Nanotechnology—should we be worried?

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From the development of the earliest stone tools to the most sophisticated microprocessor, man has increasingly, and sometimes unwittingly, shaped the world around him through the use of his technologies. These technologies impact upon all aspects of our lives. We depend upon them for the food we eat, our transport and our communications. We rely on them for clean water and an increasingly sophisticated level of healthcare. Whole periods of human history are labelled by reference to the dominant technology of the time—the stone age, the bronze age, the iron age, the industrial age, the computer age. We are all familiar with these terms and use them without thinking about the profound effect that each of the technologies had—both upon the societies that created them and on the planet itself. Frequently, we are not aware of the impacts the older technologies have had on the world in which we now live—for example, stone axes were used to fell the ancient forests that once covered the UK and created the downs and pasture that we now recognize as our "green and pleasant land".

This paper will look at one new area of technology—nanotechnology—and attempt to answer the question "Should we be worried—either about what it is doing now or where it is taking us?" I wonder whether a Neolithic farmer stopped to ask himself the same question while he was felling the trees to create a new stretch of farm land for himself and his family.

Before discussing the issue of where nanotechnology is taking us, and whether we should be worried about it, we must try to understand what it is. So, the first question that I would like to address is: "What is nanotechnology?" This is not as easy to answer as one might think, because the term encompasses a huge range of activities. Some people think it is not a single type of activity at all, while others think it is just a term that has been invented to allow researchers to extract large amounts of research funds from government

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funding agencies! Nanotechnology has received enormous attention in the last 15 years, and especially so recently; even the heir to the British throne has become involved. Some commentators and financial observers—such the finance house Merryl Lynch[1]—have even gone so far as to suggest that the impact of nanotechnology will be so great that the term will be used to describe a new era of world economic growth.

Why all the fuss? What is this phenomenon that everyone is getting so excited about? Personally, I don't like to get too hung-up on hard definitions. People are far too concerned about these—particularly so with nanotechnology. The prefix "nano" comes from the Greek word "nanos" meaning "a dwarf". Hence "nanotechnology" might well simply mean a technology concerned with small things. However, "nano" has also long been used as a prefix in scientific circles to mean one billionth (using billion in its American sense of a one followed by nine zeros). So we have the term "nanogram" for one billionth of a gram and nanometre for one billionth of a metre. A nanometre is exceedingly small—only about 10 atoms across. On that score, we might expect "nanotechnology" to have something to do with technologies that are working, for example, at the nanometre level and this is the general sense in which the term nanotechnology is used today. It is important to distinguish here between nanoscience, which is the study of phenomena at the very small scale, and nanotechnology, which implies an aim to achieve an end that is in some way "useful". The Royal Society/Royal Academy of Engineering Working Group on the subject adopted the following definitions:[2]

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

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

The scale of sizes normally discussed for the applicability of nanotechnology is usually less than 100 nm. Nanoscience, arguably, has been around since the early part of the 20th century, while the idea that there might be some technological advantages to be gained by working at the very small scale came much later. It was first put forward by the famous physicist Richard Feynman, when he gave a lecture in 1959 to the American Physical Society entitled "There's plenty of room at the bottom—an invitation to enter a new field of physics".[3] In this lecture—which actually had almost no physics in it but was

[1] http://www.ml.com/media/42322.pdf

[2] "Nanoscience and Nanotechnologies: Opportunities and Uncertainties." Working Group Report published by the Royal Society, RS Policy Document 19/04. www.royalsoc.ac.uk

[3] "There's plenty of room at the bottom: an invitation to enter a new field of physics". California Institute of Technology Engineering & Science Magazine, Vol. **23** (22 February 1960). Reprinted in "Miniaturization" (ed. H.D. Gilbert). New York: Reinhold (1961). See also: www.zyvex.com/nanotech/feynman.html

mainly concerned with the technology of making things—he explored the benefits that might accrue to us if we started manufacturing things on the very small scale. The ideas he put forward were remarkably prescient. For example, he foresaw the techniques that could be used to make large scale integrated circuits and the revolutionary effects that the use of these circuits would have upon computing. He talked about making machines for sequencing genes by reading DNA molecules. He foresaw the use of electron microscopes for writing massive amounts of information in very small areas. He also talked about using mechanical machines to make smaller machines with increasing precision. Interestingly, for a man who went on to win the Nobel Prize in Physics in 1965 for his work in the field of quantum electrodynamics, he hardly mentioned the quantum mechanical effects associated with the making of very small things, although he did talk about using the interactions of quantized spins, a kind of 'spin logic', which is only now being studied. Many of his predictions in that lecture have come true, and all are aspects of what we would now call "nanotechnology", although he did not use the term itself.

Actually, the first use of the term "nanotechnology" was by Norio Taniguchi who, in 1974, gave a talk[4] describing how the dimensional accuracy with which we make things has improved over time. He studied the developments in machining techniques over the period from 1940 until the early 1970s and predicted (correctly as it turned out) that by the late 1980s techniques would have evolved to a degree that dimensional accuracies of better than 100 nm would be achievable. He called this "nanotechnology". Incidentally, Cranfield Precision Engineering was one of the leading companies in helping to develop machines that could actually make things to this kind of precision.

You will realize from the above that all the early running in the field of nanotechnology was made by physicists and engineers who mainly thought in terms of making things more and more precisely. This means using one machine to make another, usually smaller machine to greater precision, and using machines (frequently very large and expensive machines) to make things which have incredibly precise features defined upon them. We now call this "top-down" nanotechnology. It has led directly to the hugely successful semiconductor and information and communications technology (ICT) industries, with a world market size in excess of $\$4 \times 10^{12}$, currently growing at 4.8% per annum. We all use advanced microprocessors in our portable computers. These have metal lines written on them that are only 90 nanometres wide and have upwards of 100 million transistors on a single piece of silicon a few millimetres across. They are objects of mind-boggling complexity and yet they are manufactured at incredibly low cost—a few tens of dollars each. The technologies established by the semiconductor industry are also now being applied in the manufacture of tiny micromechanical machines for sensing and

[4] Taniguchi, N. "On the basic concept of nanotechnology". Proc. Intl Cong. Prod. Engng. Tokyo: JSPE (1974); Taniguchi, N. et al. "Nanotechnology, Integrated Processing Systems for Ultraprecision and Ultrafine Products". Oxford: University Press (1996).

actutation. These "microelectromechanical systems" (also known as MEMS) are finding their way into a host of applications, particularly in the automotive and medical fields, where cost and size-based functionality are key factors. We can start to see here the enormous effects that working at the very small scale is having on our world.

There were two other themes that Feynman put forward in his lecture. He envisaged the possibility of making machines that could pick up and put down single atoms. Putting particular atoms together in particular combinations would be a new way for making chemical compounds.[5] Feynman did put forward several reasons why atomic manipulation might not work. These included the van der Waals and chemical forces that would make an atom stick to the finger picking it up, so that once picked up it would be virtually impossible to put down, let alone put it in a particular place relative to another atom. This has been called the "sticky fingers problem".

In 1981 Binnig and Rohrer, based at IBM in Zürich, invented the scanning probe microscope. This uses a very sharp metal point scanned over a surface to create images of the atoms in the surface. Incidentally they won the Nobel prize for this work in 1986. In 1989 Don Eigler used the scanning probe microscope to nudge atoms of xenon on a copper surface held at a temperature close to absolute zero to spell out the letters "IBM". Another one of Feynman's predictions had come true, admittedly under very special conditions. Eigler and his group have since done some remarkable work, mainly using the technique to explore basic physical and quantum mechanical phenomena.[6] Jim Gimzewski at IBM used similar techniques to push single molecules around on surfaces. This kind of work with single atoms and molecules is called "extreme nanotechnology".

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

Drexler combined this "clanking replicator" idea with Feynman's to come up with the concept of the "universal assembler", first put forward in his book "Engines of Creation".[7] The clanking replicator concept is reduced to very small size through the use of

[5] Now known as "mechanosynthesis".

[6] www.almaden.ibm.com/vis/stm/atomo.html

[7] K.E. Drexler: "The Engines of Creation", New York: Anchor Books (1986); "Nanosystems: Molecular Machinery, Manufacturing and Computation". Chichester: Wiley (1992).

mechanical components that are made on the molecular scale. The first assembler would be programmed to make copies of itself by atomic and molecular manipulation. The exponential growth would lead to billions of assemblers that would be programmed to work in concert with each other to build virtually anything required.[8] You could sprinkle a few assemblers onto a heap of garbage and out would come a washing machine! Clearly such a technology would have enormous economic implications, both in terms of material and energy use, effects on employment, etc. Drexler has set up the Foresight Institute in California and has raised large amounts of money for nanotechnology research based on that idea. He also was the first to raise alarm bells about the possibility of the assemblers reproducing out of control and reducing everything to a "grey goo" of tiny machines. There is now a new variant on this vision, which postulates the fusion of nanotechnology with biotechnology to create an assembler that is at least partly biologically based. In this case, the problem becomes one of "green goo" rather than "grey goo", but the outcome is essentially the same. This idea was subsequently hit upon by the author and screenplay writer Michael Crichton who used it in his novel "Prey", in which a set of assemblers, originally created for medical inspection and subsequently military purposes, goes out of control and starts hunting down and destroying their creators. I will come back to this Drexlerian vision—or rather nightmare—a little later in this article. It has a lot to answer for, apart from pulp fiction.

I would now like to move away from the ideas originally promulgated in Feynman's 1959 lecture. There have been some remarkable developments in materials science and chemistry over the last 15 years or so, particularly where small size plays a big rôle in determining basic properties. In the field of materials science, size does indeed matter! If we take a piece of a semiconductor less than about 100 nanometres across, then the electrons in them behave differently from in the bulk. For example, the colours of light absorption and emission change. Very small particles (nanoparticles) of materials like cadmium telluride are being used in applications such as the labelling of biological molecules and in new types of displays. These can be made amazingly precisely in size—say 50 nanometres, plus or minus a couple of nanometres—using reasonably standard wet chemical processes.

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

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[8] Now known as molecular manufacturing (MM).

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

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

So, what is nanotechnology? Is it a real subject, or is it just, as the cynics would have us believe, a mechanism for extracting funding from gullible government agencies and investors. Firstly, I hope you can see that it is hugely diverse. It employs all the conventional scientific and engineering subjects in order to achieve new applications. It does this through the exploitation of phenomena in which small size is the key to obtaining an exploitable property. Secondly, it is an area of endeavour where there are, as I have tried to illustrate, real and remarkable properties that we can seek to exploit. Thirdly, and increasingly, we are starting to see convergence between different areas of nanotechnology. The size range of interest between a few nanometres and 100 nanometres is one where many interesting things happen. All sorts of physical properties change and many biological systems function at this length scale. Hence, we are starting to see the use of processes such as electron beam lithography, originally developed for writing very fine scale features on silicon for electronics, being applied for the modification of surfaces on which biological species can be grown in a controlled way. The self-assembling properties of biological systems, such as DNA molecules, can be used to control the organization of objects such as carbon nanotubes, which may ultimately lead to the ability to grow parts of an integrated circuit, rather than having to rely upon expensive top-down techniques. This type of self assembly is called “bottom-up” nanotechnology. I think that the engineering complexity of integrated circuits means that the top-down methods will be with us for a long time to come but self-assembly techniques may have an increasing part to play (see Figure 1).

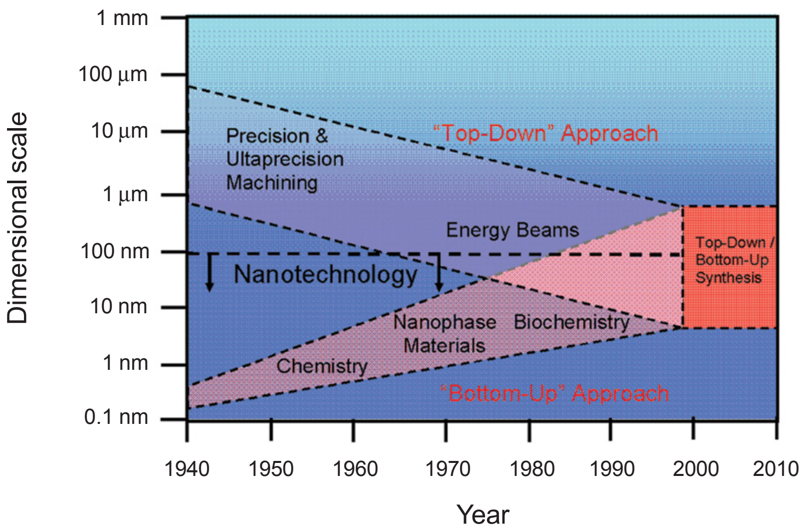

Figure 1. Illustrating the convergence of top-down and bottom-up nanotechnologies.

We are thus seeing an area that is providing real potential in its applications. Some people have predicted a world market for nanotechnology-related products of billions or trillions of dollars by the end of the decade. There is no doubt that the technology associated with our ability to manipulate matter on the very small scale is already having major impacts on our lives and this impact will only increase. Hence, we should now ask the question that our Neolithic farmer (presumably) didn’t: “Should we be worried?” Could the introduction of nanotechnology have unforeseen consequences?

First let’s consider the Drexlerian dystopia in which a rogue molecular assembler, ostensibly created for the betterment of mankind via high efficiency, low cost manufacture, goes out of control and reduces everything to a grey (or green) goo. There are many highly rated, first class scientific minds (including Richard Smalley, the Nobel Prize winner referred to earlier) who have asserted that the “assembler” is not possible for all sorts of reasons. These include the “sticky fingers” problem, problems with the storage and transmission of the huge amount of information needed and the vast complexity of the problem, which would be far, far greater than the complexity of a modern microprocessor. They imply that the assembler concept needs to stay where it belongs, firmly in the realms of Michael Crichton’s science fiction novel. There are already very real self-assemblers all around us that owe nothing to nanotechnology. They are called viruses and bacteria. They pose a very real threat, that is moreover increasing, due to our farming practices, profligate use of antibiotics and cheap international travel. The creation of this hazard obviously cannot be laid at the door of nanotechnology, although some of the nanoscale analysis techniques evolved for nanotechnology may well be able to help with combating it.

What about the less spectacular aspects of nanotechnology? I have tried to show you earlier in the lecture how materials structured on the nanometre scale can give properties that are highly exploitable. Are there aspects of these materials that we need to be careful about? There is no doubt that the properties that give nanomaterials their technological exploitability might also give us cause for concern. We have already seen in the last 100 years how a single material with hugely beneficial properties can bring equally huge problems. Asbestos was very widely used in the period between the late 19th and mid-20th centuries. It has extraordinarily useful insulating properties. The high efficiency steam engines used in ocean-going liners and steam locomotives would have been impossible without it. However, we all now know how lethal a few asbestos fibres can be if inhaled, causing occupational cancers, and many people have died prematurely because of it. Is there any risk that any of the materials that are emerging from our nanotechnology labs might be building-up a similar problem for the future? There are certainly enough physical similarities between the dimensional characteristics of asbestos fibres and carbon nanotubes to cause some concern. At the moment we just don't know whether carbon nanotubes are hazardous; there has not been sufficient research. There has been a small amount of work in which rats inhaled carbon nanotubes, but the results were inconclusive. It is important to note that in all of the applications I have come across for carbon nanotubes, such as in composites or displays, the tubes would be very firmly fixed in a stable structure and would therefore be unlikely to pose a threat to the general public, although we should still ask questions about how the product would ultimately be disposed of. Would there be a chance of carbon nanotubes being released into the environment? We should also question how the products would be manufactured and what the exposure might be for people involved in the manufacturing (or, indeed, for researchers using the materials). A full life cycle analysis is essential for these new materials.

What about nanoparticles? Should we be concerned about inhaling these, or indeed rubbing them onto our skins? There is good evidence that we have been exposed to certain types of nanoparticles in the atmosphere for millennia. Wood-based camp fires are excellent sources of nanoparticulate soot, for example. There is little cause for alarm in the sense that nanoparticles, *per se*, do not constitute a new hazard at low levels of exposure. However, there is good evidence that heavy exposure to carbon black is a serious industrial hazard, and that heavy exposure to nanoparticulate soot from sources such as diesel exhausts may be a cause of cancer. There is also evidence that, should nanoparticles arrive in the lungs, they do not remain there, but readily cross the barrier into the blood stream, whence they can migrate to various parts of the body, including the brain. There is, unfortunately, very little evidence to tell us what damage nanoparticles might cause there.

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

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

Are there other areas for concern about nanotechnology? Nanotechnology, like virtually all technologies, is being considered for the contributions it can make to defence. These include obvious developments such as improved electronic systems for communications, improved sensors and, especially, improved materials. Examples include composites using carbon nanotubes and a novel body armour that uses oxide nanoparticles dispersed in a fluid and held between two flexible Kevlar sheets. The composite fabric is flexible, but any attempt to penetrate the sheets by, for example, a projectile or other weapon causes the fluid to rapidly set into a rigid mass that protects the wearer. The applications to flexible, wearable, protection that would protect a soldier's limbs as well as his torso are obvious. Metallic nanopowders can be expected to deliver more powerful conventional explosives. These developments would certainly give the armies using them a military edge, but hardly constitute the kind of doomsday scenario that we sometimes read about in the popular press or see on our video screens in movies like Terminator II. Those images owe more to science fiction based on the Drexler vision than a level-headed scientific analysis of the advances that nanotechnology is really likely to deliver.

Paradoxically, the broad contribution that nanotechnology can potentially make to economic development has sometimes been cited as a cause for concern, especially by some pressure groups. They point out that the promise of nanotechnology would widen the disparity in development between the rich and poor nations of the world. The rich will get richer, while the poor will be unable to benefit from the nanotechnology revolution. Another criticism that has been raised against the nanotechnologists is that they are promoting their research as possibly providing cures for disabilities such as deafness. Advanced cochlear implants based on MEMS technologies can already provide profoundly deaf people with the ability to hear.[9] Such implants are much more effective if they are given to children rather than to adults because the child can more quickly adapt to the inputs from the implant and learn how to use it. However, the challenge issued by some deaf people is to say, "I am perfectly happy with the way I am. What gives you, the scientist, engineer or doctor, the right to say that I—or more particularly my child—ought to be "cured" of something that I do not consider as a disability?" Is it society that needs to change its attitude to those who are different?

These questions of how we as a society choose to deploy or employ the capabilities that nanotechnology may provide are very good ones. But it strikes me that they are ethical issues that pertain more to the general capabilities that our modern technologies can deliver, rather than being specific issues concerning nanotechnology *per se*. They are, perhaps, more in the realm of the philosopher than the engineer. Nevertheless, the success of the nanotechnologists in promoting their area makes them natural targets for these ethical questions. We nanotechnologists need to make links with the people who can help us to answer them, and this is starting to happen.

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

[9] C. Eberling, "About the Voice Finder". *J. Biol. Phys. Chem.* **2** (2002) 126–129.

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