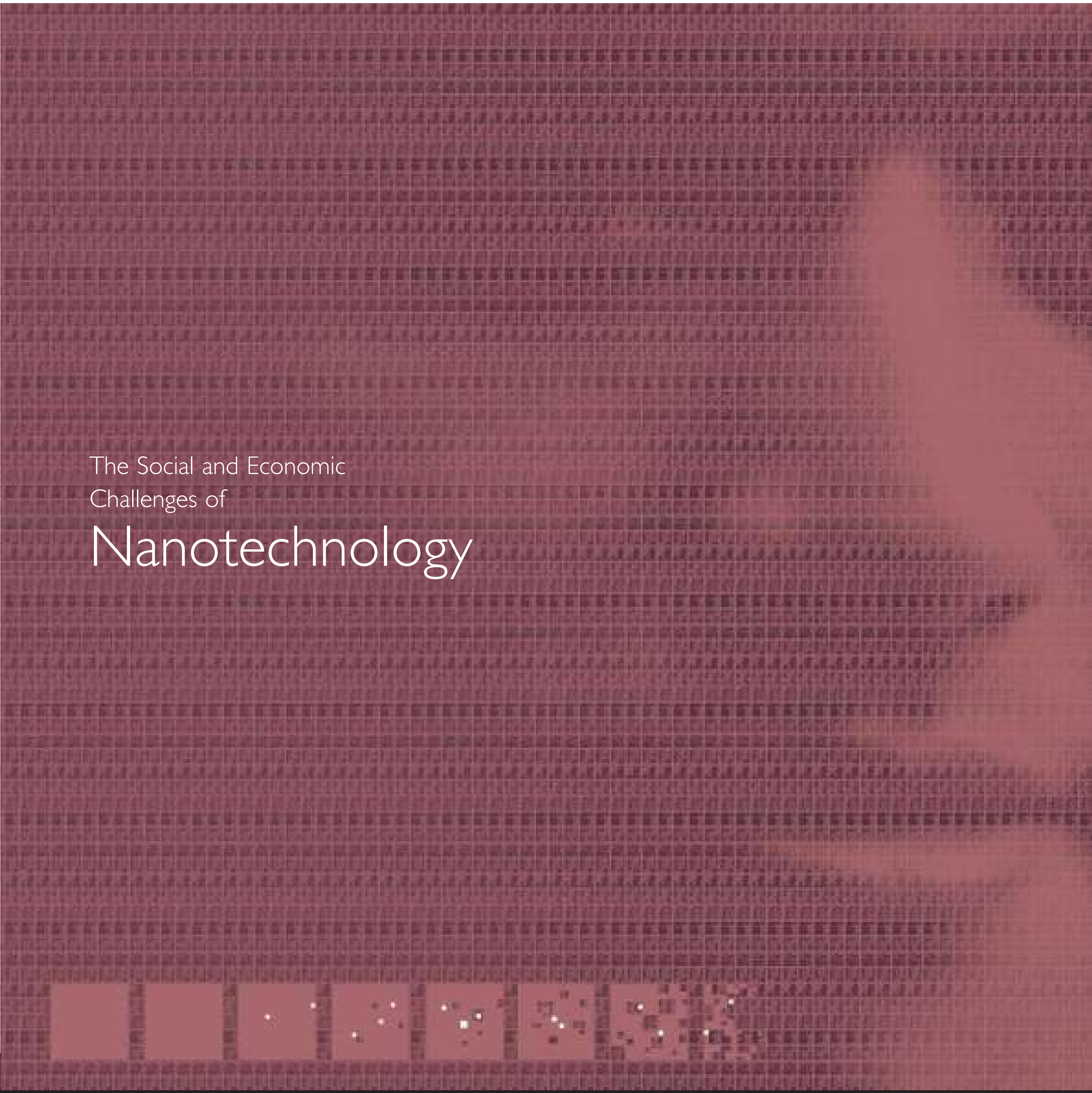

The Social and Economic Challenges of Nanotechnology

Professor Stephen Wood ▪ Professor Richard Jones ▪ Alison Geldart

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Nanotechnology is a new arena of science and engineering. Its early products mark only modest steps forward from those already in use, but its potential is immense. Its most extreme supporters claim that nanotechnology can rebuild the human body from within and effectively abolish death, while its enemies fear that instead, it could do away with life, by turning the surface of the Earth into an uninhabitable grey mess.

The truth probably lies somewhere between these extremes. But even here the consequences are certain to be significant, with novel medical technology, faster computers, new energy sources and improved materials.

It is the social, political and economic effects of nanotechnology that concern the Economic and Social Research Council. We are grateful to Professor Stephen Wood of the ESRC Centre for Organisation and Innovation and his colleagues for writing this report, which sets out the technological potential of this new field and illustrates very clearly the issues which nanotechnology raises for society as a whole. It has been produced by a team of practitioners drawn from the social and physical sciences, a form of collaboration that we are keen to encourage.

We are aware that nanotechnology is attracting the attention of governments, industry, research organisations and individuals across the world. We hope that they will find this report useful.

Professor Ian Diamond AcSS
Chief Executive
Economic and Social Research Council

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Foreword

The atomic structure of matter was quantitatively revealed by X-ray diffraction back in the early part of the 20th century. It led for example to the currently much-celebrated structure determination of DNA by Watson and Crick in 1953 based on the stunning X-ray diffraction patterns obtained by Rosalind Franklin.

But diffraction patterns, for all the quantitative information they contain, are not direct ‘real space’ representations of matter. They reveal ordered structures. With them you cannot pinpoint the position in space of a given atom, molecule or cluster. Achieving this required new developments in microscopy, and, in the second half of the century, a range of microscopes were duly developed capable of producing atomic-resolution images of atoms at surfaces.

The most dramatic of these developments was the scanning tunnelling microscope. Not only could the individual atoms and molecules be imaged; they could also be individually manipulated. Synthetic chemists and materials scientists have long demonstrated a remarkable ability to synthesise large quantities of desired products covering a size range from tenths of a nanometre upwards, including metal clusters, antibiotics, pigments, esters, polymers and a wealth of others. But here was something new: building a single molecular structure atom-by-atom. Laborious; impractical; expensive; yes, but it excited the imaginations of many around the world. A new buzzword appeared in science: nanotechnology was born.

Now the word has taken on a much broader meaning. Science and technology enthusiasts and science fiction writers – sometimes indistinguishable from each other – have picked up on this new theme. And yet others have highlighted massive potential problems for mankind in this new technology.

In this report the science and potential technologies are succinctly and clearly described. And, most importantly, the public debate, the literature spawned, and the economic and social consequences are thoroughly reviewed. It is a very timely and welcome review of this new field of endeavour.

Sir David King
Chief Scientific Adviser to HM Government

Nanotechnology is being heralded as a new technological revolution, one so profound that it will touch all aspects of human society.

Conceptions of nanotechnology are not always clear or indeed agreed upon.

Debate on the social implications of nanotechnology has largely focused not on the relatively mundane applications that have arrived so far, but on the longer-term possibilities of radical nanotechnology.

Nanotechnology will produce economic and social impacts on three broad timescales. Current applications are largely the result of incremental advances in already well-established branches of applied science.

Summary

Nanotechnology is being heralded as a new technological revolution, one so profound that it will touch all aspects of human society. Some believe that these influences will be overwhelmingly positive, while others see more sinister implications. This report assesses this debate in the light of our current knowledge of nanotechnology.

Conceptions of nanotechnology are not always clear or indeed agreed upon. The domain of nanotechnology is defined in terms of a length scale – from one nanometre up to 100 nanometres, called the nanoscale – and by the appearance at these scales of novel physical properties. These derive from the importance at these scales of physical phenomena that are less obvious for larger objects, such as quantum mechanics, strong surface forces and Brownian motion.

Nanotechnology will produce economic and social impacts on three broad timescales. Current applications are largely the result of incremental advances in already well-established branches of applied science, such as material science and colloid technology. Medium-term applications of nanotechnology will apply principles only now being established in the laboratory to overcome foreseeable barriers to continued technological progress. In the long term, entirely new applications may emerge.

Current applications for nanotechnology are dominated by tools for scientists, and by new materials that are structured on the nanoscale. Such materials are used in cosmetics, health and medicine and in a variety of manufactured goods. The electronics and information technology industries are also a prominent driver for these new technologies.

Debate on the social implications of nanotechnology has largely focused not on the relatively mundane applications that have arrived so far, but on the longer-term possibilities of radical nanotechnology. This debate anticipates a degree of control over matter on the nanoscale that permits fabrication from a molecular level of virtually any material or structure. While there is some debate about whether this vision is realisable, amongst those who accept it the discussion focuses on rather extreme outcomes, both utopian and dystopian.

There is also an emerging debate amongst those more focused on short-term outcomes. This pits those who believe that the rapid growth of nanotechnology will have strongly positive economic benefits, and those who on the grounds of environmentalism and social equity seek to slow or halt its development. One immediate issue that is growing in prominence is whether existing regulatory regimes are robust enough to deal with any special qualities that nanostructured materials may have, or whether new solutions are required.

These diverging views on nanotechnology and the increasingly public debate, involving civil society, non-governmental organisations and the media, have led to concerns that there will be a backlash against nanotechnology akin to that over genetic modification. In response the call is for social science to take a role focused on promoting social awareness and acceptance of nanotechnology.

The agenda for the social sciences needs to be broader than the public-science interface. Three themes stand out as important:

- the governance of technological change;
- social learning and the evaluation of risk and opportunity under uncertainty;
- the role of new technology in ameliorating or accentuating inequity and economic divides.

Tackling these themes will involve a range of social science issues, many of which are topical independently of nanotechnology, for instance technology transfer, ageing, the commercialisation of science, and change management. Nonetheless there may well be issues unique to nanotechnology, arising from its inherent interdisciplinarity and its capacity to affect the human-machine-nature interface. A programme of research designed to address the diverse social science issues should thus both build on existing research and develop fresh avenues, particularly through developing inter-disciplinary work that straddles social sciences, natural sciences and engineering.

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Visualising its potential is part of nanotechnology's development, as its nature and applications are discovered within the evolution of nanoscience and nanotechnology.

Nanotechnology is being heralded as the new technological revolution. For some its potential is clear and fundamental. It is so profound that it will touch all aspects of the economy and society.

Technological optimists look forward to a world transformed for the better by nanotechnology.

In this 'nano society', energy will be clean and abundant, the environment will have been repaired to a pristine state, and any kind of material artefact can be made for almost no cost. Space travel will be cheap and easy, disease will be a thing of the past, and we can all expect to live for a thousand years.

Countering the enthusiasts, pessimists see an alternative future, one that has also been transformed by nanotechnology, but in an apocalyptic way. In this world, self-replicating 'nanobots', whether unleashed by a malicious act, or developing out-of-control from the experiments of naïve scientists, take over the world, reducing the biosphere to 'gray goo'.

Introduction

Nanotechnology is being heralded as the new technological revolution. For some its potential is clear and fundamental. It is so profound that it will touch all aspects of the economy and society. Technological optimists look forward to a world transformed for the better by nanotechnology. For them it will cheapen the production of all goods and services, permit the development of new products and self-assembly modes of production, and allow the further miniaturisation of control systems. They see these social effects as an inherent part of its revolutionary characteristics. In this ‘nano society’, energy will be clean and abundant, the environment will have been repaired to a pristine state, and any kind of material artefact can be made for almost no cost. Space travel will be cheap and easy, disease will be a thing of the past, and we can all expect to live for a thousand years.

Countering the enthusiasts, pessimists see an alternative future, one that has also been transformed by nanotechnology, but in an apocalyptic way. In this world, self-replicating ‘nanobots’, whether unleashed by a malicious act, or developing out-of-control from the experiments of naïve scientists, take over the world, reducing the biosphere to ‘gray goo’. They consume its resources and render feebler, carbon-based lifeforms such as ourselves irrelevant, or even extinct.

We can expect to hear much more in the coming months and years about this potential nanotechnological nemesis. In 2002 Michael Crichton, author of best-selling books such as *Jurassic Park* and *The Andromeda Strain*, published a novel called *Prey*, in which a cloud of reproducing and evolving nano-predators escapes from a badly regulated laboratory and attempts to destroy the human race. The Hollywood blockbuster film is expected soon. Away from the world of entertainment, pressure groups have expressed concerns about nanotechnology’s dangers, which the media has seized upon. These include worries of the possible toxicity of nanomaterials, the perceived need for regulation, and the lack of public consultation in the development of the technology.

Meanwhile, scientists working in nanotechnology are slightly bemused at the extent of the furore, the first example of a backlash prior to a technology’s emergence. It is possible that scientists who have raised expectations about the potential of nanotechnology, in order to secure funding, share the responsibility for the emergence of this opposition. Meanwhile, other scientists are more cautious about what nanotechnology can achieve. For them the potential effects of nanotechnology, and even its nature, are less clear, or perhaps more mundane and incremental. Any discussion of its economic and social impacts cannot simply take the ‘new nanotechnology’ as a given.

Our starting point is not to prejudge the nature of developments in nanotechnology, but rather to assess what is currently known about its nature and potential and to link this to economic and social developments. Visualising its potential is part of nanotechnology’s development, as its nature and applications are discovered within the evolution of nanoscience and nanotechnology. Moreover, whether or not scientists themselves consider the possible social and economic consequences of their discoveries, social factors shape the development of their science and its associated technologies.

In this report we will assess the implications of nanotechnology for social science, on the basis of current understanding. We aim to:

☐ outline the basic nature of nanoscience and nanotechnology;

☐ assess the current perceptions of commercial applications of nanotechnology;

☐ consider the social and economic dimensions of nanotechnology.

The structure of the report reflects these aims: Chapter Two is concerned with the nature of nanoscience and nanotechnology; Chapter Three the applications of nanotechnology, current and foreseeable; and Chapter Four, the debate surrounding the economic and social dimensions of nanotechnology. We conclude the report in Chapter Five with a discussion of the possible implications of our analysis for the social science research agenda.

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The aim of this chapter is to set the scientific and technological context in which the potential social impact of nanotechnology can be discussed.

In discussions about nanotechnology much emphasis has been placed on its revolutionary nature and disruptive potential.

Improvements in the science of formulating the complex mixtures common in the chemical and pharmaceutical industries are another incremental advance in nanoscale science. These will lead to a reduction of the impact of agrochemicals on the environment by improving the targeting of the active ingredients, and in increasing the efficacy of pharmaceutical preparations.

Nanotechnology is likely to make an impact on medium-term timescales by providing methods to overcome well understood and long predicted barriers that stand in the way of the improvement of current technologies.

Outside the scientific community, nanotechnology has a hardcore following almost ideological in its fervour, and has now become a staple of science fiction.

Scientific Context

The aim of this chapter is to set the scientific and technological context in which the potential social impact of nanotechnology can be discussed. First, we make some preliminary remarks about the relationship between nanoscience and nanotechnology (NST) and the definitions of these terms, and about the way physics operates differently at the nanoscale. We will show that this leads to both constraints upon, and opportunities for, nanotechnology. Then some of the key technologies that have made nanoscience possible will be discussed. Finally, the most active areas of current nanoscience and technology will be reviewed. An overview of some near-term technological applications and some long-term visions will be given in Chapter Three.

In discussions about nanotechnology much emphasis has been placed on its revolutionary nature and disruptive potential. But it should be realised that many of the applications now being discussed in the context of nanotechnology are actually incremental advances in well developed areas of science, such as colloid science, metal physics, semiconductor physics and materials science. With the emergence of the concept of NST as a new branch of science there has been a considerable degree of rebadging of existing research programmes in an attempt by academic scientists and commercial technologists to associate themselves and their area of work with a very fashionable 'new new thing'. This means that some of the social impacts of NST, particularly in the short to medium-term, will be the continuation of existing trends. One particularly important long-run trend has been the reduction in the weight and amount of material in many artefacts, as materials become stronger and tougher for their weight. A consequence of this is the tendency for advanced technological societies to become less energy intensive, as measured by the amount of energy required to produce a unit of gross domestic product. Improvements in the science of formulating the complex mixtures common in the chemical and pharmaceutical industries are another incremental advance in nanoscale science. These will lead to a reduction of the impact of agrochemicals on the environment by improving the targeting of the active ingredients, and in increasing the efficacy of pharmaceutical preparations. These kinds of applications involve incremental scientific developments, though their impact on the economy and on society may be substantial.

Nanotechnology is likely to make an impact on medium-term timescales by providing methods to overcome well understood and long predicted barriers that stand in the way of the improvement of current technologies. The best-known example of this is Moore's Law, an empirical statement of the rate at which computer technology is advancing. This observes, in a simplified form, that computer power has doubled every 18 months or so. Two barriers stand in the way of the continuation of Moore's Law; limits on the way the behaviour of electronic circuits scale as their size becomes less than a certain threshold, and the dramatic increase in the capital cost of the plant required to produce each new generation of electronic devices. It is the hope and expectation of many that NST will deliver a way of overcoming both barriers. The expectation is that the ability to make and assemble nanoscale components will allow the design of entirely new architectures for logic and memory devices. These will be both more powerful and cheaper to produce than existing technologies.

Most difficult to predict are the entirely new possibilities opened up by NST. As demonstrated by a number of speculative writings (most notably by Drexler) many remarkable things are imaginable, but their practical feasibility has not yet been tested. Outside the scientific community, nanotechnology has a hardcore following almost ideological in its fervour, and has now become a staple of science fiction. One of the most important tasks in a survey of the possibilities of nanotechnology is to find a course to steer between giving too much attention to theoretically possible but scientifically improbable extrapolations, and being too conservative about the prospects for a fast-moving branch of science and technology.

Finally, it is important to recognise that the contribution of nanotechnology will not be made in isolation from other, rapidly developing areas of science. In particular, advances in biology and biotechnology, information technology, and nanotechnology, are likely to reinforce each other in a synergistic way. Many of the big themes that need consideration when discussing the potential impact of this new technology in society will be driven by advances in all three of these areas.

Right: A researcher holding a robot ‘gnat’. The gnat has its own photodetectors and logic processors, enabling it to automatically search for and hide in shadows - such simple robotic tasks are known as ‘artificial stupidity’.

Nanoscience and technology

The prefix of nanoscience and nanotechnology derives from the unit of length, the nanometer, and in their broadest definitions these terms refer to the science and technology that derives from being able to assemble, manipulate, observe and control matter on length scales from one nanometre up to 100 nanometres or so. One nanometer is a billionth of a metre or one thousandth of a micrometre, sometimes called a micron, which in turn is one thousandth of a millimetre. It is abbreviated to 1 nm. These numbers can be put into context by observing that a medium-size atom has a size of a fraction of a nm, a small molecule is perhaps 1 nm, and a biological macromolecule such as a protein is about 10 nm. A bacterial cell might be up to a few thousand nanometers in size. The smallest line width in a modern integrated circuit, such as would be found in a fast home computer, is a few hundred nm.

We should distinguish between nanoscience, which is here now and flourishing, and nanotechnology, which is still in its infancy. Nanoscience is a convergence of physics, chemistry, materials science and biology, which deals with the manipulation and characterisation of matter on length scales between the molecular and the micron size. Nanotechnology is an emerging engineering discipline that applies methods from nanoscience to create products.

What is special about nanoscience? The laws of physics operate in unfamiliar ways on these length scales, and this is important to appreciate for two reasons. The peculiarities in behaviour imposed by the nanoscale impose strong constraints on what is possible to design and make on this scale. But the very different behaviour of matter on the nanoscale also offers opportunities for structures and devices that operate on radically different principles from those that underlie the operation of familiar macroscopic objects and devices. For example, the importance of quantum effects could lead to highly novel computer architectures – quantum computing – while the importance of Brownian motion and surface forces leads to an entirely different principle for constructing structures and devices – self-assembly. Key differences in the way physics operates at the nanoscale include:

- **Quantum physics** On small length scales matter behaves in a way that respects the laws of quantum mechanics, rather than the familiar Newtonian mechanics that operates in the macroscopic world. These effects are particularly important for electrons. One example arises from Heisenberg’s uncertainty principle, which states that we cannot know accurately and simultaneously the position and momentum of a particle. If we confine an electron by reducing the dimensions of a metal or semiconductor particle, then its energy has to increase, in effect to compensate for its spatial localisation. This means that confinement can be used to modify the energy levels of electrons in semiconductors, to create novel materials whose optoelectronic properties can be designed to order.
- **Brownian motion** Submicron particles and structures immersed in water are subject to continuous bombardment from the molecules around them, causing them to move about and internally flex in a random and uncontrollable way. If we expect nanomachines to work according to the principles of macroscopic engineering, Brownian motion imposes strong constraints on the stiffness of the component materials and the operating temperatures of the device. In the view of many scientists this renders impractical some radical proposals for nanodevices which consist of assemblies of molecular-scale cogs and gears. On the other hand, some biological nanodevices, like molecular motors, are clearly not subject to these constraints, because their mode of operation actually depends in a deep way on Brownian motion.
- **Surface forces** Surfaces and interfaces play an increasingly important role for particles or structures as they are made smaller. A variety of physical mechanisms underlie the forces that act at surfaces (at a macroscopic scale, the surface tension that allows a water beetle to walk on water is an example of one of these), but the overall effect is simple; small objects have a very strong tendency to stick together. This stickiness at the nanoscale, and the accompanying strong friction that occurs when parts are made to move against each other, are an important factor limiting the degree to which microelectronic mechanical systems (MEMS) technologies can be scaled down to the nanoscale. These phenomena also underlie the almost universal tendency of protein molecules to stick to any surface immersed within the body, with important consequences for the design of biomedical nanodevices.

Although the combination of Brownian motion and strong surface forces is sometimes thought of as a problem that nanotechnology must overcome, these features of the nanoworld in fact combine to offer a remarkable opportunity to exploit an approach to fabricating devices peculiar to the nanoscale. If molecules are synthesised with a certain pattern of sticky and non-sticky patches, the agitation provided by Brownian motion can lead to the molecules sticking together in well-defined ways to make rather complex nanoscale structures. The key to understanding this mode of assembly – known as self-assembly – is that all the information necessary to specify the structure is encoded in the structure of the molecules themselves. This is in contrast to the methods of

directed assembly that we are familiar with at the macroscale, in which the object is built, whether by a tool-using human being or by a machine, according to some externally defined plan or blueprint. The attraction of self-assembly as a route to creating nanostructures is that it is parallel and scalable – the number of structures created is limited only by how many molecules are put in. This is in contrast to the serial processes that are familiar at the macroscale, in which objects are created one at a time.

Self-assembly is an example of an approach to making nanostructures which is often referred to as 'bottom-up' nanotechnology. This term indicates approaches which start with small components – almost always individual molecules – which are assembled to make the desired structure. Bottom-up nanotechnology does not necessarily involve self-assembly. An alternative, but much less well developed, realisation of a bottom-up approach uses scanning probe microscopes to position reactive molecules at the desired position on surfaces.

In the opposite approach – 'top-down' nanotechnology – one starts with a larger block of material and by physical methods carves out the desired nanostructure, as you would make a statue from a block of marble. Top-down nanotechnology is a natural extension of current methods of microelectronics, in which structures of very limited dimensions are created by laying down thin layers of material and etching away those parts of each layer that are unwanted.

The epitome of bottom-up processing technologies is provided by biology. Nanoscience is thought of as a physical science, but cell biology operates on exactly these length scales. The nanoscale devices that carry out the functions of living cells – the ribosomes that synthesise new proteins according to the blueprint provided by DNA, the chloroplasts that harvest the energy of light and convert it into chemical fuel, the molecular motors that move components around within cells and which in combination allow whole cells and indeed whole multicellular organisms to move around – are all precisely the kinds of machines imagined by nanotechnologists. Cell biology offers a proof that at least one kind of nanotechnology is possible. What interactions, then, are possible between nanoscale science and technology and biology?

Biology can provide lessons for nanotechnology. Long eons of evolution have allowed the perfection of devices optimised for working in the unfamiliar conditions that prevail at the nanoscale, and careful study of the mechanisms by which they work should suggest designs for synthetic analogues. This may lead to the design of synthetic molecular motors, selective valves and pores, and pumps that can move molecules around against concentration gradients.

Nanoscience and nanotechnology will also make substantial contributions to biology by providing new tools and methods. This has already started to happen, with single molecule methods allowing the properties of biological macromolecules to be probed one at a time, and the use of fluorescent nanoparticles to tag and track the motion of particular macromolecules and structures. There will be an increasing demand for these sorts of tools. When the complete genome of an organism is known, and one knows the complete set of proteins present in it (the proteome), then to disentangle the complex webs of interaction that convert a sack of chemicals into a living organism will become the major challenge. There will also be a demand for cheaper and faster ways of characterising organisms – a physically based instrument for directly reading the sequence of a strand of DNA would be very valuable, and is likely to be one of the outcomes of nanotechnology as applied to biology.

Biological components could themselves be incorporated into man-made nanoscale structures and devices. It is already feasible to incorporate biological molecular motors into artificial structures, and the light harvesting complexes of plants or photosynthesising bacteria can be incorporated into synthetic membranes. It is easy to imagine building up complex nanomachines by combining synthetic and natural components, an approach referred to as bionanotechnology.

More detailed applications and aspects of nanoscale science and technology will now be discussed. We first consider how the practice of science itself is being, and will be changed, by these technological developments; and then we look at current themes in NST research and development.

Technology that enables science

The relationship between science and technology is not linear. Simple models, in which developments in fundamental science are subsequently applied in technology, are highly misleading. In fact developments in technology have a huge role in accelerating the pace of fundamental science. Some of the earliest impacts of nanotechnology will, therefore, be on science itself. Certainly the first commercial applications of nanotechnology will have their major markets in science. This self-reinforcing mechanism will in turn greatly speed up the productivity of all science, including nanoscience, but also biology and biotechnology. This process has already begun, perhaps most significantly with the widespread introduction of scanning probe microscopy.

Scanning probe microscopies

The invention of scanning probe microscopies – scanning tunnelling microscopy (STM), scanning force microscopy (SFM), and a number of more specialised variants – is perhaps the single most important development in the crystallisation of nanoscale science and technology as a new discipline. In these techniques, images are obtained not by gathering reflected or refracted waves from a sample, as happens in conventional microscopies such as light or electron microscopy. Instead, a very fine tip is scanned across the surface of the sample, interacting with it in one of a number of possible ways. The picture is built up electronically by recording the changing interaction with the surface as the tip is scanned across it. This linked family of techniques was not the first form of microscopy that could provide information at the atomic and molecular scale, but a number of factors combine to make the current impact of these techniques particularly important. Firstly, they are now relatively inexpensive.

A good scanning force microscope (itself a product that relies on microtechnologies and nanotechnologies) will cost in the region of £100,000, substantially cheaper than a high-resolution electron microscope. They are now being produced in substantially higher volumes, and as a result it is possible that they will fall in price, bringing them within the budget of many more laboratories. Secondly, they permit samples to be imaged with very little prior preparation. In contrast to electron microscopy, which requires samples to be imaged in conditions of high vacuum and to be in the form of very thin sections, samples may be taken more or less straight from the laboratory and put in the microscope. Thirdly, in addition to imaging the nanoworld, they allow one to manipulate it. An image of the letters IBM, in which each letter was created with individual atoms picked up and put in place by a scanning tunnelling microscope, has proved to be a very powerful icon of our ability to manipulate and image the nanoworld.

The immediacy and convenience of scanning probe microscopy is only likely to increase as the power of computer graphics grows and the development of more intuitive interfaces proceeds. Efforts are already under way to create an interface with a scanning probe microscope that gives the user the sensation of directly manipulating the nanoworld – a so-called virtual reality interface. The aim is to make the sensation of operating the instrument as similar as possible to the way one interacts directly with the physical world. This kind of instrument is likely to have a profound impact on people's perception of the capabilities of NST.

Single molecule techniques

Chemistry and biochemistry deal with the properties of molecules, but almost invariably experiments are done on very large collections of them. A gram of material contains about ten trillion billion atoms. New techniques – including scanning force microscopy – are capable of interrogating the properties of single molecules. The optical tweezers technique, in which a molecule is attached to a micron size bead held in the focus of a powerful laser, allows single molecules to be moved around, stretched and deformed. In addition to providing information about the properties of single molecules that will be essential in the design of nanoscale devices, these experiments challenge a prevalent assumption in many branches of science that the properties of an ensemble of molecules are dominated by the molecules with average behaviour. This may be true when one has a test-tube or tank reactor full of molecules, but in a nanoscale system, such as a single cell in biology, an important molecule may be present in rather small numbers, and individual molecules which behave in a way that departs from the average may play a disproportionately important role.

Microlithography and MEMS

The tools with which sub-micron structures are made for electronic devices are now mature and highly optimised. The process involves laying down thin layers of material, putting a pattern on it and selectively removing material to develop the patterns. These make up the technologies of microfabrication underlying the global semiconductor industry. By 2004 we expect these technologies to have evolved to the point at which features 100 nm in size can be mass produced. At issue is the degree to which feature sizes can be further shrunk.

The technologies developed for the electronics industry have also been adapted to make miniaturised mechanical and optical systems from silicon. Some of these products are already commercialised, for example sensors in air bags and arrays of micron-sized mirrors, which can be individually moved around to steer arrays of light beams in optical communication applications. The extent to which these devices can be shrunk into the nanoscale, however, depends on fundamental physical limits, such as the prevalence of sticking and friction. This technology is also the basis for the production of tips for scanning probe microscopes.

Scientific Context

Electron beam lithography and focused ion bombardment

Laboratory-based tools exist which permit the extension of top-down manufacturing techniques to nanoscale dimensions. Conventional optical lithography – in which a resist polymer is exposed by being illuminated by light – is limited by the wavelength of the light, which determines the sharpness of the features that can be duplicated from the mask. The smallest feature size that can be drawn with optical lithography has been reduced because lasers have become available with shorter and shorter wavelengths, moving into the ultra-violet region of the electromagnetic spectrum. There seem to be, however, physical limits on the smallest wavelengths that it is possible to generate with conventional laser designs.

An alternative approach to lithography uses a beam of electrons rather than a beam of light to develop the pattern. Just as an electron microscope has a higher resolution than a light microscope because the wavelength of electrons is substantially smaller than that of light, so a finely focused beam of electrons can be used to pattern a resist on a much finer scale than light. This technology, known as electron beam lithography, has been available for around 30 years but its impact has been limited by its expense, and perhaps more fundamentally, by the fact that it is a serial rather than a parallel process. Rather than creating an entire pattern in one shot, as an optical lithography process does, each line in the pattern has to be drawn individually. This greatly reduces the speed of the process and the number of devices that can be made by it.

Another approach to nanofabrication uses a beam of charged atoms – or ions – which can physically shape a sample on the nanoscale, just as a milling machine can shape a macroscopic piece of metal. Again, this is a serial process capable of making only one object at a time.

Thin, precise coating technologies – MBE and CVD

Much of the emphasis of current semiconductor nanotechnology has been on controlling the structure of semiconductors on the nanoscale – typically by making devices consisting of alternating, very thin, layers of different semiconducting materials – to create new composite materials with designed electronic properties. This has already led to substantial economic impacts through the development of new lasers, light emitting diodes, and other optoelectronic devices. Very similar principles can be used to make new magnetic materials which allow the very much more sensitive transduction of magnetically stored information.

The technologies on which this progress rests involve the very precise deposition of different semiconductors on surfaces layer by atomic layer, in a way that avoids all defects in the packing of the atoms, particularly at the interfaces between each layer. The techniques that do this include molecular beam epitaxy, and various chemical vapour deposition methods.

In their simplest form, these techniques give rise to nanoscale structures in one dimension – layered structures. But in some cases one can treat a newly deposited layer so that it breaks up into tiny droplets, like a sheet of water on a dirty car windscreen. These droplets may contain only a few hundred atoms, and their electronic structure is profoundly changed by their small size. These quantum dots again give a way of designing an electronic structure that gives new and interesting optoelectronic properties, permitting the design of new types of laser, for example.

Soft lithography

The techniques that have evolved for manipulating matter on the nanoscale from the computer and optoelectronics industry have very high capital and running costs and need specialised expertise to make use of them. This has greatly limited the rate at which they have been adopted outside the semiconductor world, either in academia or in industry. One interesting recent development has been the introduction of new techniques to pattern surfaces which are ultimately less effective than conventional lithography, but which are orders of magnitude cheaper. These techniques, collectively known as soft lithographies, rely on advances in surface chemistry, which allow one to create well-ordered layers a single molecule thick on easily available substrates, like evaporated layers of gold (alkyl thiol self-assembled monolayers).

Simple printing techniques using soft elastomers allow surfaces to be patterned with these molecules on a sub-micron scale using cheap and easily available equipment. These developments have allowed branches of science and technology, such as tissue engineering, the branch of biomedical engineering concerned with the creation of new skin and organs, that would not normally be involved in conventional nanofabrication, to move into this area, and also offer the potential for cheap manufacturing routes to any products that are developed.

Computer simulation

One very obvious enabling technology for science has been the availability of cheap computing. This has had two effects. Obvious to anyone who compared a laboratory in almost any branch of science from 25 years ago with one today is the degree to which the computer control of instruments and the computer acquisition of data have become almost universal. Where previously one would see analogue chart recorders taking data and photographic film recording images, now almost every piece of equipment will have a computer attached. This has greatly increased the productivity of science, in the sense that the amount of data a single experimenter can gather, visualise and interpret has multiplied vastly.

The other important impact of computers has been in the role of simulation and visualisation. The ability of computers to model complex, highly interacting systems that would be impossible to deal with using the conventional mathematical tools of theoretical physics and chemistry has opened up entirely new areas for investigation. At a conceptual level, the availability of sophisticated modelling and visualisation packages has had almost as big an impact. The ability to model molecules and assemblies of molecules, to view them and even interact with them as three dimensional objects, has given the world at the nanoscale a new accessibility and immediacy.

This can, however, be potentially misleading in two ways. Firstly, the ability to design and execute on a computer a structure that is consistent with the laws of physics and chemistry does not mean that there is any way to make it. It is possible to use computer simulations to design very convincing structures for nanoscale machines, but it is much harder to design a strategy for producing these structures. Secondly, up to now most of these visualisations have been essentially static, which gives a misleading picture of the dynamic and fluctuating nature of the nanoworld.

An interesting development in the future would be the availability of interactive simulations that capture the physics at work in the nanoworld. Anybody who has played modern computer games will be aware that the dynamics of the everyday world can now be accurately modelled, giving a realistic feel to the virtual world that the game player inhabits. An accurate dynamic simulation of the nanoworld would be an important design tool and would allow human designers to develop a realistic intuition for the very different physics that operates on the nanoscale.

Current themes in nanoscale science and technology

Nanoscale science and technology are being researched worldwide in many academic and corporate laboratories. In some cases, this research has led to products that are at or close to the market.

We can organise these themes into the following broad areas:

- **Materials science** Here there is most continuity between the practice of the subject before and after the emergence of nanoscale science and technology as a distinct entity.

  Many advances that are being ascribed to nanotechnology could equally be regarded as an incremental development of existing technologies. Nonetheless, this area does include some radically new discoveries that could have highly significant implications.
- **Electronics and optoelectronics** The computing and telecommunications industries are driving large investments with the aim of maintaining the relentless technological advances that the structure of those industries seems to demand.
- **Biomedical science** The driving force for innovation here is as much political as economic, as spending on medical research seems to be one of the most popular and widely supported forms of public spending in western economies. Levels of public expectation that nanotechnology may bring about significant improvements in the length and the quality of life are high.

Materials science

Materials science, the science of metals, ceramics, colloids and polymers, has always concerned itself with controlling the structure of materials on the nanoscale. Here nanoscale science and technology will largely facilitate incremental advances on existing materials and technologies. The improved control over nanoscale structure, and better understanding of relationships between structure and properties, will continue the long-run trend towards materials that are stronger and tougher for their weight.

Already, this is leading to reductions in the amount of material needed to make artefacts and thus, for example, to improved fuel efficiency in cars and aeroplanes. Control of structure on the nanoscale has been used for some time to improve the performance of magnetic materials, and this progress in turn will contribute to improvements in performance of electric motors and generators. Other types of functional materials – in particular those that are used in batteries and fuel cells – are also being improved in the same way, and the results, in terms of lighter and more efficient portable power sources, are being seen in devices such as mobile phones and laptop computers. In the control of surface properties in textiles and paints, improved materials are being developed with properties such as the breathability of waterproof fabrics and stain resistance in clothes and carpets.

Some specific areas in which NST is contributing to materials science now include: new forms of carbon; nanocomposites; quantum dots and wires; and nanostructured materials produced by self-assembly.

Scientific Context

New forms of carbon Carbon is one of the most familiar elements, well-known in its common form as graphite, in its rather rarer but much-prized form as diamond, and in various impure forms such as soot and charcoal. The discovery in 1985 of new forms of elemental carbon made a large impact and was rewarded with a Nobel Prize, and today forms the foundation for many hopes for nanotechnology. The reason is that these new forms of carbon are well-ordered structures that are intrinsically nanoscaled; Buckminster fullerene is a perfect sphere, made from exactly 60 carbon atoms. A good way of thinking of the fullerenes is as variants of graphite. Graphite consists of infinite flat sheets of carbon atoms in which each atom is linked to three other carbon atoms, so the pattern of bonds consists of tiled regular hexagons, exactly like a sheet of chicken wire. In fullerenes, some of the hexagons are replaced by pentagons, so that the resulting sheet is curved. In the case of C60 the pattern of hexagons and pentagons (which is that of a standard soccer ball) is such that the molecule is spherical. Nanotubes are formed when the sheets of graphite are rolled up into tubes, the tubes being capped by fullerene hemispheres. Nanotubes can be as small as 2 nm in diameter, and can be perfectly regular in their arrangement of atoms.

A number of uses have been investigated or suggested for nanotubes. Very long nanotubes would be expected to be extremely strong and stiff, so if synthesis routes can be found to make them, they could potentially be used as ultra-strong, lightweight fibres. Even in shorter lengths, their mechanical properties should make them useful as reinforcing elements in composite materials. Nanotubes have useful electrical properties, being either electrically conducting or semiconducting, and have already been used to make nanoscale electronic devices. Nanotubes have already been used as tips for scanning force microscopes. Both nanotubes and fullerenes, such as C60, may find uses in new types of solar cells. A substantial effort has gone into devising routes to synthesise usefully large quantities of fullerenes and nanotubes, and we may expect the wider availability of the materials to lead to more intensive study and further applications.

Nanocomposites The introduction of composite materials like glass- and carbon-reinforced plastics has led to new materials that have significantly higher performance for their weight than conventional ones. The benefits are now appearing in the aerospace sector. In these materials, a reinforcing material provides stiffness and strength while a much less stiff matrix material ensures toughness and reduces the weight. In current composites the reinforcing material is on a fairly large scale, and there are potential advantages if it could be made much smaller. The most popular realisation of this idea uses exfoliated clay platelets as the reinforcement, and applications of this technology in the automotive sector and the packaging industry are already with us. Many groups are working on using carbon nanotubes as a reinforcing material. To some extent this can be thought of as a development of carbon fibre reinforcement in which the fibres are particularly small and much more free from structural defects than the carbon fibres currently used. The resulting materials would be stronger, lighter, and stiffer than existing composite materials (such as carbon fibre reinforced plastics) and would find applications in the aerospace and automotive industries, if the price permitted.

Quantum dots and wires made by colloid chemistry Ever since Faraday, in the 19th century, made a dispersion of nanosized particles of gold in water, chemists have been devising ways of creating such fine dispersions or colloids of a variety of materials. The recent growth of interest in these materials has come about for three reasons. The chemistry has now been refined to an extent at which there is considerable control over both the size and the distribution of sizes of the particles. New physical techniques, including scanning probe microscopy, now permit the accurate characterisation of particle sizes. It has also been realised that the physical properties of such finely divided matter – particularly the electrical and optical properties – are strongly influenced by quantum effects. Nanoscale particles of semiconducting materials, such as cadmium selenide and gallium arsenide, are known as quantum dots – their size is such that quantum effects change the energy levels of their electrons. This means that their optical and fluorescence spectra depend on their dimensions. In simpler terms, their colour changes with size.

These have potential applications in new kinds of lasers and light emitting diodes. They can also be used instead of dyes as markers for molecules in biological experiments. Similarly, chemical techniques are now available to make rods of semiconducting material whose cross-section is of nanoscale dimensions. These quantum wires may be useful as components in molecular electronics.

Nanostructured materials by self-assembly Molecules such as soap, which have two or more sections with a distinctly different chemical character (amphiphiles), can form complex nanostructured phases by self-assembly. The key feature of the resulting materials is that they are hierarchical. A number of molecules come together to make a structure, such as a sphere or a rod, with dimensions in the nanometre range, and then these units themselves assemble in a regular way. Some of the final structures can be quite complicated and rich in their topology; for example in a combination of oil, water, and a soap-like molecule it is possible to arrive at a structure in which the oil and water are

Left: Scanning electron microscope.

localised in separate compartments, each of which is continuous through space. Such structures – known as surfactant mesophases – are widely exploited in personal products, such as shampoos and hair gels, as well as in cosmetics and pharmaceutical preparations (of which more will be said in Chapter Three). Soap has always been nanostructured, and soap-boilers have over the centuries crafted knowledge about how the compositions of soaps can be adjusted to give different physical properties. More recently the relationship between their nanoscale structure and properties has been elucidated, permitting a much greater degree of rational design.

The nanoscale structures that are formed by soap-like molecules are intrinsically soft, but they can be used as templates for the synthesis of hard materials which will then have a precisely controlled nanoscale porosity. Such materials, which have a very high ratio of surface to bulk, are attractive candidates for new, efficient catalyst materials, and offer the potential to improve all sorts of chemical engineering processes.

Polymeric molecules may also have an amphiphilic character which allow them to self assemble into complex morphologies whose basic units have dimensions on the nanometre scale. Some of these materials are already commercialised, for example as thermoplastic elastomers – materials with the elasticity and resilience of rubber, but which, unlike rubber, can be melted and moulded repeatedly. In the future such materials could be used in optoelectronics as photonic crystals and in biomedical science as scaffolds for artificial skin and organs.

Perhaps the most specific and finely engineered examples of self-assembly are to be found in nature, in the folding of proteins and the base-pairing mechanism of DNA. Protein folding has some superficial resemblances to the type of self-assembly that occurs in block copolymers with a water soluble block and a hydrophobic block. In water, such a molecule will fold up in a way that keeps the hydrophobic part of the molecule in the centre, sheltered from the water by an outer layer formed from the hydrophilic block. A protein molecule also has hydrophobic units and hydrophilic units, and in water it folds in such a way as to keep the hydrophobic parts out of the way of the water. But rather than folding into any one of a large number of roughly similar arrangements, as a block copolymer would do, a protein folds into a completely defined shape. This is the shape that is precisely optimised for catalysing chemical reactions or for being a component in a molecular machine. At the moment the physics of this process is just beginning to become understood. Creating synthetic molecular machines by a similar route is an attractive target but will require major steps forward in both physics and chemistry.

The self-assembly mechanism that underlies the operation of DNA is much simpler to understand. Attached to the backbone of a single strand of the DNA molecule is a sequence of 'bases', each of which is chosen from one of four (conventionally represented by the letters T, C, A and G). These four bases make up two complementary pairs; A binds strongly to T, and C to G. Thus for every distinct strand of DNA, defined by a sequence of bases (CTCAGGACT, say), there is a complementary strand (in this case GAGTCCTGA); these two complementary strands will associate very strongly in the famous double helix structure. Because synthetic DNA can now be made with arbitrary sequences of bases, one can imagine making assemblies of DNA molecules that are programmed to come together in specific shapes. Quite complex shapes have been made in this way; these shapes can be used as scaffolds on which other materials can be deposited, opening the way to the creation by self-assembly of intricate, three-dimensional nanoscale structures.

The possible toxicity of nanoparticles Given that many other properties of materials change when they are present in very finely divided form, it is reasonable to ask whether nanoparticles could be harmful when inhaled or ingested. Clearly some nanoscale particles (such as asbestos fibres and some particulates produced from exhaust emissions) have deleterious effects connected with their size. But many nanoscaled materials have been in use for many years (and in the case of dispersions of nanoparticulates of natural origin, like milk, for much of human history) without ill effects.

The wide variety of nanoscaled materials and the variety of potential exposure routes suggests that it does not make sense to attempt to generalise about the putative toxicity or harmlessness of such materials as an entire class.

This question is currently of particular relevance to carbon nanotubes, as multi-walled nanotubes have some structural similarity to asbestos fibres. The number of published studies on nanotubes is small, and has not yet produced unequivocal evidence of toxicity. We should anticipate further studies on carbon nanotubes, and on other, newly introduced, nanoscaled materials, that should provide more definitive information to guide practices for working with and disposing of such materials before they enter bulk production.

Electronics and optoelectronics

Our second major theme is in the area of electronics and optoelectronics, which underlie the information technology and communications industries. Modern consumer electronics is already approaching the nanoscale, and the drive to continue the spectacular advances in capability of electronics that have occurred over the last 25 years is a major driver for research programmes in nanotechnology. Continuous incremental improvement is taking place in industrial laboratories, in the technology for making integrated circuits for central processing units and memory chips, and this will continue.

Scientific
Context

Meanwhile, in academic laboratories, the groundwork is being laid for new technologies that may take over from the current ones somewhere between ten and 20 years hence. Here we discuss the current state of the art, before considering the potential new technologies.

Semiconductor optoelectronics Modern communications technologies – high capacity telephone networks and the internet – have been built on a combination of digital electronics and the use of light to carry data in optical fibres. The interaction between electronics and light and the conversion of information-bearing signals between the two media is the realm of optoelectronics. Here much effort has been devoted to controlling the structure of semiconductors on the nanoscale to create new light-emitting diodes and lasers. This is already a commercial technology, and most people will be aware of the much wider use of light emitting diodes as light sources following the development of reliable blue emitters. These together with existing green and red devices permit the generation of white light far more efficiently than with conventional incandescent or fluorescent light bulbs.

Photonics Photonics has been described as optoelectronics with less electronics and more religion; that is to say it aspires to a much more sophisticated level of control of the propagation of light within matter than has hitherto been possible. Light travels faster than electrons in semiconductors, so if one could make logic circuits that use light rather than electrons to carry and process information, in principle much faster and more powerful computers and communication networks would be possible. A key idea here is that of a photonic crystal, a material with a completely ordered three-dimensional structure whose length scale is comparable to the wavelength of light – that is several hundred nanometres. Such a structure might be obtained by the ordered stacking of spheres with this kind of diameter – a colloidal crystal. A familiar natural example is the gemstone opal, a natural colloidal crystal of silica particles. Its spectacular iridescent colours are a result of the rather complicated interaction between light and this periodic structure. If certain conditions are met light of certain wavelengths proves to be completely unable to propagate within the structure. This situation is analogous to the behaviour of electronics in semiconductors.

Currently there are two approaches to making photonic structures. Top-down approaches use lithography techniques to pattern materials on the appropriate length scales. This is very convenient for systems in which we restrict the light to two dimensions, but is more difficult to extend to three dimensions. The bottom-up approaches rely on self-assembly, either of colloidal crystals or of structures made from self-assembling block copolymers. The advantage of these approaches is that in principle they should be much cheaper and much easier to scale up for large-scale production. The disadvantages are that currently there are some fundamental obstacles to be overcome. One is to do with the prevalence of defects in such self-assembled structures, while another is that the materials with which it is possible to apply these self-assembly techniques are not the ones with ideal optical properties. These difficulties are currently being worked on, but at present the goal of an entirely light-based computer seems quite distant.

Memory and data storage Computer data storage has progressed over the last 50 years from the highly macroscopic – punched cards – towards the microscopic, with magnetic tapes and disks. In these materials information is stored as a pattern of magnetised regions. In a hard disk, information is stored on tracks separated by a few microns. Along the track a single bit of information might be stored on a length of track of less than 100 nm, giving a net storage density of one Gbit per square centimetre. This can be compared with a storage density of about 360 kbit per square centimetre in a floppy disk, a factor of about 3000.

This remarkable feat of miniaturisation has been made possible by a combination of extreme precision microengineering and the development of very sensitive read heads, which depend on the phenomenon of giant magnetoresistance.

This very sensitive response of the electrical properties of a material to an applied magnetic field can be obtained in composite materials consisting of nanometre thick multilayers of metals with different magnetic properties.

Given the very rapid progress made in conventional magnetic storage, where a mature solution (by the fast moving standards of information technology) is being refined under the pressure of very large markets, one might wonder whether there is any point in looking for a radically different solution. Nonetheless, should physical limits prevent the continuation of recent trends in miniaturisation, some alternative approaches are beginning to take shape. One possible approach is to use self-assembled structures, made using block copolymers, as templates for arrays of magnetic particles in the 10 nm range. This could potentially lead to increases in data density of another factor of 1000, but there are a number of potential difficulties to be overcome related to the lack of perfection in the long ranged order of these structures.

The other familiar storage device is the optical disk – the compact disk or DVD. Here information is stored as a pattern of craters in a flat polymer surface, which are read by a laser beam. The ultimate limit on the density of craters, and thus on the density of information that can be packed on the surface of such a device, is set by the wavelength of laser light. This limit has already been reached in DVDs. Some further incremental gains can be obtained by using blue light, because of its smaller wavelength. But to take this conceptually straightforward approach to information storage, in which we use physical marks on a surface, to smaller sizes we would need radically different ways both of writing and of reading the information. One such approach would be to use an atomic force microscope (AFM). IBM has developed a system whereby modified AFM heads 'write' marks in a plastic surface by heating, to melt small pits. The pits are read by a parallel array of more than 10,000 heads. The ultimate in data density would be achieved if a unit of information could be stored in a single molecule. Approaches to this goal are described in our section on molecular electronics (*see page 15*).

New methods for data input and output Although these words are being processed by computers of a complexity unimaginable 50 years ago, the method by which the words are transferred from the authors' brains to the machine – a typewriter keyboard – and from the machine to the reader – a piece of paper – represent very old technology indeed. Although the virtues of keyboards and paper are very great, it seems hard to imagine that different and more powerful methods for getting information into and out of computers will not be developed.

For some of these methods – speech recognition, for example – the problems are essentially ones of software, so NST will only contribute indirectly inasmuch as they will be helped by the general increase in computer power. On the input side, inputs from the physical world are obtained from a variety of sensing technologies – for example of temperature, chemical composition and pressure – and NST will lead to smaller and more sensitive sensors, capable, for example, of detecting biochemicals in the blood without the need to remove it from the body. Developments in the human interface should greatly benefit the disabled, though much technology will be developed by the defence industry in an attempt to make the interface between a soldier or airman and a weapons system even smoother. Such interfaces could rely on the direct detection of electrical signals in the brain, or a physical connection between the nervous system and semiconductor logic.

On the output side, there have been substantial improvements in display technologies, with cathode ray tubes now essentially obsolete, replaced by liquid crystal displays, plasma displays, and field emission displays.

Displays made from light-emitting polymers are discussed in the next section; the point to make here is that developments in NST are leading to displays that are cheaper, larger, brighter, and more efficient than current ones. A more radical display technology would form an image directly on the retina. An interesting combination of the old and the new is provided by so-called electronic inks; these combine the crispness and contrast of printing onto paper with the switchability of an emissive or liquid crystal display. Particles of electronic ink can be switched from black to white by the application of an electrical field.

Usually the output from a computer is now an image or a piece of text, but since computers are used so frequently to design artefacts, it would be useful to provide an output that was the three-dimensional artefact itself. Various technologies for rapid prototyping achieve just this goal. This can be done by repeated ink-jet printing using, instead of ink, a material that solidifies after printing, to build up a three-dimensional image made from plastic. Alternatively, a container of liquid monomer can be scanned by a laser beam, whose light initiates the polymerisation of the monomer to form a solid plastic object.

Plastic electronics Many readers will have noticed that as time goes by computers seem to get very much faster, but not significantly cheaper. This reflects the fact that efforts in the information technology industry has been devoted to increasing performance almost at any cost (speaking here of the capital cost of semiconductor plants).

One area moving against this trend is the field of plastic electronics, in which semiconducting polymers are used as the active materials to make logic circuits and display devices. Semiconducting polymers have significantly worse electronic properties than conventional semiconductors like silicon or gallium arsenide. But they are very cheap to make. Rather than using expensive lithography to pattern them to form circuits, very cheap processes such as ink-jet printing or soft lithography can be used. They can also be made into devices that are flexible. Currently there are three major areas of research.

Firstly, polymer light emitting diodes have been commercialised already; the potential here is for large area, flexible display devices such as roll-up computer or TV screens to be made cheaply. Entirely new products, such as clothing with an electronic display, can also be envisaged.

Secondly, field effect transistors are the basic element of logic and memory circuits, so very low cost printed logic circuits would be possible, with potential applications in packaging.

One can imagine a radio frequency ID device being incorporated in packaging or in an artefact that would identify itself and announce its presence. This would have a major impact on the way supply chains are managed in manufacturing industry, retail and distribution.

Finally, being actively researched, but currently furthest away from commercialisation, are photovoltaic devices, such as solar cells. In fact solar cells made from semiconducting polymers form just one class of novel solar cell architectures made from unconventional nanostructured semiconductors; Grätzel cells, made from nanosized titanium dioxide particles (a cheap and widely available substance which is the major pigment in white paint) sensitised by organic dyes are another example, and variants are being experimented with which use C60 particles. Once again, the efficiencies and lifetimes of these unconventional solar cells currently compare poorly with conventional materials based on inorganic semiconductors. However, if significant improvements can be made the processing technologies that would be available to make very large areas of material cheaply could transform the economics of renewable energies, bringing down the cost of energy generated by solar cells towards the cost of non-renewable sources such as gas and oil.

Molecular electronics One way to overcome the limits that lithography suffers on feature size would be to use conducting molecules as wires and as the elements of active components such as transistors, diodes, and switches. These could be carbon nanotubes or conducting polymers of the kind developed for plastic electronics. Although some fascinating preliminary work has been done to showing that transistors can be made from carbon nanotubes, significant difficulties remain. Although it is now clear that a semiconducting device based on a single molecule can be made, it is not at all clear how such devices could be wired together to make logic systems. One possibility would be to use the base pairing mechanism of DNA to design connections that would form by self-assembly.

These devices will work quite differently from larger scale transistors, because new physics comes into play at these very small length scales. But when understood properly, this new physics will give rise to new opportunities. An example is the Coulomb blockade effect, which arises from the fact that in a very small system the injection of a single electron can effectively change the electrical properties of that system. This effect can be used to make memories that depend on the presence or absence of a single electron.

The idea of a molecule whose state can be switched between two configurations has also been suggested as a unit of memory. The most developed examples of such molecules are the rotaxanes, in which a molecule ring is threaded on a spindle, along which it can be shuttled from one position to another. Again, although this idea has been shown to work in principle, the practical problem is in addressing the individual molecules.

Nanotubes and semiconductor nanowires are likely to be important components of a new molecular based computer architecture. Field effect transistors based on nanotubes have already been reported, and progress has been made towards integration using the flow of fluids on the nanoscale to align the nanowires.

New concepts in computing It is striking how completely one form of computer architecture (due to John Von Neumann) and one class of circuit designs (CMOS, or complementary metal oxide semiconductor) have come to dominate this global industry. To continue the trends of Moore's Law, however, entirely new concepts in computing may become necessary.

One major limit to further miniaturisation comes from the sensitivity of modern integrated circuits to faults, arising from dust or other impurities. The need for ever more stringent cleanliness in fabrication plants is a key element in their huge cost.

Another approach would be to find a way of designing computer systems so that a single fault in an integrated circuit did not, as now, doom the whole system. Defect tolerant architectures could use redundancy and self-testing to live with a relatively high proportion of faults.

More radical concepts use fundamentally different ways of storing and manipulating information from current semiconductor logic, which relies solely on the charge of electrons. In spintronics, information is carried in the spin of an electron as well as its charge. This requires materials which have both semiconducting and magnetic characteristics controlled on the nanoscale.

Most potentially revolutionary is the idea of quantum computing. The idea here is that information is carried not in physical variables but in quantum states. Because a quantum state does not have to correspond to a single value of a physical quantity, but can be a superposition that expresses the possibilities of the different values that physical quantity can take, very much more information can be stored in a single unit of quantum information than in its classical counterpart. Applications in principle include methods of transmitting the information necessary to reproduce with complete fidelity a physical system (quantum teleportation), ways of producing an unbreakable code, ways of breaking what are currently considered to be unbreakable codes, and solving certain classes of very complex problems which take too long to be solved on conventional computers.

The problem with quantum computing is to find physical systems in which it can be executed. To maintain the property of coherence on which the subtle features of quantum mechanics rely, a system needs to be isolated from perturbations from the outside world, while of course it is just such perturbations that are needed to get input into and output out of one's computer. But the precise control of nanoscale interactions between systems is exactly what NST promises to provide, and systems such as quantum dots may well prove to be what is needed.

Biomedical science

Our third theme relates to improvements in medicine. If the biggest economic driving force for nanotechnology now comes from information technology, the area with the most resonance with the general public probably comes from the possibility of applying new technology to medicine. This area combines the very incremental with the highly futuristic. Some of the sharpest ethical and social dilemmas arising from nanoscale science and technology will have their origin in the success in this programme.

Because so many major applications for nanotechnology are likely to come from medicine, there is going to be a general need to understand the interaction between artificial nanodevices and living systems. This will be an important barrier to the use of nanotechnology for medicine; the body has extremely well developed mechanisms for recognising foreign bodies and neutralising them, and these mechanisms will in turn need to be overcome if our nanodevices are to do their job.

Drug delivery A high proportion of drugs that are administered today are delivered to the body in ways that would have been familiar to physicians one hundred years ago; orally, by injection, or by inhalation. Nanotechnology promises to yield much more sophisticated and precisely targeted ways of delivering drug molecules to the relevant part of the body. This may be necessary simply as a consequence of the widening search for new drug molecules. Highly insoluble compounds may be considered; these may be made usable by being prepared in the form of nanoscale particles. Classes of compounds that cannot survive passage through the stomach, like polypeptides, may become more widely used. For these, means of delivery other than frequent injection would be desirable. Other potentially useful drugs, particularly anti-cancer agents, may have very unpleasant and dangerous side effects, which could be minimised if the agents could be delivered selectively to their destination without affecting other parts of the body. Finally, gene therapy combines an extremely fragile and delicate molecule – DNA – with the need to target destination cells rather precisely. In many of these cases what is needed is a way of wrapping up a molecule, either to protect it from a hostile environment, or to protect the environment from the unwanted side-effects of the molecule.

One approach to this task which exploits NST is to use the soft nanostructures known as liposomes or vesicles. These are synthetic enclosures made from self-assembled bilayers of amphiphilic (soap-like) molecules, rather like very crude synthetic cells. The basic liposome that one would obtain by ultrasonic treatment of a phospholipid solution is relatively fragile. They are used in the formulation of high-value cosmetics. Various developments on the basic theme provide structures which are considerably more useful for pharmaceuticals. If water-soluble polymer chains are incorporated in the structure they can greatly reduce the interactions that the liposome has with the environment. In the medical context this means that they will circulate much longer in the bloodstream before the body's methods for dealing with foreign bodies destroys them. These have been termed 'stealth liposomes' and this drug delivery technology is already commercialised. Simple liposomes are rather fragile objects, but they can be made more robust by chemically linking their components to form two dimensional solid sheets, or by using polymeric amphiphiles (block copolymers). The ideal is to make a delivery vehicle that would be robust until triggered to release its contents, and various strategies are emerging to achieve this.

The ultimate robust and selective delivery vehicle is a virus, whose entire purpose is to introduce its own genetic material into a target cell. Currently gene therapy relies on the use of viruses to introduce the necessary genetic material into a cell. This process is not without its dangers, so a synthetic analogue would be very desirable.

Tissue engineering The obvious limitations of organ transplants are that there are not enough organ donors, and that problems of rejection by the host immune system are very severe. The solution would be to grow new organs from cells provided by the host. This is not easy, because although all the cells in a body have the same genetic blueprint – that is to say, the same DNA – cells are social organisms and they need to be persuaded to grow into skin or bone or a liver or whatever organ is required. Tissue engineering attempts to get round this problem by providing a scaffold for the cells, which defines the structure that is required to produce the organ in question. The scaffold will be made from a biocompatible or natural polymer which has been patterned on the microscale or nanoscale, and which may have its surface treated in a way that makes the cells respond in the desired way. Although the goal of making organs like hearts and livers is still quite far away, the tissue engineering of skin for grafts is well advanced and in use in clinical practise.

The laboratory-on-a-chip Classical chemistry and biochemistry carry out their operations on rather large scales; if these scales could be miniaturised this could increase the sensitivity of chemical analysis and the ease with which it could be automated. A laboratory-on-a-chip would combine very small scale manipulation of chemicals with sensitive detection and direct interfacing to a computer for automatic control and analysis of the results. The manipulation of liquids on small length scales involves some interesting new problems. Very small channels and reaction vessels can be created by etching patterns on the surface of glass or silicon. At these small scales, however, the movement of fluids is dominated by viscosity, making it difficult to get the fluids either to flow or to mix. Progress in microfluidics, as this field is known, will involve developing ways of overcoming these difficulties; electrophoresis, for example, can be used to move fluids using applied electric fields, and gels which respond to their environment by swelling or shrinking can be used to provide switchable valves.

An example of the way in which the detection of very small quantities of a wide variety of target molecules can already be achieved is provided by the DNA microarray. In this technology, thousands of spots of different sections of DNA (each corresponding to a single gene) are printed in an array onto a surface. The aim of the analysis is to find out which of these genes are expressed in a group of cells under study; to do this the messenger RNA from the cells (or mRNA, the intermediary in the process of making the protein corresponding to each gene) is extracted. The complementary DNA sections corresponding to these mRNA molecules are made, fluorescently labelled and washed over the microarray. The presence of mRNA corresponding to each expressed gene is detected as a fluorescent signal at the corresponding point of the microarray. This technology illustrates how self-assembly combined with fluorescent detection of surface associated molecules can lead to the simultaneous detection of very many analytes with very high sensitivity. It could in principle be scaled down to considerably smaller dimensions than are currently used, given the extremely high sensitivity (down to single molecules) with which fluorescent signals can be detected.

The automation and scaling down in size of chemical processes has been tremendously powerful, and achievements such as the sequencing of the human genome have relied on this approach. Nonetheless, sequencing DNA is still resource and labour intensive. A seductive vision in nanotechnology is the idea of taking a single DNA molecule and physically reading off the sequence.
In fact this vision is not entirely far-fetched; one can certainly manipulate single DNA molecules using techniques such as atomic force microscopy and laser traps. Having isolated a single DNA molecule, one approach to sequencing it would simply be to read along it with an atomic force microscope. Another would be to thread the molecule through a pore in a membrane, detecting small changes in, for example, the ionic conductivity of the pore as the molecule was pulled through. Whatever the details, given our rapidly growing capacity to handle single molecules of DNA, it seems likely that some physical (and therefore fast and cheap) method of reading the DNA sequences will be developed in the relatively near future. This would greatly speed up the progress of molecular biology, but would also open up new challenges and opportunities in medicine. If the complete genome of any individual were readily available then screening for all kinds of diseases with a genetic component would become very straightforward indeed.

Conclusions

This overview emphasises the diversity of nanoscience and technology and its essentially interdisciplinary nature. One of the most interesting issues is the question of whether nanoscience and technology should be considered as a continuation of long pre-existing trends, or whether it does represent a fundamental discontinuity in the practice of science and technology. We have seen that many of the current achievements of nanoscience and technology represent an extension of developments that were proceeding before the concept of NST as a separate entity became widespread. Advances in materials science and colloid technology – permitting lighter and stronger alloys, better magnetic materials, improved formulations of cosmetics and personal products – have come about as a result of a growing appreciation of the role of nanoscale structure that has developed continuously over the last 50 years. Of course, the fact that these developments are essentially incremental does not mean that they are without impact on society, or indeed that these impacts may not be very disruptive. They continue the long-run trend of developed economies to be less intensive in both materials and energy.

In addition, they may also contribute to major innovations, such as the development of a sustainable energy economy not based on hydrocarbons. Such a development, which would need major contributions from nanoscale science and technology, would be revolutionary in its effects on society.

Functional devices that operate at the nanoscale would normally represent a discontinuity within their area. The paradigmatic example of such a device is the transistor, which is the basic component of an integrated circuit. The huge increase in computer power and memory capacity that is familiar to everyone is the result of advances in microelectronics. These have made it possible to reduce the size of the components of integrated circuits towards the nanoscale, allowing many more such components to be integrated on a single chip. But this process of miniaturisation has until now been incremental in character, with the continual refinement of an essentially mature technology. The issue now is how much longer this process of incremental improvement can continue. In microelectronics, we are waiting for a breakthrough. In order to deliver the ongoing increases in computing speed and memory capacity that has characterised the past two decades, we are relying on NST to provide such a discontinuous advance.

It is in the development of entirely new functional nanoscale devices that the revolutionary promise of nanoscale science and technology will be delivered. Many of these potential applications are still some years off achieving a stage at which they will be commercial, but driven by strong market demands, particularly from medicine, we can anticipate new biomedical devices based on nanotechnology that will have far-reaching implications.

3

Nanotechnology is a multifaceted and malleable group of technologies, and it is difficult to associate it with specific areas of application.

The science of the nanometre scale, and the discoveries that have been made so far, offer new possibilities for a multitude of industries.

Carbon nanotubes have potential applications in electronics, improved materials, and drug delivery.

A few commercial applications of nanotechnology are already here, such as improved hard-disks for computers, sunscreens, and improvements to telecommunications.

Much of the potential for the translation of nanoscience into useful and viable products is likely to be realised within the next decade or two. As the knowledge and tools improve, it is likely that at least some of the possible applications will become commonplace in our everyday lives.

Commercial Applications of

Nanotechnology

Nanotechnology is a multifaceted and malleable group of technologies, and it is difficult to associate it with specific areas of application. There is not one nanotechnology industry, comparable for instance with computers, but many different applications for the growing ability to manipulate materials on the nanoscale, most of which will be in combination with non-nanotechnologies. The science of the nanometre scale, and the discoveries that have been made so far, offer new possibilities for a multitude of industries. Carbon nanotubes have potential applications in electronics, improved materials, and drug delivery. A useful comparison might be the discovery of electricity; it has proved to be an enabling technology which, decades after its initial conception, has produced unforeseen and indirect applications, such as the internet. In this way, nanotechnology could be said to be potentially pervasive.

In Chapter Two we investigated the science, research and development in nanotechnology fields. Here, we survey current perceptions of the major commercial applications of nanotechnology. In the material we have surveyed there is typically a lack of clarity about how developed these applications are and when they are likely to be in production. Some transfer from laboratory to market has already taken place, but the majority of nano-enabled products currently on the market are tools for scientists to apply to nanotechnology research. It is also clear that there is a lack of consistency in the way in which the nanotechnology label is applied to new materials and products.

Many materials, both new and old, depend for their value on the control of their structure on the nanoscale, but by no means all such products advertise their nanotechnological elements. The cosmetics and paints industries are perhaps perceived as being the most developed in incorporating nanoparticles into their products, with, for example, the shampoos, skin creams, and sunscreens already being used by consumers. We will focus on these and other actual and envisaged developments that appear to be reasonably near to commercial application. However, we conclude with the contrasting more radical and potentially disruptive proposed uses for nanotechnology, which are often the context in which more prosaic uses are conceived.

A few commercial applications of nanotechnology are already here, such as improved hard-disks for computers, sunscreens, and improvements to telecommunications. Much of the potential for the translation of nanoscience into useful and viable products is likely to be realised within the next decade or two. As the knowledge and tools improve, it is likely that at least some of the possible applications will become commonplace in our everyday lives. For instance, new lithographic techniques to make nanoscale components for computers are highly likely to replace current methods and materials. Nanotechnology applications in development can be broadly divided into several thematic areas: the development of the tools that enable the research and ultimately the technology; applications relating to new or improved materials; applications within the sphere of electronics and IT; advances in health and medicine; improvements in cosmetic products and advances in food technology; developments in products for military and security use, and space exploration; and products and processes to improve the environment.[1]

Tools

The technologies that enable the science were discussed in the previous chapter. Scanning Probe Microscopies (SPM) are the most widespread, and include the atomic force microscope (AFM) and the scanning tunnelling microscope (STM), both of which have been around since the late 1970s. This equipment allows the visualisation of molecular behaviour on the nanoscale, as well as the manipulation and engineering of individual atoms. These are expected to be part of the bottom-up approach to manufacturing on the nanoscale. The majority of bespoke nano companies currently operating are dedicated to the production of these tools.

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[1] The sources used for this section include Institute of Nanotechnology (2003) *Report prepared for the ESRC Centre for Organisation and Innovation*, University of Sheffield, (2002) *What is Nanotechnology* CD Rom; CMP Científica (2002) *Nanotech: The Tiny Revolution;* DTI/OST (2002) *New Dimensions for Manufacturing;* ETC Group (2003) *The Big Down;* Valerie Jamieson (2003) *Open Secret.*

Nanoscale lithography is another tool, one that is being scaled down from conventional lithography. Soft lithography, for instance, can produce components for the computer industry and other applications, potentially on a smaller scale, and certainly at lower cost. These techniques are likely to be able to compete with traditional methods, where semiconductor devices are produced through optical lithography, and are hence limited in their feature size by the wavelength of light.

Materials

Composite materials are commonplace, but they are being affected by the introduction of nanotechnology to production processes. Clay nanoparticles, for instance, are of new relevance to materials, due to their ability to make the materials stronger, lighter, more durable, and often transparent. These materials are already being applied in the US automotive industry; the GM Motors Safari and Chevrolet Astro vans, for instance, use a nanocomposite material for a 'step-assist', an optional extra to improve access to the vehicle. The materials are also being developed for use in packaging and aerospace. Nanocomposite plastics are being used for consumer and industrial packaging, and carbon nanotubes have been incorporated to improve packaging for electronics components. Carbon nanotubes are excellent candidates for composite materials, again making the end product lighter and stronger. Smart food packaging that senses if the product has spoilt or has been tampered with is an extension of these improvements.

Nanoporous silica compounds hold possibilities for improved insulating materials. The low-density, highly porous solid can be used within a wide range of temperatures, with applications in many fields, from refrigerators and freezers to pipe insulation. They also hold potential as insulating materials with low dielectric constants, which are increasingly important in the microelectronics industry.

Nanoparticles are highly effective catalysts, due to the increased surface area at such a small scale, and are being tested for use in plastics manufacturing to improve the properties and versatility of the resulting materials. Nanoparticles are also used in colloids, which in turn are being used in sunscreens, printer ink, and paints. Zinc and titanium oxide sunscreens, for instance, use nanoparticles that are so small they do not scatter light, leaving the end product clear instead of white.

Coatings are an important nano-material. Such coatings, sometimes made of self-assembling monolayers (SAM) (thin layers one molecule thick spontaneously formed by a substance), are applicable in many ways, from scratch resistant coatings for glass to self-cleaning surfaces.

Smart textiles are also being developed, from stain and crease-resistant fabric to a material that is responsive to its environment, perhaps alerting the wearer to a toxic substance. Lee Jeans have already developed and commercialised stain resistant khakis which incorporate 'nanowhiskers' in ordinary cotton fabric to produce their unique property whilst maintaining the usual feel of the material.

Electronics and information technology

The technologies in this area that were discussed in Chapter Two are at the forefront of nanotechnology's commercialisation. Nanotechnology has the potential for smaller and faster computers with larger memories than current processes of making transistors and other components permit. These will reach their limits in miniaturisation within the next decade or two, creating the demand for new methods of manufacturing, nanotechnology being one of them. Techniques such as soft lithography and bottom-up approaches to forming nanoscale components by self-assembly could produce cheap and effective microscale circuits. Molecular electronics, with molecular switches and circuits only a few atoms wide, offers the possibility of using molecular components in electronic devices, greatly reducing their size, although there are many practical issues to be addressed before this technique can be fully developed. However, new defect tolerant architectures for computing make highly integrated molecular electronics a possibility.

Carbon nanotubes are also likely to be used in IT. These tubes can be either conducting or semiconducting and have the potential for memory and storage as well. Other options for data storage include the use of SPMs as a tool for information transfer. This is exemplified by the IBM 'millipede' system, which employs an array of AFM tips to make indentations in a polymer and then read them, much in the same way as a laser reads a CD but at a considerably smaller size scale and with a much higher density of information (*see page 13*). Nanotechnology also has prospective applications for display devices, such as the replacement of cathode ray tube technology by electron-producing carbon nanotubes.

The timing of these applications is uncertain, but nanotechnology is already contributing to increased data storage capacity and processing speeds.

Commercial Applications of Nanotechnology

Medicine and health

The medical area of nanoscience application is one of the most potentially valuable, with many projected benefits to humanity. Cells themselves are very complex and efficient nano-machines, and chemists and biochemists have been working at the nanoscale for some time without using the nano label. Some areas of nanoscience aim to learn from biological nanosystems, while others are focusing on the integration of the organic and inorganic at the nanoscale. Many possible applications arising from this science are being researched.

The first field is implants and prosthetics. With the advent of new materials, and the synergy of nanotechnologies and biotechnologies, it could be possible to create artificial organs and implants that are more akin to the original, through cell growth on artificial scaffolds or biosynthetic coatings that increase biocompatibility and reduce rejection. These could include retinal, cochlear and neural implants, repair of damaged nerve cells, and replacements of damaged skin, tissue or bone.

The second area is diagnostics. Within MEMS, laboratory-on-a-chip technology for quicker diagnosis which requires less of the sample is being developed in conjunction with microfluidics. In the medium term, it could be expected that general personal health monitors may be available. Developments in both genomics and nanotechnology are likely to enable sensors that can determine genetic make-up quickly and precisely, enhancing knowledge of people's predisposition to genetic-related diseases.

Finally, drug delivery is likely to benefit from the development of nanotechnology. With nanoparticles it is possible that drugs may be given better solubility, leading to better absorption. Also, drugs may be contained within a molecular carrier, either to protect them from stomach acids or to control the release of the drug to a specific targeted area, reducing the likelihood of side effects. Such drugs are already beginning pre-clinical or clinical trials, adhering to the strict regulatory requirements for new pharmaceuticals. Due to this, development costs are often high and outcomes of research sometimes limited.

The ultimate combination of the laboratory-on-a-chip and advanced drug delivery technologies would be a device that was implantable in the body, which would continuously monitor the level of various biochemicals in the bloodstream and in response would release appropriate drugs. For example, an insulin-dependent diabetic could use such a device to continuously monitor and adjust insulin levels autonomously. There is no doubt that this is the direction that current advances in which microfluidics and drug delivery are heading.

Cosmetics and food

Cosmetics and personal products companies have been extremely active in using nanotechnology to improve their existing products and to develop new ones. The company L'Oreal famously holds more nanotechnology patents than many companies in high-technology sectors (though again this is in part a matter of labelling). Cosmetics companies were among the first to get products that were labelled as being nano-enhanced to market. Shampoos and skin creams, containing nanoparticles with the ability to deliver the desired ingredient to where it is needed, for example deeper into the epidermis, are already on the market. The nanoparticulate zinc oxide sunscreen is an obvious advance in this category. 'Cosmeceuticals' are being conceived that may combine cosmetics with drug delivery.

The idea of using nanotechnology as a method of delivering molecules to specific targets is also being pursued for the development of novel foods which can deliver specific nutrients or drugs to the consumer. Foods may also be designed to suit individual profiles, and even selected tastes and textures. Nanotechnology is being applied to studies into improved flavour delivery, encapsulating flavour particles in nanoparticles to protect them from the environment until they are released, thereby maintaining freshness.

Military, space and security

In the USA, which can boast the most government financial support for nanotechnology research in the world, nanotechnology funding given by the federal government to the Department of Defense is second only to that given to the National Nanotechnology Initiative. The Massachusetts Institute of Technology hosts the US Army Institute of Soldier Nanotechnologies, a research unit devoted to developing military applications for nanotechnology, its aim being to improve the "survival of the soldier of the future".[2] The Institute's ultimate goal is to "create a 21st century battlesuit". To this end they are investigating smart materials able to be responsive to the conditions of their environment, sensors able to detect chemical or biological warfare agents, and lightweight bullet-proof materials. There are also attempts to incorporate wound detection and treatment systems within uniforms. For example, responsive systems, such as the material hardening to provide an instant splint for a broken bone, are in development. The five-year contract awarded in 2002 to MIT by the US Army implies the time-scale for the development of these projects is rather near term. Lighter and stronger weapons and equipment are being developed, although information on this area is scarce and it is assumed that much of this

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[2] See http://www.mit.edu/isn/ for full details

research is classified. In addition there is a focus on improving the human-machine interface, perhaps including sensory enhancement such as direct retinal displays or communication to the ear, as discussed in Chapter Two. Should these products be developed, and be able to be manufactured, it is likely that they will be transferred to the space programme and eventually into wider usage.

Improved materials, lighter but with tough, heat resistant properties, are being used in the design and construction of spacecraft and satellites, and this process will gain from nanotechnology. (Confusingly, the term nanosatellite is in use but refers to a small satellite, not one using nanotechnology.)

There is also the possibility of nanotechnology facilitating improvements in civilian security equipment. The Institute of Nanotechnology suggests fingerprinting will become cheaper, quicker and more effective using DNA techniques involving nanotechnology, and there is also the possibility that nano-based sensors could be used as electronic detectors ('sniffer dogs') for improved airport security. Quantum dots, fluorescent nanoparticles which glow when exposed to ultraviolet light, may be used as tags and labels to prevent theft and counterfeiting, and to trace the course of drugs within the body.

Environment and energy

Nanotechnology research is forming part of the quest to prevent and reverse environmental damage. Researchers aim to use nanotechnology to provide efficient and effective filters for water and air, leading to reduced pollution. A membrane that can purify water and is also self-cleaning to avoid contamination should be available in the near to medium-term. Improved catalysts, composed of nanoparticles, are already in use in petrol and chemical processing, resulting in less waste in these processes.

Perhaps the most promising application in both the environmental and energy areas is the development of fuel cells, with many different uses. Research is being undertaken into the effectiveness of carbon nanotubes at storing hydrogen; these have the potential to power cars, amongst other things, with water as the only emission, although this is some way from commercialisation.

Photovoltaics are another focus of nanotechnology development, with the ultimate aim being highly efficient, cheap, lightweight, possibly flexible, solar cells made from plastics. A breakthrough in this field is predicted to occur by 2020. Biomimicry is one key element in this research, as scientists attempt to copy plants' photosynthesis mechanism. The conversion of sunlight to hydrogen would bring together photovoltaics and biomimicry, and should be possible in the medium-term. Taken together, improvements in sources of renewable energy, with the development of storage of gaseous hydrogen and the improvement of fuel cells, could lead to a viable 'hydrogen economy' in which the energy needs of society were no longer reliant on fossil fuels.

Radical proposal of molecular manufacturing

The starting point of the recent nanotechnology vogue was the potential applications of molecular manufacturing, as proposed by Eric Drexler. Although these applications may not currently be commercially viable, they have been an influence on what researchers are attempting to make possible. Using molecular manufacturing, radical scientists see the potential for self-replicating nano machines, perhaps biomimetic, that are able to construct anything by placing atoms together in the required structure. These assemblers will require instructions on what to make, energy to power them, and enough materials (usually elemental atoms) to make what is required. The hope is that, in the future, each home will have its own self-assembly unit that can construct anything the user requires, using blueprints purchased from the designer. This form of nanotechnology has been termed 'molecular manufacturing' and, according to Drexler, is the original conception of nanotechnology. These assemblers could also be used to clean the environment of all pollutants, by using surplus atoms (such as carbon) in the atmosphere to create artefacts. The expectation is that molecular manufacturing will be incredibly cheap, leading to material abundance across the globe and thereby eliminating poverty in the Third World.

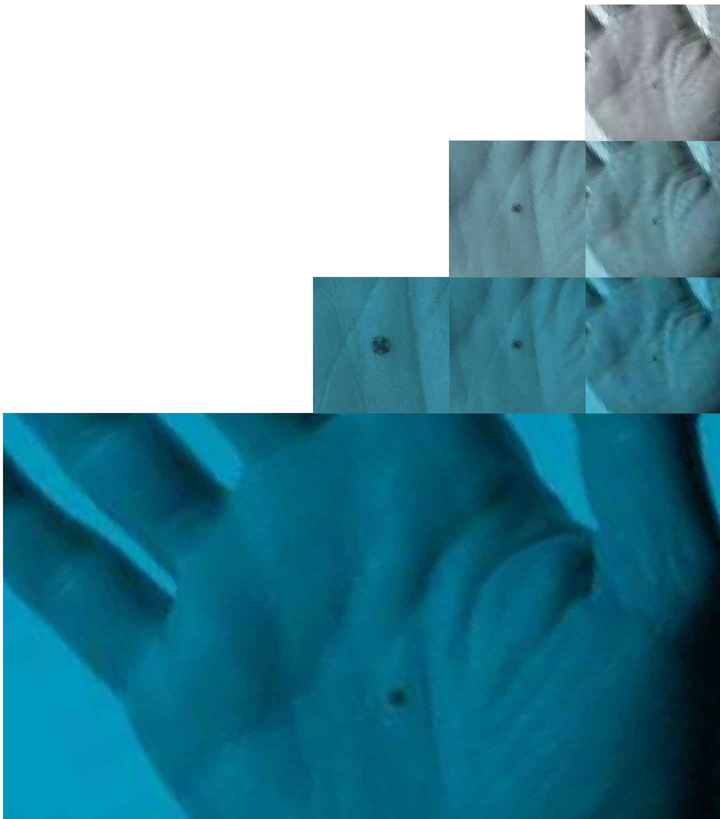
Molecular manufacturing has also been heralded as eventually being able to prolong human life through the eradication of disease and the ageing process, even leading to speculations of immortality. This stems from gaining control of matter at the atomic scale, leading to the capability of repairing such nanoscale structures as cells. Applications range from 'nanosubmarines' in the bloodstream targeting and eliminating malignant cells (such as cancerous tumours) to the improvement of human performance through the replacement of body parts with nanosynthesised substitutes. These could be as ordinary as biocompatible bone replacements to the more radical idea of improving intelligence through design or technological assistance. The feasibility of all this is a major debating point in the discussion surrounding nanotechnology.

Conclusions

Governments and research bodies are strongly encouraging both the research and development of nanotechnology, with national programmes well developed in the USA, and the European Union assigning it special status in the new Sixth Framework Programme. Many new and improved products are anticipated to follow from this research. Yet it is difficult to judge, at this stage, how much the application of nanotechnology will extend beyond relatively mundane, but commercially important products such as shampoos and skin creams, to develop truly new ways of doing things.

We have to accept that we have not yet imagined some of the most profound nanotechnology applications. Moreover, technological development and its implementation do not operate in a vacuum, and nanotechnology will be influenced by other scientific developments, social reactions, and local and global politics. Many of the applications arising from nanotechnology may be the result of the convergence of several technologies. It is probable that advances in biotechnology and information technology will have an equally important, and in many cases complementary, role in the advent of new products and processes.

The uncertainty surrounding nanotechnology makes any assessment of nanotechnology's social and economic implications more difficult and provides the catalyst for a greater concern for social issues to be incorporated into decisions about its development. The uncertainties are reflected in the commentary on nanotechnology, which is already highly diverse in its conceptions of the technology and the associated social and economic changes. The multitude of perspectives from varying stakeholders in its development has created a debate on nanotechnology. The next chapter examines these perspectives, particularly those built on nanotechnology's assumed revolutionary potential, and their implications for social and economic development.

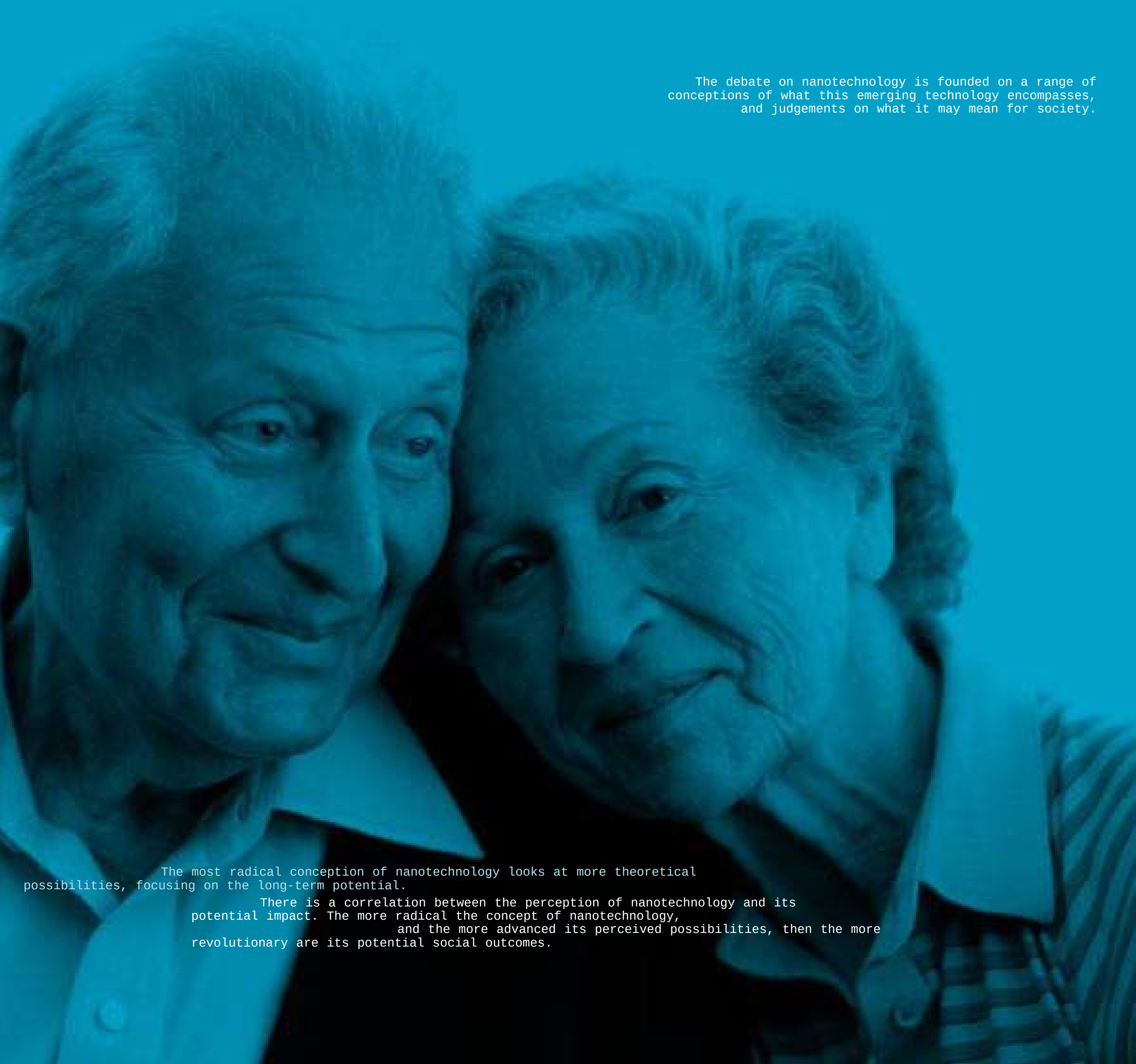


Right: Hand holding microcogs forming a microgear mechanism. This could be used in a micromachine, or Micro Electro Mechanical System (MEMS). MEMS include microscopic sensors and robots (nanorobots).

4

A range of views about nanotechnology’s implications and the social challenges it may pose exist.

The different perspectives reflect differences in underlying conceptions of nanotechnology.



The debate on nanotechnology is founded on a range of conceptions of what this emerging technology encompasses, and judgements on what it may mean for society.

The most radical conception of nanotechnology looks at more theoretical possibilities, focusing on the long-term potential.

There is a correlation between the perception of nanotechnology and its potential impact. The more radical the concept of nanotechnology, and the more advanced its perceived possibilities, then the more revolutionary are its potential social outcomes.

The Nanotechnology Debate

A range of views about nanotechnology's implications and the social challenges it may pose exist. The different perspectives reflect differences in underlying conceptions of nanotechnology. We thus first outline these conceptions before presenting the various predictions of nanotechnology's social and economic consequences. We will then assess these various perspectives, on the basis of our earlier discussion of nanotechnology, and conclude by outlining how we should approach the social and economic challenges surrounding nanotechnology and the social scientific study of them.

Conceptions of nanotechnology

The debate on nanotechnology is founded on a range of conceptions of what this emerging technology encompasses, and judgements on what it may mean for society. Within the literature, this spectrum of conceptions has at the one end a clear-cut revolutionary vision which views nanotechnology as a radical discontinuity from current developments. On the other extreme, the nature of the technology is seen as far less obvious, and it is acknowledged that the technology is likely to develop in a more evolutionary way. The most radical conception of nanotechnology looks at more theoretical possibilities, focusing on the long-term potential. The more cautious view is very much rooted in present realities. Within the continuum of degrees of radicalism, the majority between the two poles focus on near-term prospects. This literature can be grouped into two broad categories: that which champions nanotechnology, and promotes its benefits, mainly for economic reasons; and that which can best be labelled commentary, focusing more on current developments. The individuals or organisations that fall in each group do not necessarily have conflicting views on what nanotechnology is and means, but their varied aims mean that they make different judgements on the technology and its possible implications.

There is a correlation between the perception of nanotechnology and its potential impact. The more radical the concept of nanotechnology, and the more advanced its perceived possibilities, then the more revolutionary are its potential social outcomes. Few of the articles explore the social and economic dimensions of nanotechnology in any depth as many of the ideas regarding possible implications are not yet crystallised. The papers, books and articles discussed here are summarised in Appendix II.

Radical discontinuity

The radical view of nanotechnology, which was prefigured by the theoretical physicist and Nobel Laureate Richard Feynman in a much quoted lecture, was first presented to a broad audience in Drexler's *Engines of Creation* (1986). Here he outlines his goal of molecular manufacturing, the manufacture of nanoscale devices and artefacts capable of sophisticated operations, including the manufacture of other nanoscale devices, in which the basic units of construction are individual atoms or molecules. Moreover, Drexler proposes a particular potential route to achieve his goal, which involves the precise positioning of reactive molecules to build up structures with atom-level precision. He made an extensive theoretical analysis of this approach in his MIT PhD thesis, subsequently published as *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (1992).

These radical, sometimes termed 'Drexlerian', predictions arise frequently in any discussion on nanotechnology, and self-replicating 'nanobots' have become the benchmark of what nanotechnology can achieve. As Drexler puts it in *Engines of Creation*, there will be "assemblers [that] will let us place atoms in almost any reasonable arrangement… [and] will let us build almost anything the laws of nature allow to exist". Fifteen years later, an article by Drexler in a special issue of *Scientific American* debating nanotechnology is no different in its assertions. The piece, 'Machine-Phase Nanotechnology', is a rebuttal to a group of sceptics, George M Whitesides, Gary Stix, and Richard Smalley, whose contributions to the same issue we discuss later. In it, Drexler acknowledges the role nanotechnology can play in incremental change, asserting that "materials' properties and device performance [will] be greatly improved". But he also restates the radical vision, that "nanorobots are envisaged that could destroy viruses and cancer cells, [and] repair damaged structures", thereby eradicating disease and ageing.

Jamie Dinkelacker, a writer in Los Altos, California with a background in information and communication technology research, presents in his paper *Transitions to Tomorrow* (2002), an equally radical vision of nanotechnology. Nanotechnology heralds a new industrial era, a 'Molecular Epoch' that involves major social changes. Founded on the science achieving "Total (or near total) control over the structure of matter", this era promises "novel materials and capabilities, leading to novel living patterns, new ways of socialising, and yielding fresh approaches to cooperation and competition"; or in more hyperbolic terms, "stunningly new materials,… fabulously enhanced health; and a profusion of marvellous benefits". Dinkelacker speculates that nanotechnology offers the potential for global material abundance, and it is the loss of scarcity that has the "potential for dramatic social change".

The Foresight Institute (of which Drexler is Chairman and Dinkelacker is on the advisory board) is an umbrella organisation which promotes this radical notion of nanotechnology, having been established by Drexler after the success of *Engines of Creation*. In its *Guidelines on Molecular Nanotechnology* (2000), the Institute defines the most important aspect of nanotechnology as "Molecular Nanotechnology", the ability to "programme matter with molecular precision". Statements on its website further illustrate this concept, describing molecular nanotechnology as the "thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and byproducts of molecular manufacturing".[3] The guidelines for the development of this technology are based on the belief that artificial self-replicating nanostructures will be possible and relate to the design of such devices and machines. They include such recommendations as "programming termination dates into devices" and designing nanostructures that are "not… capable of replication in a natural, uncontrolled environment".

In 'Why the future doesn't need us', appearing in *Wired* in April 2000, Bill Joy, chief scientist of Sun Microsystems, also adopts the radical conception of nanotechnology, where the "replicating and evolving processes that have been confined to the natural world are about to become realms of human endeavour". Joy accepts that nanotechnology, coupled with advances in genetics and robotics, is highly revolutionary and transformative. Glenn Harlan Reynolds uses his paper *Forward to the Future: Nanotechnology and regulatory policy* (2002) to contemplate the possible regulatory structures for nanotechnology. The paper is published under the aegis of the Pacific Research Institute, a US public policy think tank which, with regard to technology, aims to "identify and limit harmful government regulation".[4] Reynolds is also professor of law at the University of Tennessee and co-director of the Foresight Institute. His concept of nanotechnology is radical, yet he gives more prominence than do Drexler or Dinkelacker to the embryonic nature of nanotechnology, as he acknowledges that it is "so new… it barely exists", and that the potential it holds will not be realised for quite some time. Instead of focusing solely on molecular manufacturing, Reynolds is more explicit about other aspects of the technology such as "molecular electronics and even high-resolution photolithography", although he implies these techniques do not belong in this category. This breadth of definition, where the term 'nanotechnology' denotes more than the manipulation of atoms, makes the technology difficult to regulate; the banning of one aspect, such as assemblers, "would leave unregulated huge amounts of research that would be readily translatable into such devices".

Exploring Drexler's ideas, and those he terms 'optimistic nanoists', in more detail is Damien Broderick in his exposition on technological development for the lay audience, *The Spike: How our lives are being transformed by rapidly advancing technologies* (2001). Broderick is a science and literature scholar and science fiction author, and his conception of nanotechnology focuses mainly on the possibility of Drexlerian molecular manufacturing, but his argument is broader than this. Broderick predicts that technology is developing at an exponential rate, ever quickening, and at some point in the future will reach a "Spike" or "Singularity". This describes the point at which technological progress is so rapid that a line showing change with time goes off the top of the graph. In Broderick's words, it is "an upward jab on the chart of change, a time of upheaval unprecedented in human history". This rapid progress encompasses several emerging technologies, particularly nanotechnology, artificial intelligence, and genomics. Combined, Broderick sees these technologies as having the power to alter society completely: "Plenty of things are *going on* [author's italics] and will not stop before humankind and our world are changed forever". For us in the present, this future is so strange and such a radical departure that it is unimaginable.

In a paper to the joint EC-NSF Workshop on Nanotechnology (2002) examining social implications, Mark C Suchman makes a distinction between 'nanates' and 'nanites', the former being new materials and the latter, nanoscale machines, or Drexlerian nanobots. In this way, Suchman, an associate professor of sociology and law at the University of Wisconsin-Madison, adds further to the lexicon of nanotechnology terminology. He also argues that properties such as invisibility, self-locomotion, and self-replication

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[3] http://www.foresight.org/NanoRev/index.html#NTFAQ

[4] www.pacificresearch.org/about/index.html

are inherent to nanotechnology and define it as innovative, echoing the radical conception. However, his acknowledgement of the diversity of the technology, in that it may incorporate both new materials and functional nanomachines, is unusual to the radical viewpoint.

Cautious evolutionism

In his article 'The Once and Future Nanomachine' (*Scientific American* (2001)), George M Whitesides, an experimental surface chemist and pioneer of new nanotechnology techniques, is much more sceptical about the radical view; he contends that nanotechnology could learn much from biology. Whitesides accepts that the goal of radical nanotechnology is in principle possible, as "nanoscale machines already do exist, in the form of the functional molecular components of living cells". Since these machines are a product of evolution rather than man-made design, the challenge nanotechnology faces is trying to mimic these machines in synthesised analogues. He is sceptical about whether the means to achieve this feat are imminent, stating that it would be a "staggering accomplishment to mimic the simplest living cell". Whitesides seems reluctant to believe new forms of sophisticated nanoscale machines are feasible, particularly not from scaling down macro-machines. Instead, "biology and chemistry, not a mechanical engineering textbook" may hold solutions for nanotechnology; Whitesides is sceptical that the Drexlerian vision of molecular manufacturing is possible, though he does not explicitly rule it out.

Richard E Smalley, chemist and one of the Nobel prize winners for the discovery of fullerenes in 1996, takes scepticism further in 'Of Chemistry, Love and Nanobots' in the same issue of *Scientific American* as Whiteside's paper. For Smalley, chemistry is the most effective method of molecular manipulation, as atoms perform a "complex dance involving motion in multiple dimensions" in chemical reactions. He argues that nanobots or assemblers "are simply not possible in our world", due to constraints imposed by the limitations of the scale. In his view, the need to control all the atoms surrounding the reaction site would require so many manipulators that there would not be room, while the atoms forming the nanobot would themselves bond with the atoms to be manipulated. Smalley terms the space problem "fat fingers" and the bonding problem "sticky fingers". Drexler does not accept that Smalley's characterisation of his proposed route to achieving the goal of radical nanotechnology is an accurate representation of his position.

Writing in the journal *Nanotechnology* (2002), science journalist Philip Ball looks to both biology and chemistry for nanotechnology techniques and designs. Although he acknowledges that macroscale engineering has had little need so far to learn from nature, the fact that the nanoscale is shared with cells and bacteria makes biomimicry imperative. In his words, "either we embrace chemistry or resign ourselves to perpetually swimming upstream". Nature has some "awfully good" ideas from which nanotechnologists can perhaps build synthetic machines. To Ball, this argument is so obvious that he dismisses Drexler's ideas of nanorobots and submarines: "the literal down-sizing of mechanical engineering… fails to acknowledge that there may be better, more inventive ways of engineering at this scale". Thus Ball accepts that the goal of radical nanotechnology is at least partially achievable, though he argues that there may be better routes to achieving the goal than the design philosophy underlying Drexler's original writings. In particular, he notes that using design principles evolved by nature at the cell biology level is likely to provide a smoother path to functional nano-devices. In fact, he goes further, suggesting that in most cases it will be easier and better to use nature's machinery directly rather than attempt to emulate it using synthetic materials: "Rather, I envisage this being one of many areas where 'learning from nature' becomes a matter of adapting nature's existing machinery for technological ends".

Whitesides, Smalley and Ball represent the scientific argument against the radical viewpoint; they are particularly sceptical that the Drexlerian vision of molecular manufacturing is feasible. These highly respected scientists argue that this conception of nanotechnology does not fit within the laws of physics and chemistry as they operate on the nanoscale, or is redundant due to the superior power of biological processes.

Less focused on the nanoscientific issue, but also cautious of the claims made by Drexler and others, is Denis Loveridge, (who, after a career in corporate venturing is now a science policy commentator), in his paper *Nanotechnology: its potential as the 'next industrial revolution' and its social consequences* (2002). In this essay from his 'Ideas in Progress' series, Loveridge criticises radical conceptions of the kind we have discussed so far for their inaccuracy and generality. He questions the use of 'nanotechnology' as an umbrella term, emphasising that the field has three elements: "Science, technology, and engineering at the nanometre scale" is the essence of nanotechnology, and the products it creates may be termed 'nanoartefacts'. Loveridge would prefer that we abandon the term 'nanotechnology,' as the key issue in the production of any nanoartefacts is one of systems integration. The issue is not only the integration between the scientific, technological and engineering elements, but between scientific and technological possibilities and social or human needs. For Loveridge, we need to outline the "frontiers of fundamental science" in order to have a more meaningful discussion of the potential social consequences. These are termed the 'possibilities' of science, and applications will only arise when scientific possibilities converge with economic feasibility and social desirability. Potential limits to scientific possibilities are brought into the argument, and Loveridge contends that new modes of thought, incorporating concepts such as systems integration in nano-artefacts, and quantum physics and electronic structure, need to be used when examining the possibilities of nanotechnology.

The nature of applications, then, is less clear for Loveridge, and the realisation of any groundbreaking potential is not a foregone conclusion. Indeed, he emphasises the need to "challenge the current perception that 'nanotechnology' will provide the basis of a new industrial revolution", a view favoured by nanotechnology champions courting investment and one even "promulgated by the scientific and technical community". In this paper, his conception of nanotechnology is rooted in near-term perceived possibilities. Moreover, Loveridge emphasises that any technological developments in this field are not based on ideas that are a significant departure from previous scientific thinking. He states that "neither [nanotechnology's] ideas nor embodiment are entirely new", and that "nanoscale science has been commonplace in biology and chemistry… for many decades".

Other writers are equally dismissive of the revolutionary potential of nanotechnology, and more cautious of what they see as overstated claims surrounding it. Disparaging the nanotechnology vogue as "long on vision and short on specifics", science journalist Gary Stix, in his piece 'Little Big Science' in *Scientific American* (2001), attempts to separate the speculation from the reality of scientific research. According to Stix, however, this is more difficult than it first appears, as even the "science establishment itself is a little unclear about what it means when it invokes nano", and the fact that the concept often lacks coherence and cohesion. Nevertheless, the article outlines the varied notions of nanotechnology, concluding that it encompasses science and engineering at the nanoscale, with the ultimate aim of improving electrical, chemical, mechanical, and optical properties of materials.

Nanotechnology champions

The writing that falls between the poles of radicalism and cautious practicality can be divided into two clusters: nanotechnology promoters and technology commentators. Of the first group, the majority are government or industry organisations that are optimistic about nanotechnology, and though not as radical in their conception as are Drexler or Joy, they still see nanotechnology as having at least an important, if not revolutionary, potential.

New Dimensions for Manufacturing: A UK Strategy for Nanotechnology (2002) is a report commissioned by the Department of Trade and Industry to investigate the current state of nanotechnology research and development in the UK, and produced under the chairmanship of the Director General of the Research Councils, John Taylor. The aim of the report is to examine the "potential impact of nanotechnology and nanoscience on industry in the UK", and develop a strategy accordingly. This distinction between nanoscience and nanotechnology is brought out at the beginning, but is not developed throughout the report, and the terms are often used interchangeably. The report does attempt to identify nanotechnology, as a "collective term for a set of technologies, techniques and processes", but also emphasises that the field is so broad that it "is dangerous to rely on definitions that could restrict thinking". The report is reluctant to place boundaries on the conception of nanotechnology, seemingly lest there be worthy projects omitted from funding, or wealth creation opportunities may be missed. Nanotechnology is defined in broad terms as an innovation with immediate potential, and as "the application of science to developing new materials or processes", or "new approaches to manufacturing". It is heralded as a 'disruptive technology', that will "generate major paradigm shifts in how things are manufactured".

CMP Científica, in its report *Nanotech: the tiny revolution* (2002), also emphasise industrial applications. CMP Científica, now Científica Ltd, is "Europe's first integrated solutions provider for the nanotechnology community", a Europe-based company offering information to businesses, access to nanotechnology networks, and consultancy services.[5] Like the DTI report it is interested in the industrial and commercial aspects of nanotechnology, yet this report is more concerned than the DTI about the difficulties involved in defining the boundaries of the technology. Seemingly also not wanting to pigeonhole the technology, the report questions whether nanotechnology is a single technology, and concludes that its boundaries are "certainly not easy to define." Indeed, the report emphasises the sheer diversity of nanotechnology as the reason why it will be a revolutionary technology. Nanoscience and technology are posited as "enabling technolog[ies], allowing us to do new things in almost every conceivable technological discipline". It even predicts that "the current trend of grouping technologies under the one mantle will probably reverse". This underlines the notion that conceptions of a technology are not static and often transient; the diverse technologies covered by the term 'nanotechnology' will no doubt acquire more precise terminology as they mature.

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[5] www.cmp-cientifica.com

The US National Science and Technology Council (NSTC) report, *Nanotechnology: Shaping the world atom by atom* (1999), also embodies a very broad conception of nanotechnology. The fundamental description of nanotechnology is the ability to control material properties at the nanoscale. According to the report, "emerging nanotechnology may provide humanity with unprecedented control over the material world" through the ability to understand and manipulate atoms and molecules. Nonetheless the report does acknowledge that the technology itself is very early in development: "The field is roughly where the basic science and technology behind transistors was in the late 1940s and 1950s".

In the National Science Foundation's (NSF) report on the *Societal Implications of Nanoscience and Nanotechnology* (2001), the emerging technology is described as "qualitatively" new. Again, the boundaries are very general, encompassing the "control of matter at its building blocks", and its revolutionary nature stems from the notion that it will impact on a diverse range of areas, namely "healthcare, the environment, sustainability, and almost every industry".

Although it cannot always be assumed that the opinions of the authors of these reports are embraced by these agencies, it seems that public bodies are keen to adopt an all-embracing conception of nanotechnology, anxious that a too-narrow notion of the technology may limit what can be achieved.

Nanotechnology commentators

Our fourth group of writers, in contrast, focuses on particular aspects of nanotechnology. While they see nanotechnology as rapidly advancing and highly diverse, the technological fervour of those promoting the technology is absent. These articles focus less on what nanotechnology is and more on what the implications may be, with the emphasis on three concerns: the speed of technological development, as studies of social implications lag behind; possible ethical issues presented by nanotechnology's convergence with biotechnology, and learning about the potential social impacts of nanotechnology from the introduction of other technologies.

Anisa Mnyusiwalla, Abdallah S Daar and Peter A Singer, a group of bioethicists from the University of Toronto, Canada, acknowledge the important potential of nanotechnology, "a rapidly expanding field, focused on the creation of functional materials, devices, and systems through the control of matter on the nanometre scale". Their concern is with the speed with which the technology is advancing, or more specifically, the way in which the "speed of scientific development" in the "rapidly progressing field" of nanotechnology is outstripping considerations of its social impact. This broad conception considers the wide range of possible applications of the technology, including both the Drexlerian vision and the enthusiasm of the nanotechnology exponents, where the development of nanotechnology will be "at least the equivalent of the combined influences of microelectronics, medical imaging, computer engineering, and man-made polymers".

Also identifying nanotechnology as having extensive applications and concerned about the pace of their development is *The Big Down* (2003), a comprehensive report from ETC Group, a civil society group "dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights".[6] This report comments on the emerging variety of technologies operating at an atomic level, and calls them 'Atomtechnologies', a term which "refers to a spectrum of new technologies that seek to manipulate atoms, molecules and sub-atomic particles to create new products". This definition incorporates both nanomaterials and molecular manufacturing, and seeks to describe what is being manipulated (for instance, biotechnology) rather than the length scale. The variety of uses for the technology is emphasised, and nanotechnology is taken to refer to the several "vastly different faces of a technology that have dramatically different implications". The broad concept of 'Atomtech' used by ETC also acknowledges the importance of the interaction of nanotechnology with other technologies when considering its impact.

This convergence of enabling technologies, most commonly consisting of nanotechnology, biotechnology, genetics, robotics, and information technology, is a defining feature of emerging technological capabilities for other commentators too.

The second concern is the convergence of nanotechnology with biotechnology. In a paper for the third EC-NSF Workshop on Nanotechnology, entitled 'Nanobiotechnology and its Societal Implications' (2002), Debra R Rolison, a surface chemist at the Naval Research Laboratory in Washington DC, projects that the greatest challenges to society will be posed by the confluence of nanotechnology and biotechnology. Rolison's vision of nanotechnology stems from basing the technology on "objects, devices, and processes that blend biomolecular function and specificity with nanoscopic fabrication and manipulation". In the same workshop, Vicki Colvin, associate chemistry professor and executive director of the Center for Biological and Environmental Nanotechnology at Rice University, Texas, assumes a similar definition. However, her argument is more slanted towards nanomaterials and systems interacting with other systems: "Artificial nanomaterials are engineered to be active systems that interact, in some cases strongly, with chemical and biological systems". Jesús Mosterín, of the Madrid-based Instituto de Filosofía, in

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[6] www.etcgroup.org/about.asp

Right: A processed silicon wafer containing hundreds of micromechanic pressure sensors.

'Ethical Implications of Nanotechnology' again at the same EC-NSF workshop, also identifies one of the most important aspects of nanotechnology as its convergence with other technologies. In Mosterín's words, a "confluence of nanotechnology with molecular biology and genetic engineering can be confidently predicted", leading to the development of "immense opportunities, risks and challenges".

The third area of concern is to learn from previous emerging technologies so that past mistakes are not repeated in the development of nanotechnology. The Better Regulation Task Force (BRTF) is an independent body that advises the UK Government, and attempts to ensure that any regulation and its enforcement adhere to good regulatory principles.[7] From the outset of their report *Scientific Research: Innovation with Controls* (2003), it is clear the BRTF has little yet to report on nanotechnology and the possible challenges it poses to governance. However, the field is described as "vast", the "potential applications numerous", and the "very breadth of possible applications… [indeed] makes it difficult to predict where the greatest risks of nanotechnology lie". Its location with the topics of genetically modified seeds and plants and embryonic stem cell research, though, suggests comparisons can be made between these and nanotechnology. The implication is that parts of nanotechnology will either incorporate or be similar to both biotechnology and genetic engineering, and it is already being labelled as a 'risky' technology which will need regulating.

In her essay 'From genetic modification to nanotechnology: the dangers of 'sound science'' (*Science: can we trust the experts?* (2002)), Sue Mayer explicitly compares the emergence of nanotechnology to that of GM. Mayer, a veterinary biologist and executive director of genetic-technology focused public interest group, Genewatch UK, draws parallels between these two technologies. Her emphasis is less on any similarities between the nature of GM and nanotechnology, and more on the way the emergence of nanotechnology is being handled. As with GM, Mayer argues, nanotechnology's promise is that it holds "precision and control in shaping the future". This potential is leading to "excitement and hype… reminiscent of the way in which genetic modification was first seized upon". This hype may create the same resistance faced by GM, if debate over nanotechnology is "contained in the scientific and industrial communities and couched in technical and scientific terms". The scientific community and society "seem to be repeating the path" taken by genetic modification.

The authors we have discussed present perspectives that have varying levels of certainty on the nature of nanotechnology and its future possibilities. The scale of decisiveness ranges from Drexler and the Foresight Institute, who are convinced molecular manufacturing will be possible, through to the nanotechnology champions who are hesitant to define the technology yet believe it to be economically important, to those who believe it to be just too diverse to resolutely characterise.

Perhaps the major point of contention, however, lies between the radicals and the cautious evolutionists. At issue is the possibility of controlling and improving nature. Dinkelacker states the core of the radical position succinctly, in that "Nurture will surpass nature, and design will take over destiny". The implicit aim of nanotechnology is that, through technology, humans will be able to do better than nature and improve on evolution. This is echoed by Broderick, with the assertion that "evolution does not have a plan for us" and is a "gigantic, stupid lottery". This justification allows us to "choose [a path] for ourselves", and the radical conception of nanotechnology suggests that this path should lead to immortality, the enhancement of human faculties and material abundance. This notion seems implausible to the cautious evolutionary standpoint, and the many critics of Drexlerian ideas. Members of this group are often experienced physicists, chemists and biologists. They argue that science and technology are capable of controlling nature but dispute that it can improve on it, at least at the level of cell biology. Ball, for instance, acknowledges that "nature has not necessarily found all the best ideas already", but recommends scientists turn to "nature's principles and practices" when developing nanoscale systems to achieve the "kind of superior properties and special functions that natural systems exhibit". Whitesides argues that cells are incredibly sophisticated nanoscale machines, which have been perfected through millennia of evolution. The self-replication systems of a cell are "probably unbeatable for [their] efficiency"; in Whitesides' view, "It would be a marvellous challenge to see if we can outdesign evolution".

Social and economic effects

Despite the general lack of depth shown by the authors, it is possible to identify four themes underlying the discussion of the social implications of nanotechnology within the literature: a positive vision of the outcomes for society, or what may be termed a 'utopian' view; a negative view of the impacts of the development of the technology, leading to a 'dystopian' scenario; a concern to overcome barriers to developing the technology and gaining public acceptance; and the need for specific regulation due to the uncertainty of nanotechnology's effects on humanity and the environment. Both utopian and dystopian visions are generally predicated on the assumption that the goal of radical nanotechnology, molecular manufacturing, is achievable (in some views inevitable), and both sides of the debate draw heavily on Drexler's book *Engines of Creation*, which in fact considers both positive and negative outcomes of this technology.

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[7] *See* www.brtf.gov.uk *for more details*

Utopian visions

The crux of the positive radical view of nanotechnology is the ability to design and construct nanosized robots, capable of many functions. Its effects will first be felt in manufacturing. In *Scientific American*, Drexler presents the vision that nanotechnology will 'revolutionize manufacturing', and this is elaborated on in *Engines of Creation*: "Assemblers will be able to make virtually anything from common materials without labour, replacing smoking factories with systems as clean as forests…They will indeed be engines of abundance." This points to the assembly of any product from the bottom-up, using replicating nanobots which will "copy themselves by the ton, then make other products such as computers, rocket engines, chairs, and so forth", and hinting at a domestic system that will build anything the user needs from blueprints. Dinkelacker develops this vision as he speculates that "manufacturing may become local" with the introduction of "a general household appliance, about the size of a microwave oven, that can make many diverse products according to programmed instructions". The total control over matter at the atomic level that nanotechnology entails may yield "entirely new devices and products, better medicine and healthier foods, better cars and aircraft, as well as better lightbulbs and household appliances". Such a device, Dinkelacker speculates, could make everything, including food.

Glenn Harlan Reynolds extends these possibilities and envisages new molecules and materials formed by this method. With true bottom-up manufacturing, any substance could be made if the correct elemental materials were present: "The desired molecule would be modeled on a computer screen, the assemblers would be provided with the proper feedstock solutions, and the product would be available in minutes."

The second broad theme of the radical concept is the medical uses of nanorobots. Drexler in *Scientific American*, for instance, envisions nanorobots that "could destroy viruses and cancer cells, repair damaged structures…and bring the body back to a state of youthful health." Reynolds predicts injectable "specially designed nanodevices… programmed to destroy arterial plaque, or cancer cells, or to repair cellular damage caused by ageing". Dinkelacker further extends the possible medical uses of nanotechnology into something that attempts to improve humanity. In addition to eliminating disease and ageing, he suggests that "the entire human body could be incredibly enhanced by means of technology: unbreakable bones, eagle-eye vision, [and] a bloodhound's acuity of smell".

Both of these themes, of manufacturing and health care, are used by the authors to create a positive vision of nanotechnology's effects, a time of "wondrous prosperity and freedom" according to Dinkelacker. This perspective suggests that the use of nanotechnology can take society into a utopian heaven on Earth. For these radicals, nanotechnology signals a clean environment; not only will manufacturing processes be wasteless and pollution-free, but environmental damage already done will be reversed and fossil fuels will become obsolete. In *Engines of Creation* Drexler suggests cleaning machines that will "render…harmless" toxic substances by rearranging their atoms, solar energy that is cheap and abundant, and "solar-powered nanomachines [that] will be able to extract carbon dioxide from the air and split off the oxygen", as plants do. Dinkelacker adopts this view, and speculates that "manufacturing at the molecularly precise scale could take today's waste and pollution and use it to fabricate products of heretofore unheard of quality". Nanotechnology is also predicted to be fast and cheap, bringing material abundance to the world and, for Dinkelacker, signalling the "end to scarcity of food, knowledge, and other critical things". Dinkelacker suggests that the "times ahead hold promise of bounty and abundance for everyone, not just today's stakeholders of wealth and power". In his view, this amounts to the "potential for dramatic social change" as power is lost from those who maintain their position through the control of scarce resources.

Of all the writers, Dinkelacker elucidates best the potential implications of changes in the structure and means of production of goods. With the possibility of domestic manufacturing systems able to create anything, issues arise over intellectual property rights "in terms of design and fabrication methods". It is not objects that are transported but the information to make them. Dinkelacker also speculates that such a device may render "obsolete nearly all of the basic underlying assumptions of our economic and social institutions, the usages of currency, the nature of employment, and how we structure our daily activities". Work itself would become unrecognisable from that of the 'industrial era', turning ever more into a knowledge economy where valued traits would include "human uniqueness, creative spark, useful knowledge, and worthwhile relationships". According to Dinkelacker, "productive human work will require education, training and mental discipline", and to "drop out of school [would] be dropping out of life for all intents and purposes". His paper, however, tends to link social change solely to technological progress and the creation of new devices and artefacts. Other factors in the transformation of societies are not considered. The implications of other applications predicted by the optimistic radicals, however, are far more profound.

In the most optimistic outcome, the radicals suggest that there will be not only plentiful resources for all, but also the health and lifespan to enjoy them. With nanobots able to destroy disease and repair damaged cellular structures (leading to the end of illness, ageing and, ultimately, death) radical social impacts could be foreseen, yet of the radicals only Dinkelacker really addresses the issues. He foresees a fundamental change may occur in the "current and eons-old presumption of generational cycles", thereby changing society and its recognised structures. He also predicts that longer life-spans will lead to a better developed "sense of consequence", as "future generations will not be the only ones to inherit pollution, deficits and foolish policies".

However, Dinkelacker in particular acknowledges the ethical issues and potential abuse faced by these capabilities; possible outcomes such as the ability to design humans 'to spec' and genetic weapons leading to genocide by genetic trait will challenge society. Although all the radical authors foresee possible negative outcomes for the technology, the tone of the Drexler, Dinkelacker, Reynolds, and their common link, the Foresight Institute, is largely optimistic. They are, however, concerned with the regulation of the technology, and with ensuring that it is developed in a responsible and beneficial way.

Broderick, who is also broadly positive about society's technological future, voices more doubts than the others as to the feasibility of the predicted applications of nanotechnology. The outcomes that characterise Broderick's radical conception of the future, his Spike, are many, reflecting nanotechnology's convergence with artificial intelligence and genomics. First is Drexler's conception of molecular nanotechnology (MNT), labelled 'minting' from its acronym. Broderick suggests that molecular assemblers will be developed which are literally capable of manufacturing anything, 'nanofacturing' as Broderick terms it. He does, however, question the viability of such machines, technically and economically. Drexler's predictions are described as "quiet, madly sane anticipations", and Broderick believes his "timetable can be questioned as ambitious". Even the desirability of MNT is questioned: "perhaps it's a waste of time and effort, as nature already does it for us". Overall, though Broderick does not question the plausibility of nanoartifacts such as medical nanobots, but more their feasibility. Nevertheless, he is not totally convinced by the goal of material abundance and material products at negligible or zero cost. He notes that "the feasibility of molecular nanotechnology must be considered from within the context of real-world economies", as market forces may change but are unlikely to disappear. These cover such issues as the cost of assemblers themselves, and the necessity of companies to make profits.

Other forecasts are such claims as "Ageing, and even routine death itself, might become a thing of the past", and the creation of conscious, superhuman artificial intelligence. In combination, these could lead to a scenario where, "By the end of the 21st century, there might well be no humans (as we recognise ourselves) left on the planet". According to Broderick, the transition will take us through 'transhuman' to becoming 'posthuman', where our minds are uploaded into computers, our bodies become redundant, and we are immortal. Although generally positive about this scenario, Broderick does acknowledge that the "cake is always far more than the recipe". He argues that evolution has implanted a millennia of experience within our cells, and this cannot be replicated in an artificial way.

The very nature of this proposed transcendental event which Broderick refers to as the Spike makes this future impossible for us to imagine, let alone comprehend. Nevertheless, Broderick recommends forethought to deal with these "changes so drastic, coming at us so thick and fast, that we can't yet truly imagine the shape of things to come". He recommends that society should start discussing the issues, and perhaps discover ways to prepare for them. He criticises the Foresight Institute's approach and says that strong regulation and licensing, intended to restrict dangerous minting and "forestall planetary doom", put assemblers out of reach of the average person and "defeats the utopian dream".

Dystopian visions

Drexler, in *Engines of Creation*, discussed the possibility that the successful achievement of the goal of radical nanotechnology could lead to an extremely negative, dystopian vision of the future, as well as to his optimistic view. This dystopian vision was taken up by Bill Joy in *Wired* (2000) and even described by Jamie Dinkelacker as the possibility of "a wretched, hard-scrabble existence under cruel oppression". In Joy's view, the applications of his conception of nanotechnology (molecular manufacturing) are inextricably entwined with its implications for society. The convergence of nanotechnology (in particular, self-replicating assemblers) with robotics and genetics is likely to happen incrementally, as "a sequence of small, individually sensible advances". But he thinks that this will lead to "an accumulation of great power and, concomitantly, great danger", with the knowledge behind the technologies available for abuse, specifically by "individuals or small groups". As Joy elaborates, it is "far easier to create destructive uses for nanotechnology than constructive ones" as there is one crucial difference with the emerging technologies of nanotechnology, genetics, and robotics. Unlike potentially dangerous technologies such as nuclear weapons, these will "not require large facilities or rare raw materials. Knowledge alone will enable the use of them". Joy fears that this knowledge could fall into the wrong hands, leading to weapons of "knowledge-enabled mass destruction".

In addition to nanotechnology being intentionally used for harmful purposes, the ability to control nanomachines may be lost even to the technologists. Joy believes that the self-replicating assemblers could run wild, capable of obliterating life. This is the 'gray goo' scenario, in which nanomachines spread like bacteria, reducing (as Joy quotes Drexler) the "biosphere to dust in a matter of days". Although not so radical, Debra Rolison presents a correspondingly ominous argument. She points to the 'revenge effects', or unanticipated consequences, of previous technologies, and ordinary accidents that have led to disaster. These include drug resistance of viruses and bacteria, the persistence of chemicals in the environment, nuclear accidents and oil spills. Focusing on the confluence of nanotechnology and biotechnology, Rolison asserts that their effects on society will be no different nor less unpredictable than previous technologies: "Unanticipated consequences. Revenge effects… All affect society and create change in ways not always intended. We can expect no less from nanobiotechnology." Combine this with advances in robotics and artificial intelligence, and this may lead to Joy's scenario of "our own extinction", where the environment is destroyed by 'gray goo' and technological accidents, and we "gradually replace ourselves with our robotic technology".

In order to avoid this 'hell on Earth', Joy recommends complete "relinquishment" of nanotechnology. He compares this to the United States' cancellation of research into, and development of, biological weapons in the 1970s. Joy suggests that the success of such an initiative would depend upon researchers, who would have to "adopt a strong code of ethical conduct" and be responsible for any social effects of new technologies. This call for a moratorium on research is shared by the ETC Group. It maintains a neutral position on whether the ultimate goal of Drexlerian molecular manufacturing is feasible, but sees negative outcomes for society in the development of all forms of nanotechnology. ETC has concerns over the safety of nanoparticles for humanity and the environment because "the potential cumulative impact of human-made nano-scale particles on human health and the environment" is not yet known. However, the majority of ETC's criticisms and predictions for disaster stem less from the nature of the technology itself than from the political issues surrounding its development. ETC summarises this approach in the report: "The point is not that the technologies are bad… [but]… the evaluation of powerful new technologies requires broad social discussion and preparation". ETC's concern is that society will not be consulted and will instead have 'all-pervasive' nanotechnology and its possible challenges thrust upon it.

This viewpoint is shared by Sue Mayer, who sees parallels between the emergence of nanotechnology and of GM 15-20 years ago. The lack of democratic consultation keeps the assessment of any risk within the realm of the 'expert'; the public is then considered ignorant, and the authorities attempt to calm any fears with 'sound science', a concept that to Mayer is shaped "not by scientific facts but by its political, social, economic and cultural context". Mayer's concerns, however, extend beyond the lack of democracy in technological development to the effects that this may have. While the applications of nanotechnology may appear "distant and speculative", investment and commitment from industry is growing at a rapid pace. If there is no public engagement now, it will 'burst on the scene' when it is too late to have a debate. Too much "will have been invested economically and intellectually to go back" and it may then be a case of imposing nanotechnology on an unwilling public, much as with GM. Moreover alternatives will not have been explored and the economic benefits of nanotechnology may be less than they would be if the public had been involved in its design.

The perceived lack of democratic consultation also raises concerns regarding the control and ownership of the technology, the possibility of its monopolisation and the "implications of corporate control over matter" (Mayer (2002)). With discoveries at the level of atoms and molecules, and elements being modified, ETC Group fears that these fundamentals of life and science, or more likely the processes by which they are constructed, could become the subject of patents. This leaves the control in the hands of the company filing the patent, and with multinational corporations investing early in nanotechnology development, monopolies could be formed. In ETC's words, "Nanoscale manipulation in all its forms offers unprecedented potential for sweeping monopoly control of elements and processes that are fundamental to biological function and material resources". ETC envisages that the recent trend of the control of technology development being lost to the public arena, the "privatisation of science and a staggering concentration of power in the hands of giant multinational enterprises" will be further reinforced by nanotechnology. In ETC's picture of the future, the "control of the technology will accrue to those with power and the commercialisation of the technology will inevitably give them greater monopoly control". ETC does not trust big business, or governments, to use this knowledge, power and control ethically.

Allied to these issues of monopoly and control is the negative vision that nanotechnology will reinforce global inequalities between rich and poor. As we have seen, nano enthusiasts assert that nanotechnology will "trigger a new economic renaissance that combines the dream of material abundance, sustainable development and profit", thereby benefiting everyone. But ETC labels this, and such claims as eradicating Third World poverty, as "recyclable myths". Theoretically it believes 'Atomtechnologies' could be used for the global good, but is sceptical that this will happen because of the commercial forces that are purely concerned with profit. Comparing the dawning of a nanotechnology revolution to previous industrial revolutions, ETC raises the question of "a decline in the well-being of poor people and increased disparity between rich and poor", as only those with sufficient wealth may have access to the technology. Joy's 'gray goo' scenario is mentioned, and is joined by the 'blue/gray goo theory' which sees humanity taken over by intelligent machines, and the 'green goo theory' in which combined biological and non-biological systems run wild. Less fancifully, ETC has concerns about human performance enhancement, in areas such as artificially enhanced senses and intelligence, similar to those outlined by Dinkelacker, and about artificial intelligence. It is concerned that these may lead to an erosion of human rights, for instance through discrimination against the "unimproved", and is also worried that the technology "poses a major threat to democratic dissent". In other words, ETC predicts a future in which the ruling elite has "unlimited surveillance capacity" at the nanoscale leading to an Orwellian scenario of "Big Cyborg Brother".

Symbolic of this to the ETC Group is what it sees as governments' attempts to overcome any barriers to nanotechnology's development. Although participants in government workshops suggest that there is a need for studies of nanotechnology's social impacts in any research programmes, this report proposes that the "social sciences were largely understood to operate in the service" of the technologies. This is often inadvertently conveyed by the reports we have discussed.

Barriers to development

The DTI report champions nanotechnology, hoping that it may bring about an investment boom and have a large impact on manufacturing and industry. It recommends that investment opportunities be taken and utilised to have a beneficial impact. The report states that nanotechnology will deliver "smaller, cheaper, lighter and faster devices with greater functionality, using less raw material and consuming less energy". The impact on industry, it claims, will be significant, and "few industries will escape the influence of nanotechnology". Due to this, the report voices concerns that falling behind in technology development will seriously harm the economy. Industries which "are early to incorporate nanotechnology into their products" will have a clear advantage, and "the failure to respond to the challenge [of incorporating nanotechnology] will threaten the future competitiveness of much of the economy". The assumption is that nanotechnology will have a significant positive impact on industry and the economy if developed effectively. The aim, then, becomes one of ensuring any barriers to the economic success of nanotechnology are overcome.

Some of these barriers are financial and strategic, and are explicitly stated. The lack of critical mass in UK R&D activities, the absence of specialist interdisciplinary facilities, and the potential shortfall of skilled workers are three examples. Another obstacle is more implicit; there is the suggestion that public acceptance of nanotechnology is vital and controversy and hostility to the technology would be a serious barrier. The report recommends an "awareness programme" to inform and educate the "business sector, universities, the media and others on the implications and possibilities that will arise from nanotechnology". Without this public education, it is felt that the country could miss out on the economic opportunities presented by nanotechnology: "The need to raise public awareness is pressing and cannot await the formation of the nanofabrication centres. Indeed, it can help to pave the way for them." This is echoed by both Rolison and Mnyusiwalla et al, whose views are mindful of the opinions of Joy and possibly ETC. Rolison notes that "popular dissent can and will thwart research".

Mnyusiwalla et al also imply that "public engagement" could be used as an educational tool to assuage any fears of the new technology, and advocate the use of journalists as they "have an important influence on public perception".

A similar sentiment is expressed by the NSF in the executive summary for the report from its workshop on the *Societal Implications of Nanoscience and Nanotechnology* (2001). The workshop was convened as part of the National Nanotechnology Initiative (NNI), the funding umbrella for US research which includes provisions for research on the social implications. Indeed, as the report states, "The study of the societal implications of nanotechnology must be an integral part of the NNI"; investment is needed to "Study the evolution of disruptive technologies, the winners and losers in major technological transformations, and the implications for the economy" and apply the findings to nanotechnology. Research on the "social acceptance, resistance, or rejection of nanotechnology" is encouraged, and the NSF has set aside specific funding for this as part of the nanotechnology programme.

The workshop report states that social science research will "boost the chances for NNI's success", reducing any barriers or opposition to the technology and making the most of its potential economic worth. The report's authors are aware that misinformation and a lack of understanding may impede public acceptance of nanotechnology, and hope that "technically competent research on the interactions between nanotechnology and society will help mute speculative hype and dispel some of the unfounded fears that sometimes accompany dramatic advances in scientific understanding". Social scientists, it is suggested, are the link between the scientists and the public, and their "input may help maximize the societal benefits of the technology while reducing the possibility of debilitating public controversies". The implication is that the main role for social science is within public debate, as a tool to gain public acceptance of an emerging technology. This is an example of a top-down approach (Barbour (2002)) to public involvement in technology development, one which can lead to mistrust of authorities Public controversy is seen as a barrier to technological development, and government agencies are paternalistic in their conception of society, taking the view that the public need to be persuaded that the technology is a good thing.

Regulatory responses

One of the ways of increasing public confidence in nanotechnology is by introducing a comprehensive regulatory regime, a less extreme option than the moratorium proposed by Bill Joy and ETC. This is something that the final group of commentators focuses on. Much of the discussion on the need to regulate nanotechnology development and applications is caused by uncertainty. This section, therefore, is comprised mostly of those authors whom we classified as nanotechnology commentators. The exception is Drexler's Foresight Institute, the aim of which is to guide the development of radical nanotechnology along a responsible and beneficial route.

In order to avoid "reflexive, or poorly informed" regulation laid down by legislators, the Foresight Institute's guidelines attempt to encourage self-regulation in the scientific community, and are "intended to provide a basis for responsible development of molecular nanotechnology". Conscious that risks and social issues will arise with the development of the technology, particularly security and environmental issues, the Institute believes that dealing with these "proactively will be critical to the positive development of the field". Only this will allow the possibility of "widespread material abundance" and the alleviation of "conflicts that stem primarily from rivalry over resources".

The guidelines have been produced largely because of the Institute's belief that molecular manufacturing may be approaching rather fast. Its image of nanotechnology is very clear, and so the guidelines are very specific. In order to avoid any "negative ecological and public health impact", such as the 'gray goo' scenario, the Institute recommends several safety measures to be built into the technology. These include creating devices with "absolute dependence on a single artificial fuel source… [unavailable] in any natural environment", and "programming termination dates into devices".

In contrast, the UK's Better Regulation Task Force (BRTF) has an open conception of nanotechnology, and mentions few specifics. They wish to raise the profile of possible "risks of nanotechnology", but acknowledge that concerns may decline should the benefits of the technology become apparent. The BRTF recognises that research needs to be guided in a positive direction while policy minimises the risks to society. The BRTF urges the authorities "to be ready to deal with concerns" and advocates a "dialogue with the public", in order that research can continue in beneficial areas and opportunities are not lost due to public opposition. The implication is that a regulatory structure will not only protect the public but also assuage their doubts.

Considering such a wide and imprecise conception of nanotechnology, Mnyusiwalla et al are less concerned with specific regulatory issues, and more with the pressing need for general research on the social and ethical concerns raised by nanotechnology. Some commentators, explicitly Joy but most likely Drexler and the other radicals too, are criticised for focusing too often on "distant, controversial applications" instead of more probable and more immediate ones.

Nonetheless the field is developing rapidly and a gap is emerging between the level of science, and the slow progress of social scientific research. Regardless of the technology, if ethical and social research are not on a par with technological development, the resulting gap allows public fears to spread and be exploited by pressure groups. Much like the BRTF, it is felt lessons can be learnt from the scientific community's experience with GM foods.

In a similar vein Mnyusiwalla et al argue that nanotechnology will create distinctive challenges to society, separate from previous technologies, that will need specific serious discussion and possibly specific regulation. Unlike other analysts who too often make "generalizations and motherhood statements", they divide these challenges into several areas, encompassing issues of equity, privacy and security, the environment, and "metaphysical questions concerning human-machine interactions". Nanotechnology raises particular challenges with regard to the environment, such as the life-cycle of nanoparticles, and privacy and security, in the possibility of invisible monitoring and tracking devices. It is such developments that may require specific controls.

Jesús Mosterín in his treatise on nanotechnology and ethics, however, is less sure of the possible social challenges, and instead estimates that most of the "ethical problems posed by nanotechnology are inextricably entwined with those posed by biology and biotechnology". He emphasises that the technology itself is ethically neutral, and its impact depends on how it is utilised. Mosterín argues for a "cost/benefit analysis of the technology's prospects", but is sceptical of any stricter regulation: "The fact of something being new and still untested is no reason to rush to forbid it. It is only reason to test it".

Sue Mayer takes a different position, which acknowledges technologies are not neutral but instead are "shaped by the prevailing social, political and economic climate", which means that the development of one technology may be at the expense of another. In order to ensure successful development of technologies, and drawing on *Wising Up*, a study by Grove-White et al (2002) on the lessons to be learnt from the public reaction to GM, Mayer recommends that firstly technologies be recognised as "social processes". If nanotechnology is socially constituted through processes that involve the public, the need for specific regulations or moratoria will not be necessary. Indeed these are portrayed as "technical solutions". The Foresight Institute's regulations are singled out for particular criticism for ignoring the issues of enforcement of the regulations, any new ethical questions associated with nanotechnology, and the control of the science and technology, particularly of corporate control.

More reluctant than most to speculate on any specific social challenges posed by nanotechnology, Denis Loveridge roots his discussion of nanotechnology's impacts in the near future. His main concern is that "populist visions of new wonder artefacts", promulgated by nanotechnology champions and also within the scientific community, are creating "a degree of exaggeration that is unhelpful". In the immediate future, the overselling of nanotechnology may cause problems both for research and development activities and for investors. As has happened in the past, most recently with information and communication technology, Loveridge is troubled most with the "unquestioning exploitation of new science and technology for wealth creation and competitiveness". Any explosion of interest and investment prompted by the over promotion of nanotechnology as the next 'big thing' may lead to the "next stock market bubble". More research and careful development are needed to avoid this and to assess whether nanotechnology really is the "harbinger of the next industrial revolution".

Whether or not the "orderly rather than chaotic investment" that Loveridge counsels comes to pass depends on the responsible development of the technology, taking into account Loveridge's three elements of scientific possibility, technological feasibility, and social desirability. Whether assessing technological feasibility can be ethically neutral or not, the overall assessment of potential should not be. In his view, social desirability of a technology "covers that area of contention where people discuss and argue about which artifacts may be acceptable to and be expected by society". Of the development triptych, Loveridge asserts that this "may turn out to be the most important" aspect, as the successful evolution of nanotechnology will rely on its acceptance by society. Indeed, the technology will be redundant without it.

The need to consider the social desirability of nanotechnology has implications, in Loveridge's view, for regulation and policy. In order to uncover what is needed and would be accepted, a public consultation would be required; Loveridge asserts the "need to create informed debate" to confront and examine "society's hesitancy in accepting new artifacts". This would promote "widespread and realistic understanding of nanoartifacts to facilitate government and industry policy making". He says in effect that such an exercise would enable the development of the technology to be commensurate with society's needs. In this scenario, regulation would become redundant.

Conclusions

A number of linked debates about nanotechnology are developing. The first is fundamentally scientific in character, about whether the radical view of nanotechnology, leading to molecular manufacturing, is feasible or practical, whether by the route sketched out by Drexler or by some other means. Those who consider this radical view of nanotechnology to be feasible are divided as to whether it will lead to a positive or negative outcome for society. This debate takes for granted that nanotechnology will have a revolutionary effect on society, and the contrasting visions are correspondingly utopian or dystopian.

There is also an emerging debate between those who believe that rapid growth of nanotechnology defined in its broader sense will have strongly positive economic benefits, and those who on the grounds of environmentalism and social equity seek to slow or halt the development of nanotechnology. This debate is anchored in current applications, contrasting, for example, the economic benefits of new materials with the possible toxicity of nanoparticles. But the revolutionary implications of success in the more radical programme form an implied backdrop to both the positive and negative side of this argument.

Much of this debate is being channelled into the issue of regulation and other forms of intervention. At issue is whether the existing regulatory framework for food, drugs, cosmetics, and workplace and environmental safety is sufficiently robust to incorporate any special features of nanoparticles, or whether new structures need to be set in place.

Right: Microgears. Coloured scanning electron micrograph (SEM) of an interlocking array of micromotor gears. Tiny gears and cogs such as these are the basis of designing tiny machines.

5

We have seen an emerging concern that the needs of society be considered as part of the development process and that nanotechnologists not be left alone to dictate what materialises.

The belief that nanotechnology is a radical discontinuity from previous science and technology naturally implies that the social effects will be huge.

The dominance of radical perspectives has meant that the emerging debate surrounding nanotechnology has seemingly become polarised before it has been allowed to mature.

On the one hand, there is an excessive positivism that associates nanotechnology with improvements... on the other are expressions of concern, often rooted in the fears of self-assembly robots taking over the world.

Both sides of the debate have an interest in the social acceptance issue. The positivists wish to guarantee that the development of nanotechnology is not impeded by public opinion, the negativists to ensure it is not too readily and blindly accepted.

The Social Dimensions of

Nanotechnology

We have discussed the writing on nanotechnology in terms of two dimensions: its conception of nanotechnology and its perception of the possible social and economic effects. We have seen an emerging concern that the needs of society be considered as part of the development process and that nanotechnologists not be left alone to dictate what materialises. This implies that any assessment of possible social and economic effects be incorporated into this process as early as possible, and hence that social science, as a major provider of such understanding, can help shape the future of nanotechnology. In this chapter we explore how the social dimensions of the nanotechnology debate are defining a need for social science involvement, show that the need is being defined in either rather general or unduly narrow terms, and outline the kinds of issues surrounding nanotechnology that social science is well placed to investigate. We conclude with the implications for social science policy.

Developing social science involvement

We categorised the various concepts of nanotechnology in terms of whether it is seen as a continuation of scientific development or a radical departure from current approaches. The perceived effects have been classified by a mixture of how radical these will be and the extent to which nanotechnology's overall outcome is seen as positive or negative. The belief that nanotechnology is a radical discontinuity from previous science and technology naturally implies that the social effects will be huge. Conversely those who conceive nanotechnology as an extension of current research have a less extreme view of its impact; comparisons to other technologies, past and emerging, are made more frequently, and more emphasis is placed on short-term implications, particularly for industry. As we have shown, they tend to be more cautionary and circumspect, perhaps reserving judgement until applications become more apparent and numerous.

The dominance of radical perspectives has meant that the emerging debate surrounding nanotechnology has seemingly become polarised before it has been allowed to mature. On the one hand, there is an excessive positivism that associates nanotechnology with improvements in "almost every aspect of our lives, right down to the water we drink and the air we breathe" (Foresight Institute web site). On the other are expressions of concern, often rooted in the fears of self-assembly robots taking over the world, or in parallels being made with the lack of consultation over GM and the subsequent apparent public rejection of it. As the negative arguments become more prominent, there is a fear of a backlash against nanotechnology that may thwart its development. Indeed, an article in *The Engineer* (Knight and Pierce (2003)) implied that it is here already: "nanotechnology research is facing a similar backlash to the one that put the biotechnology industry on the back foot". Consequently developing a realistic perspective on nanotechnology is seemingly becoming part of its challenge.

Both sides of the debate have an interest in the social acceptance issue. The positivists wish to guarantee that the development of nanotechnology is not impeded by public opinion, the negativists to ensure it is not too readily and blindly accepted. With this in mind, and with an eye to avoiding any premature absolute resolution either way, Mnyusiwalla et al (2003: 9) perceive that exponents and critics "seem to be on a collision course towards a showdown of the type that we saw with GM crops".

The Royal Institution, the *Times Higher Education Supplement*, the Biotechnology and Biological Sciences Research Council, and the Institute of Nanotechnology hosted a conference on nanotechnology in March 2003 to stage a mini-showdown on the matter, albeit in civilised debating format. The focus became the need for the wider involvement of the public in the debate on nanotechnology. The implication is that it would help both sides of the argument to expand the influence of non-scientists in science policy and this would encourage the acceptance of nanotechnology that its exponents seek. It was also clear that the negative concerns are part of a wider concern about a democratic deficit. The emerging parameters of the public debate seem to have two main preoccupations: that the UK will be left behind as investment in nanotechnology and science is growing apace in the USA, Germany and the Far East and that nanotechnology is being linked to GM and may face the backlash alluded to by Knight and Pierce and the confrontation described by Mnyusiwalla et al. The obstacles to development, then, are those of finance and public acceptance.

The concern to address the social acceptance issue led the March 2003 meeting to social sciences. Initially in the discussion social science was placed in the role of a conduit in the process of social education, or facilitator of the public debate. But its potential role in developing an understanding of the attitudes of the public emerged as more significant. This illustrates the vital way in which the social dimension is increasingly being framed not so much in terms of nanotechnology's implications, but in terms of ensuring that nanotechnology's potential is realised.

In these terms, the implications of the positive perspective on nanotechnology are that any social science research should be orientated towards ensuring that nanotechnology emerges and that any barriers to this, including negative fears, are overcome. The implications of the negative perspective are that what may appear to proponents as a social acceptance issue is the need for public involvement in science policy as an end in itself, as part of the widening participation of all in the decisions that shape the destiny of the world.

The agenda for social sciences must, in our judgement, be broader than the public-science interface. First, this should be seen as part of the bigger issue of the governance of technological change, which itself cannot be reduced to the incorporation of concerns and perceived needs into the process of technical development. It requires the injection of a greater understanding of how the choices that constitute these processes are made, and may vary with types of application, into the social processes by which institutions of governance are created. Currently, corporations, entrepreneurs and technologists are the main driving forces behind technology and the market the main mechanism for public participation in its governance. A crucial starting point for social science research, then, is to acquire an understanding of the drivers and processes of decisions at the various choice points in the process of technological development. The extent to which the choices are themselves path-dependent is an important related question in order to assess how much any involvement at latter stages is limited by earlier decisions.

Second, the governance issue, while partly a question of enhancing the democratic processes, is also a question of social learning and of how we learn to evaluate risks and opportunities under uncertainty. It asks how conflicts of interest can be identified and clarified in a way that fosters informed two-way debate; how science, technologists and firms can best be regulated; and the limits of the nation state as a regulator in an increasingly international world.

Third, there is the perennial issue of equity and economic divides. Will the scale of investment required lead to applications aimed primarily at the rich (e.g. cosmetics, high-tech fabrics, individualised medicines, even life extension) and further accentuate the division between nations or will the benefits also be more widely felt (e.g. affordable water treatment and cheap power for poorer nations)? If developments in information technology are a major vehicle for nanotechnology, will a course between these two extremes be the most likely trajectory? Is a benign late development effect realisable through nanotechnology, for example as China uses nanotechnology as a foundation for building its scientific enterprise?

Social science issues

Social scientists have the capacity and willingness to take on the issues surrounding nanotechnology. To avoid grand narratives and excessive futuristic conjecture the study of nanotechnology should be organised around a set of key issues and manageable sub-questions. It is imperative to find distance from the simplistic, polarised debate that appears to be emerging.

To help orientate discussion we would classify the issues surrounding nanotechnology into five categories thus:

- ☐ issues related to ensuring that nanotechnology develops its potential;
- ☐ issues relating to social awareness of nanotechnology and public involvement in science;
- ☐ social and economic issues that will be concurrent with, or even intensified by, nanotechnology;
- ☐ issues associated with any new technology;
- ☐ issues unique to nanotechnology.

There is overlap between the categories, and even those in the last group will not exist in isolation.

The first two issues directly reflect the terms of the debate so far. Attending to the other issues will serve to move it forward and enrich the reflection surrounding it that will inevitably occur in the coming years. At this stage, though, it would be foolhardy to think one could list all the topics that could fall under each category. We will however list illustrative examples under each.

- Issues related to ensuring that nanotechnology develops its potential: technology transfer; the relationship between firms, governments, and universities; R and D investment; financial institutions; entrepreneurship.
- Issues relating to social awareness and involvement in science: the role of the public in science policy formation; the perceived needs of people for technological advances; the role of workplaces, non-governmental organisations, and consumer groups in democratic processes; ethical issues.
- Social and economic issues that will be concurrent with, or even intensified by, nanotechnology: commercialisation of science; the UK's perceived innovation problem; intellectual property; risk management and regulation; privacy and the growth of information and its ownership and control; ageing.
- Issues associated with any new technology: managing the unforeseeable nature of problems; organizational development; change management; user-friendliness; skills that are needed to produce and use a new technology.
- Issues unique to nanotechnology: the dependency for its development on interdisciplinary science and engineering; potential new risks; the human-machine-nature interface; specific ethical issues concerning artefacts which mix synthetic and living elements.

The illustrative items under the first four issues are familiar topics in the social sciences. Those under category five may require some explanation. First, nanotechnology's inherent interdisciplinary nature, coupled with the uncertainty about its final destiny and the multifaceted linkages with other developments adds bite to its study. If nanotechnology both depends on and provides a means for the enhanced integration between the disciplines of sciences and engineering, the social and economic processes through which this is done will be fertile ground for social scientific investigation and theorising, for example on group processes, perspective taking and virtual working. The merit in this does not, of course, depend on the integration being totally successful, and the research itself could be vitally important to its development (as in the socio-technical approach). Moreover, how nanotechnology combines with developments in other domains, some of which may be unknown now, will involve social and economic processes which again will be ripe for study.

Second, the human-machine-nature interface. As mentioned in Chapter Two, it is likely that the machine will become even more of an extension of ourselves. One of the most interesting lines of speculation that has emerged from the development of computers and the internet has been the idea of a new, non-physical space which humans can in some sense inhabit and interact with. The notion of virtual reality has been coined to express this; this may be as mundane or primitive as the imagined environment of a video game, in which the interaction occurs very crudely by the observation of a computer screen and interaction with the non-physical environment through the controls of a keyboard or joystick. Slightly subtler are the ideas of a space of information that underlie some writing about the internet. A major driver for the design of the interface between human and machine is the aim of making the machine as much like an extension of the human body as possible, with a seamless and intuitive relationship between intention and realisation. Technical developments, including the formation of images directly on the retina, and the direct translation of nerve impulses into computer inputs (in many cases substantially driven by the military) will make the interaction between human and computer much more immediate in the near future. When this kind of sophisticated interface design is combined with instruments that observe and interact on the nanoscale – such as scanning probe microscopes – we have the intriguing possibility that human operators of these instruments increasingly feel themselves to be physically operating in this new space at the nanoscale. There are even speculations that advanced technologies will eventually allow us to 'upload' our minds, thus enabling immortality and survival without biological roots.

The implications for social science policy

Formulating the issues as we have done reveals just how few, if any, of the issues are likely to be unique to nanotechnology. They may nonetheless yet be the most profound, being concerned with the human-machine-nature interface, changing conceptions of human kind, and fresh ways of thinking.

The fact that the issues are predominately not unique to nanotechnology does not make them any less important or relevant to the social sciences. It may, though, have implications for the way one approaches the decisions about social science investments. If nanotechnology turns out to be very diverse and the implications of its applications are highly context-specific, a strategy of relying on researchers including nanotechnology into their studies as and when it is perceived to be relevant might suffice. However, at the other extreme, if nanotechnology is predicted to be a unique and overwhelmingly powerful force which will affect all aspects of social life, then the social scientist has no choice but to focus on it, and as early as possible.

The implications of our analysis for social science policy are between the two extremes. We can say that: nanotechnology is a sufficiently developed concept to anticipate that it will be important; nanoscience and nanotechnology need to be differentiated; the complexity of the issues surrounding nanoscience and nanotechnology often lie in their linkages with other developments; and the precise applications and significance are uncertain but will be varied. Some will be mundane, few have thus far been realised, and all have context-specific features. Given nanotechnology's apparent importance, and that it is evolving at a time when there are other pressures on issues such as ageing, intellectual property and risk management, it provides social scientists with an opportunity to study the effects of technology on these issues. Similarly, it provides them with an opportunity to study issues associated with any emerging technology. Moreover, nanotechnology's infancy offers social science an opportunity that past technological development did not, probably because of the underdevelopment of the social sciences. The uncertainty surrounding nanotechnology and the lack of current applications should not be reason for postponing social science research.

It would be timely for social science funding agencies to invest in this area. It would not be sufficient to wait for proposals from social scientists in 'non-technology' areas as and when they are affected by nanotechnology. Waiting for proposals from researchers working with technology issues, for example within the science policy and innovation areas, might be more successful. Nanotechnology's social implications should be a high priority for those already working in science and innovation, or no doubt will be.

Specific initiatives on nanotechnology would, however, guarantee that the opportunity provided by nanotechnology is not missed and that the research does not become fragmented. The uncertainty, complexity, and diversity of nanotechnology mean that any such initiative should not be a rigidly preconceived closed programme. Flexibility will be needed to stay abreast of developments as they arise.

In our judgement a number of implications for the design of a research strategy flow from this analysis.

☐ If the effects of nanotechnology are potentially as wide-ranging, while having context-specific dimensions, it is unlikely that concentrating resources in one centre will provide the best value for money.

☐ If nanotechnology's characteristics and effects are not primarily idiosyncratic, then the existing expertise of researchers and, particularly, centres working on technology and innovation issues, or issues assumed to be affected by it (e.g. ageing and risk), should be capitalised upon.

☐ If nanotechnology will develop in diverse ways in association with complex developments elsewhere, then social scientists will have to work with scientists and technologists, academic and industrial. They will have to understand and be aware of developments, and at best be equal partners in the shaping of future technology and its applications.

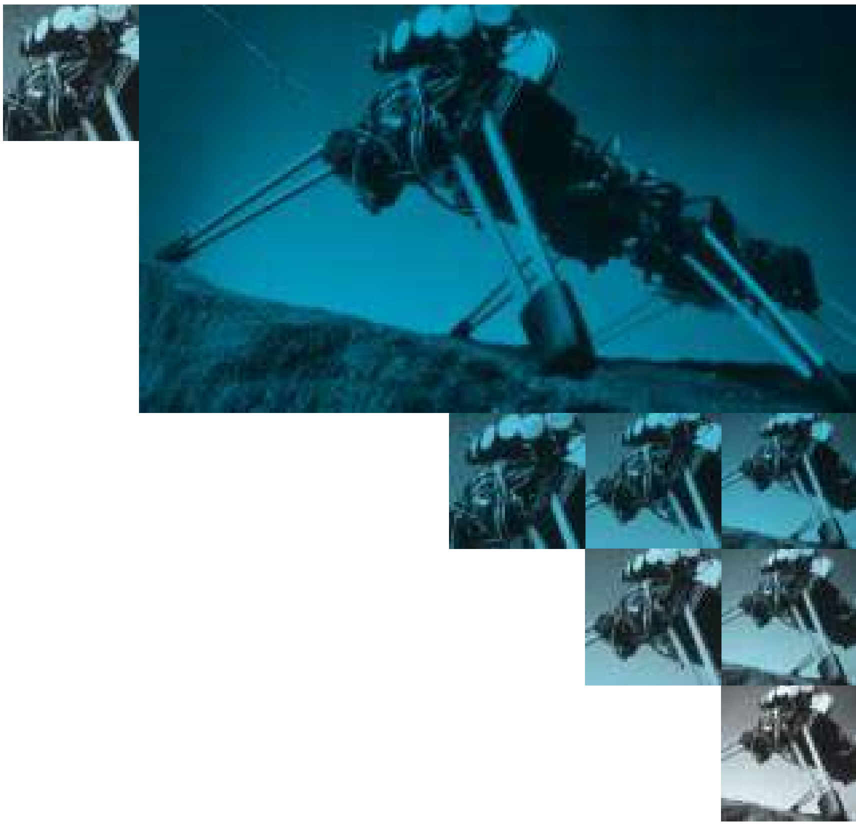
☐ If different nanotechnologies have different development trajectories, a comparative study of these (as well as with other technologies, both historically and contemporary) would be fruitful.

☐ If governance and regulatory regimes vary between countries (with some perhaps designing elements specifically for nanotechnology) international comparisons can be made of how existing regulations impact on the development of nanotechnology and any regulations specific to nanotechnology emerge and operate.

☐ If a core aspect of the nano-project turns out to be new issues in the relationship between human beings and nature, with possible implications for a growing closeness between the natural and social sciences, then better working relationships between scientists and social scientists will be vital.

Not all research projects need involve scientists and any need may diminish over time. But maximum benefits from any investments in social science are likely to be reaped with teams of representatives from disciplines across the whole spectrum of the social and natural sciences, pure and applied.

The Social Dimensions of
Nanotechnology



Above: 'Genghis', one of several robot insects produced during nanotechnology and micromechanics research. It uses 'artificial stupidity' to perform very simple tasks.

I

The implications of the negative perspective are that what may appear to proponents as a social acceptance issue is the need for public involvement in science policy as an end in itself, as part of the widening participation of all in the decisions that shape the destiny of the world.

Social scientists have the capacity and willingness to take on the issues surrounding nanotechnology.

One of the most interesting lines of speculation that has emerged from the development of computers and the internet has been the idea of a new, non-physical space which humans can in some sense inhabit and interact with.

If nanotechnology turns out to be very diverse and the implications of its applications are highly context-specific, a strategy of relying on researchers including nanotechnology into their studies as and when it is perceived to be relevant might suffice.

Appendix I

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II

The scientific community and society “seem to be repeating the path” taken by genetic modification.

The crux of the positive radical view of nanotechnology is the ability to design and construct nanosized robots, capable of many functions.

In addition to nanotechnology being intentionally used for harmful purposes, the ability to control nanomachines may be lost even to the technologists.

While the applications of nanotechnology may appear ‘distant and speculative’, investment and commitment from industry is growing at a rapid pace. If there is no public engagement now, it will ‘burst on the scene’ when it is too late to have a debate. Too much “will have been invested economically and intellectually to go back” and it may then be a case of imposing nanotechnology on an unwilling public, much as with GM.

Appendix II

Literature Summary

Author, year Title	Conception of Nanotechnology	Applications Mentioned	Social and Economic Implications
Drexler, K.E. (1986). Engines of Creation	Introduced the term nanotechnology to describe the radical goal of molecular manufacturing, based on the vision put forth by Feynman in 1959.	Self-replicating assemblers, able to create almost anything by guiding chemical reactions.	Molecular manufacturing holds many positive possibilities, such as reduced energy use, material abundance, and the elimination of disease and ageing. Many other radical visions, such as a self-cleaning house and communities in space. Possibility of molecular manufacturing also being used as an agent of power, like a weapon; the 'gray goo' scenario, where self-replicators get out of control and destroy the biosphere, and possibly humanity.
Drexler, K.E. (2001). Machine-Phase Nanotechnology	No change from his earlier view.	Bottom-up construction, mimicking cells; strong materials for space travel; molecular repair of the body and disease eradication.	Assumes molecular manufacturing will be a reality, and manufacturing will be revolutionised, with cleaner processes. Society will need to make decisions regarding nanotechnology and these should be based on coherent facts and critiques, and policies should be made to stop abuse of technology. New technologies should be effectively managed. Focuses on potential positive impacts on society (such as eradicating disease and poverty), making brief mention of the potential for large negative impacts.
Dinkelacker, J. (2002). Transition to Tomorrow	Unique because it may enable complete control over matter at a fundamental scale.	Nanotechnology may affect all areas of industry and life, including new materials, faster computers, electronics, health applications giving longevity.	Absolutely revolutionary, whether or not the outcome is arrived at through molecular manufacturing or less radical means. Social institutions and structures will change; the nature of work will change; quality of life will be improved with materials abundance for all; longevity will change the relationships between generations and make humanity more responsible for its actions.
Foresight Institute (2000). Foresight Guidelines on Molecular Nanotechnology	Highly revolutionary, defined as molecular manufacturing; it "presents an unprecedented new set of technical and economic opportunities".	Material abundance for the whole world, new techniques in medicine, improved space travel.	Implications for society will be 'unprecedented', such as eradication of poverty. Guidelines have been developed to address these possible issues through risk management (including cost/benefit analyses) and self-regulation. Scientists are responsible for considering the social and ethical implications of their work.
Joy, B. (2000). Why the future doesn't need us	A new technology that threatens human existence.	Self-replicating nanorobots, the integration of man with machine.	Completely revolutionary – work will no longer be necessary; technology will be controlled by a powerful elite; unintended consequences will be commonplace such as replicators spiralling out of control creating a 'gray goo', scientific knowledge could be abused. Policies must be put in place or research relinquished to protect against 'technical arrogance'.

Author, year Title	Conception of Nanotechnology	Applications Mentioned	Social and Economic Implications
Reynolds, G.H. (2002). Forward to the Future: Nanotechnology and regulatory policy	The Drexlerian vision of molecular nanotechnology.	Self-replicating assemblers, able to create almost anything by guiding chemical reactions.	Many revolutionary effects: cutting energy consumption, curing and preventing disease and making weapons and military devices more effective. Any concerns over these effects can be moderated with self-regulation.
Broderick, D. (2001). The Spike: How are lives are being transformed by rapidly advancing technologies	The Drexlerian vision of molecular nanotechnology.	Self-replicating nanomachines enabling in vitro cellular repair and the fabrication of anything.	Convergence with other technologies will lead to exponentially increasing technological changes, creating massive social upheaval, and such effects as immortality or the amalgamation of humans with artificial intelligence. The long-term future will be unimaginably different from the present day.
Suchman, M.C. (2002). Social Science and Nanotechnology	Distinguishes between 'nanates', nanostructured materials, and 'nanites', novel devices and machines.	Assumptions made that possibilities such as self-locomotion and self-replication will be realisable and widespread.	Very revolutionary. The technology will generate new and unfamiliar properties such as invisibility. Currently no mechanisms in place to monitor nanotechnology. Implications in areas such as ownership and control. Social science needs to monitor the situation.
Whitesides, G.M. (2001). The Once and Future Nanomachine	Sceptical about the radical Drexlerian view: regards biology as an appropriate model for nanotechnology.	Nanomachines will not merely be scaled-down versions of existing machines, e.g. nanosubmarines. Self-replicating systems, such as cells, already exist.	Dangers to society lie in self-replicating systems – these are already feared as viruses in biology.
Smalley, R.E. (2001). Of Chemistry, Love and Nanobots	Encompasses chemistry, biology and physics at the nanoscale. Attacks the radical Drexlerian view.	Does not forecast any applications, but examines proposed uses of nanobots in the manufacturing.	Dismisses the notion of molecular assemblers as unfeasible and "not possible in our world".
Ball, P. (2003). Natural strategies for the molecular engineer	Nanotechnology should apply lessons learnt from nature.	Nanomachines will not merely be scaled-down versions of macroscale machines.	Nanoscience and technology will benefit from studying the self-assembling and self-replicating processes of nature, particularly the chemical mechanisms employed by cells. Implications for society at large are not investigated.

Appendix II

Literature Summary

Author, year Title	Conception of Nanotechnology	Applications Mentioned	Social and Economic Implications
Loveridge, D. (2002). Nanotechnology: its potential as the 'next industrial revolution' and its social consequences	A misleading term, and it's ideas are not new but evolutionary. The technology should be viewed as science, technology and engineering on a nanometre scale.	Systems integration at the nanoscale – in manufacturing, drug delivery, electronics and biomimetics.	Societal-wide discussion is needed now as nanotechnology techniques are already influencing industry and society; "unquestioning exploitation" must be avoided and the social desirability of technologies taken into account. Nanotechnology presents an opportunity now to discuss a possible emerging "industrial revolution" and avoid "unachievable investor expectations".
Stix, G. (2001). Little Big Science	Difficult to define, being so diverse. It is not novel, with areas emerging from materials science and chemistry.	Data storage devices, sunscreen, waste reduction, lighter materials for spacecraft.	Nanotechnology's association with a "cabal of futurists" predicting utopia through technology creates sensationalism and controversy amongst the public. However, this may draw people into science. If nanotechnology gains cohesion, it could be revolutionary.
DTI/OST (2002). New Dimensions for Manufacturing: A UK Strategy for Nanotechnology	Encompasses new ways of manufacturing and will be disruptive.	Many, across the sectors of electronics and computing (e.g. hard-disks), materials (e.g. scratch resistant coatings), energy (e.g. improved photovoltaics), and medicine (e.g. targeted drug delivery).	Focus on economic implications, particularly how the UK will lag behind the rest of the world (the USA especially) if a strategy is not formulated and investment ploughed into facilities and research very soon. An opportunity to improve technology transfer.
CMP Científica (2002). Nanotech: the tiny revolution	Unique, due to its broad and diverse potential impact, and it being an 'enabling' or generic technology.	Many, across the sectors of life sciences and medicine, materials, electronics, and tools and techniques. Also describes ideas of molecular manufacturing.	Enormous economic potential for investors and start-up companies. Revolutionary in the breadth of its impacts, which will build cumulatively over time. There will be social implications, but they are difficult to predict.

Author, year Title	**Conception of Nanotechnology**	**Applications Mentioned**	**Social and Economic Implications**
National Science & Technology Council (1999). Nanotechnology: Shaping the World Atom by Atom	Distinctive as a "launch-pad to a new technological era", (due to the ability to manipulate on the scale where properties of materials are defined.	Many, across the sectors of electronics (e.g. increased data storage), medicine (e.g. implants with biomimetic surfaces), manufacturing (e.g. clean, bottom-up techniques), materials (e.g. fuel efficient vehicles).	Improved materials leading to new and improved products. Raises questions of affordability (equity), control, and ensuring it is not misused.
National Science Foundation (2001). Societal Implications of Nanoscience and Nanotechnology	A 'qualitatively' new technology, dominated by quantum physics. Its central theme is controlling matter at the molecular scale, but it is diverse.	Many, across the sectors of manufacturing, electronics and health care.	Nanotechnology will lead to changes and unfamiliar processes in materials, devices and systems. The impact will be wide-ranging, so social implications should be studied in conjunction with technological development. Science education is important, both in educating a new generation of scientific workforce and educating the public as to the benefits and risks of new technologies.
Mnyusiwalla, A., et al (2003). 'Mind the gap': science and ethics in nanotechnology	A new technological wave with benefits to be optimised and risks to be minimised.	Sensors/detection systems, safer drug delivery and lower energy needs. Applications will be diverse.	Society should take the prospect of nanotechnology seriously. Currently, ethics and social research lags behind the scientific research; these need to be accelerated rather than scientific research slowing down. Areas of concern are equity, privacy, security, environment, human-machine interface. Lessons can be learnt from previous emergent technologies, such as biotechnology.
ETC Group (2003). The Big Down – Atomtech: Technologies Converging at the Nanoscale	Most revolutionary is the convergence of several technologies at the nanoscale, including biotechnology, neurosciences and IT.	Many, from current and near-term developments to radical visions. A range across the sectors of materials, IT, medicine, the military, agriculture and food.	Far-reaching social impacts. Concerns about impacts related to ownership and control of the technology. The perceived threats posed by nanotechnology to democracy and dissent and human rights are examined. Do not believe the technology will be entirely positive and beneficial. Possible socio-economic, health, and environmental implications are unknown, therefore a moratorium on the commercial production of new nanomaterials is recommended.

Appendix II

Literature Summary

Author, year Title	Conception of Nanotechnology	Applications Mentioned	Social and Economic Implications
Rolison, D.R. (2002). Nanobiotechnology and its Societal Implications	Distinctiveness stems from its amalgamation with molecular biology.	Nanobiotechnology solutions such as 'smart dust', which would clean air/water of toxins; other applications may be possible that are not yet considered.	Comparisons with previous technologies that have had unintended or unanticipated consequences, such as drug resistant bacteria and viruses and environmental persistence of chemicals. Quite ominous. Scientists must be responsible for consequences of work but a public debate is desirable.
Colvin, V. (2002). Nanotechnology and its Environmental Applications	Defining feature is the interaction of chemical and biological systems.	Potential to reduce waste production, remedy industrial pollution, clean water, improve energy efficiency.	Research must be undertaken into life-cycle of nanoparticles once in environment, the potential uptake of these particles into organisms and cells, their possible accumulation in the environment. Transformative, in both positive and negative ways.
Mosterín, J. (2002). Ethical Implications of Nanotechnology	All technologies are ethically neutral, and nanotechnology is no different.	Biomedicine, diagnosis and gene therapy, through the convergence with biotechnology; improvements in computers and telecommunications.	The area that will cause most ethical problems will be bionanotechnology. Much debate will surround issues such as the prolonging of life at all costs and altering the genetic make-up of the biosphere. Ethics itself may have to change and invent new ways to address the potential problems.
Better Regulation Task Force (2003). Scientific Research: Innovation with Controls	In a regulatory context, be viewed in similar terms as biotechnology.	Nanoceramics as bone replacements, sunscreens, cancer treatments, molecular submarines.	Comparison with GM seeds and crops where regulation should consult relevant stakeholders and not restrict innovative and beneficial research. The need is for the UK government to have open communications and anticipate public concerns.
Mayer, S. (2002). From genetic modification to nanotechnology: the dangers of 'sound science'	Nanotechnology's promise and threat lies in its potential to control matter precisely.	The possibility of assemblers; sensors for use in medicine and computers.	Concerns lie with: the 'gray goo' scenario of uncontrollable self-replicating nanobots; the transformation of working practices; control of atoms being in the hands of corporations holding patents. The emergence of the technology is compared with the emergence of GM; fears that nanotechnology will follow same path as GM and face resistance due to its mishandling by the authorities.

Much of the discussion on the need to regulate nanotechnology development and applications is caused by uncertainty.

The uncertainty surrounding nanotechnology and the lack of current applications should not be reason for postponing social science research.

Nanotechnology raises particular challenges with regard to the environment, such as the life-cycle of nanoparticles, and privacy and security, in the possibility of invisible monitoring and tracking devices.

Notes

Chapter 3

1 The sources used for this section include Institute of Nanotechnology (2003) *Report prepared for the ESRC Centre for Organisation and Innovation*, University of Sheffield, (2002) *What is Nanotechnology* CD Rom; CMP Científica (2002) *Nanotech: The Tiny Revolution*; DTI/OST (2002) *New Dimensions for Manufacturing*; ETC Group (2003) *The Big Down*; Valerie Jamieson (2003) *Open Secret*.

2 See http://web.mit.edu/isn/ for full details

Chapter 4

3 http://www.foresight.org/NanoRev/index.html#NTFAQ

4 www.pacificresearch.org/about/index.html

5 www.cmp-científica.com

6 www.etcgroup.org/about.asp

7 See www.brtf.gov.uk for more details.

All technical pictures courtesy Science Photo Library

Right: Eric Drexler seated in front of a computer simulation of a diamondoid molecular bearing model of a robot he designed. This nanotechnology robot is so tiny it is made up of a precise number of atoms (orange and grey spheres). A robot like this may one day eat up pollutants, function as computers the size of a virus, or patrol the human body in search of cancer tumours.

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