Nanotechnology in fact and fiction

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There is a Powerpoint presentation to accompany this talk

What is the scariest thing? I suspect that all writers of horror and thrillers will agree on this: the thing that scares us most is the thing we cannot see. It is, let's be frank, a grim time to be reminded of the terrors of the invisible foe, but there is nothing new in that. Some historians argue that the Black Death in the 14th century drove all of Europe to a state of collective madness, creating an obsession with death and with the invisible demons that were believed to torment humankind. The plague was blamed on poisonous airs, pestilential vapours, and on the agency of devils and witches.

Well, the novelist Michael Crichton seems to have tapped into these fears of the unseen. In *Jurassic Park*, Crichton gave us monsters that were all too monstrously tangible, and his resurrected dinosaurs spiced the debate about gene splicing in biotechnology. But in Crichton's latest book *Prey*, which dominated the bestseller lists over this Christmas, the danger is invisible. It comes from robots, each the size of a bacterium, which swarm in the air like particles of dust and are capable of reducing anything to a featureless sludge. In *Prey*, which is soon to be made into a blockbuster movie, the enemy is nanotechnology.

Crichton has lifted his little villains from a futuristic scenario described in the 1980s by a scientist named K. Eric Drexler, who was one of the first people to bring nanotechnology to the public attention. What Drexler was thinking about was a way to shrink manufacturing technology literally out of sight: to make machines and structures too small to be visible. He was talking about building robots and other devices on the scale of not centimetres but nanometres. A nanometre is a millionth of a millimetre. To put that in perspective, if you blow up a pinhead to the size of a football field, one of Drexler's nanometre-scale robots, or 'nanobots', would be about the size of a grain of sand beneath the goalie's feet. Why do we call it a nanometre? The word comes from the Greek *nanos*, which means dwarf: nano-objects are very, very small.

You might imagine that Drexler's nanobots would be pretty hard to make. How do you put together something that small? Well, Drexler had a neat idea: he would get the nanobots to make themselves. They take raw materials and pluck out the atoms they need, one by one. They grab hold of them and put them in place to assemble a new nanobot, like a robotic assembly line in a factory that builds a copy of itself. Drexler's nanobots were built mostly from diamond, which is a form of pure carbon. He figured this would make the robots hard and tough: diamond is the hardest material known. So the raw material that nanobots need to make copies of themselves is full of carbon. It could be sugar; it could be wood – or it could be humans.

Now, a rogue nanobot wouldn't be too much of a threat on its own, because the amount of material it could manipulate and reprocess is tiny. Our bodies are losing cells all the time, and it shouldn't do us much harm if a nanobot floated by like a little dust particle in the air, landed on our skin, and pulled a cell apart in order to fashion it into something new. But here's the catch. If nanobots are capable of making copies of themselves – that's to say, if they can replicate – then one makes two, and two make four, and four make eight. They begin to multiply exponentially, just as pathogenic bacteria or viruses multiply to cause disease. That's the problem with entities that can replicate: they grow in number very quickly. And so we are faced with the prospect of a few rogue nanobots proliferating before we know it into a swarm that pulls apart every living thing in its path, atom by atom, converting the material into yet more nanobots. Each one is an incredibly precisely engineered little machine, yet they are all smaller than motes of dust, and Drexler imagined that this rampaging swarm might look like a kind of grey goo. According to one estimate, it would take replicating nanobots just three or four hours to transform the entire biosphere – all living things on earth – to grey goo.

Now do you see why Michael Crichton thought this would make a great scenario for a thriller? It sounds very scary indeed.

Drexler wrote about this so-called grey goo problem in his book called *Engines of Creation*. He was worried that these nanomachines might instead become engines of destruction; indeed, Doomsday machines.

The grey goo problem didn't really reach the public consciousness until 2000, when Bill Joy, the chief scientist of the electronics company Sun Microsystems, wrote an article in Wired magazine in which he suggested that some new technologies might be so dangerous that we should consider voluntarily forgoing them, or at least suspending research into them. He proposed that nanotechnology might be one of these. Bill Joy had read *Engines of Creation*, and he was worried.

Since that article, grey goo is everywhere. It has prompted some environmental groups to call for a moratorium on nanotechnology. Even the UK's astronomer royal, Martin Rees, has speculated about a nanotechnological Armageddon. The British government recently commissioned a report from as special task force to look into the safety issues around nanotechnology, and Lord Sainsbury, the government's science minister, has confessed that his worries about nanotech were mainly about the grey goo problem.

Now, I am a cautious person. I don't necessarily trust scientists to put their research to the best of uses, to ensure that it is not abused, or to foresee or admit to all the possible risks. But I am not losing any sleep over grey goo. I think that, when the only thing people learn about nanotechnology is that it threatens to dissolve us all into sludge, we have a serious problem of misinformation. Nanotechnology will deliver to us many things, and I hope some of them will be marvellous, and I fear that some of them will be scary, since the military have a strong interest in it. But I don't believe that one of these things will be grey goo.

My confidence here is based not just on my belief that Drexlerian nanobots will not work but on my knowledge both that they far exceed current scientific capabilities and that no one is seriously trying to make them anyway. Professor George Whitesides at Harvard, one of the world leaders in nanotechnology, puts it this way: he says that the atom-by-atom assemblers envisaged by Drexler are "less the solution of a problem than the hope for a miracle."

This, then, is not the way to do nanotechnology. So having spent some time telling you what nanotechnology is not, I want now to look at what it is, and what it might become.

We must surely begin by asking: what was Eric Drexler thinking of in the 1980s, to imagine shrinking manufacturing to the nanoscale? Why do that?

There are, it turns out, lots of good reasons. One of the main driving forces for the miniaturization of technology is the information revolution. Revolution is not too strong a word. The Internet and the World Wide Web between them provide an encyclopaedia, a library, a postal service, a social network, a travel agency, a legal adviser, an entertainment parlour and goodness knows what else, all available in an instant at the push of a button. What has made this possible? The phenomenal increase in computer power. The computing power available on board Apollo 11 when it flew to the moon in 1969 was less than you can probably find today inside some kettles – certainly less than in a Gameboy. This increase has happened because the size of the circuit components – the transistors and diodes and so forth – on silicon chips have been getting ever smaller, so that more of them can be crammed onto a chip. That's why a computer that used to occupy an entire room is now the size, and the price, of a Palm Pilot personal organizer. There's a rule of thumb in the microelectronics industry, called Moore's Law, which says that the number of components on a chip of a given size roughly doubles every 18 months. This law was first proposed by Gordon Moore, cofounder of the electronic giant Intel, in 1965. Then, a typical integrated circuit – an electronic circuit miniaturized on a chip – might contain around 50 components. Moore predicted that by 1975 a typical chip would contain 65,000 components. He clearly considered this to be a bold, even a foolhardy prediction. Today some chips contain something like 65 million components. [pic]

Moore's Law had held steady for the past four decades. But to sustain it into the future, electronic engineers can't any longer rely on the same manufacturing methods they've been using so far. There are limits to how finely they can carve electronic devices and wires into silicon chips. So they need new ways of making things even smaller. They need nanotechnology.

You can see from this, perhaps, why nanotechnology is, to a large extent, a challenge to materials science. It is all about fashioning and shaping materials on the nanometre scale. We have become very adept at working with materials on the everyday scale – the macroscale – and we have got pretty good at doing the same kind of thing on the microscopic scale, the scale of dust particles and human-hair widths. That's how we can carve pieces of silicon into computer circuits. But when it comes to the nanoscale – then things get really tough, and we may have to start thinking again about how we do materials science at this scale.

There will be benefits of nanotech in other areas too. In *Engines of Creation*, Drexler spoke about nanobots that cruised through our bloodstream like the miniaturized submarine in the movie *Inner Space* [pic], patching up cells and tissues and repelling invading bacteria and viruses. It now looks as though this is not only a hopelessly optimistic picture but not in any case the best way of doing nanoscale medicine. However, Drexler was right to think that nanotechnology would have medical applications. This is in fact one of the most important emerging directions for nanotechnology. The National Nanotechnology Initiative established by the American National Science Foundation, which is like our Research Councils, considers that for the next three or four years at least, so called nanobiology is going to be the hottest area of nanotech. Some researchers hope to use nanotechnology in so-called regenerative medicine, in which damaged tissues and even spinal-column injuries are helped to repair themselves naturally. Professor Richard Smalley, a scientist at Rice Univeristy in Texas who won a Nobel prize in chemistry a few years ago for one of the most important pieces of foundational work in nanotechnology, has said that

> "the impact of nanotechnology on health, wealth and the standard of living for people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering and man-made polymers in [the 20th] century."

Fundamentally these applications in health and medicine exist because, since nanotechnology operates at the same scale as cells and viruses, it offers new possibilities and new tools to do things we simply had no way of doing before.

The idea of making nanoscale machines wasn't conceived in the 1980s, however. It goes back further than that. Most scientists acknowledge that the first clear vision of nanotechnology was laid out in 1959, when the famous physicist Richard Feynman gave an after-dinner talk to the West Coast section of the American Physical Society. He called it 'There's Plenty of Room at the Bottom.' What Feynman meant by the 'bottom' was the smallest scale most scientists ever had to think about: the scale of atoms and molecules.

'What I want to talk about', he said, 'is the problem of manipulating and controlling things on a small scale.' He didn't mean small as in tweezers and magnifying glasses. He meant small as in atoms.

'Imagine', he said, 'that we could arrange atoms one by one, just as we want them.' If you could do that, what could you make? Well, Feynman didn't want this to be just idle speculation; he wanted to see this dream come true. To that end, he offered two prizes of a thousand dollars each – a lot of money in 1959 – to anyone who could meet two challenges. One was to make an electric motor no bigger than 1/64th of an inch in any dimension. The other was to write down the information on a page of a book in an area scaled down by a factor of 1/25,000. That's to say, each page would be 25,000 times smaller. Feynman still anticipated that these would be tremendously difficult things to do and that his money would be safe for some time to come. On this occasion, however, even the great Richard Feynman underestimated the existing skills of engineers, for the first of these prizes was claimed only several months later.

All the same, his notion of arranging individual atoms one by one was a challenge of a different order entirely. In 1959 no one had even seen an atom, although all scientists knew they must exist. If you think a nanometre sounds small, now consider that in the space of one nanometre you can line up a dozen or so hydrogen atoms. What kind of tool can pick up objects this minuscule?

In the 1980s such a tool was invented. Two scientists at IBM's research laboratories in Zürich, Switzerland, devised the scanning tunnelling microscope or STM, which they conceived of as a device for seeing the structure of matter far below the resolution of a normal light microscope. To the amazement of everyone, including I think the STM's inventors, this instrument proved capable of seeing individual atoms. Roughly speaking, the STM feels the shape of a surface, like someone reading Braille with their fingertips. It traces out the contours of the surface, showing all the bumps and dimples. A single atom stuck to a smooth surface can show up as a lone bump. [pic]

But the STM can do more than that. At IBM's Almaden labs near San Jose in California, researchers found that they could use the STM to pick up atoms and move them around. The STM feels its way over the surface using an incredibly fine needle. The IBM scientists discovered how to use this needle to drag atoms around. To show how much control they had, in 1990 they used the STM's needle to write their company logo using just 35 atoms of the element xenon stuck to the surface of nickel, like the dots of a dot-matrix printer. [pic]

By writing at this scale, you could fit the entire Bible onto the surface of a human red blood cell. It is a miniaturization of a book page not by the factor of 1/25,000 that Feynman was looking for, but by about 1 to 200 billion. Well, no one has yet written the Bible in atoms, but they are doing things that are pretty close. [Pic] This is a part of Feynman's speech, written using a device related to the STM as if it was a pen, and you can see that each letter is just tens or hundreds of nanometres wide. A red blood cell would more or less cover this page.

The atom-pushing that you can do with an STM seems to start making Eric Drexler's idea of building nanoscale machines atom by atom look feasible. But there are big problems with that. For a start, to keep the atoms still you have to make them very cold indeed. The IBM team did their experiments at minus 269 ºC, four degrees above absolute zero. And it doesn't work for any old atoms – they had good reasons for choosing xenon, which is a very unreactive element. If you bring two reactive atoms close enough for them to form a chemical bond and join together, they release a lot of energy and might go flying out of control. And the construction process is very, very slow and laborious. This is one reason why Drexler wanted to build replicating nanobots: so that you could quickly make lots of them, and they could then be set to their atom-building work simultaneously, like a tiny labour force.

Some scientists think that the idea of building structures and devices atom by atom faces problems that make it, to all intents and purposes, impossible. Many others think that, even if you could do it in theory, it is not a very sensible way to advance nanotechnology in practice. So the vision of nanotechnology outlined in *Engines of Creation*, incuding its nightmare of grey goo, is most probably a false one. If nanotechnology, in the sense of making nanoscale machines, is going to become reality, I think it will look very different.

Different in what way? Well, Richard Feynman was not the only person to foresee engineering at the scale of molecules. In the novel *The Monkey's Wrench* by the Italian writer Primo Levi, written in 1978, a bridge-building engineer is talking to the narrator, a chemist. Levi was himself an industrial chemist – perhaps his best-known book is called *The Periodic Table* - and it was this profession that saved his life when he was imprisoned in a Nazi concentration camp in 1943. So Levi knew very well what it is that chemists do, and in *The Monkey's Wrench* his narrator sees an analogy between the work of a chemist and the work of an engineer. One builds molecules; the other builds bridges. Except, the chemist laments, we are not very good at building molecules. We tend to throw a lot of chemical substances together, shake them around and maybe heat them up a bit, and hope they join together in the way we want them to. Chemistry is now not usually quite as crude as this, but it is certainly very hard for chemists to put their molecular components in place as accurately as an engineer can position and assemble the struts and girders and nuts and bolts of a bridge. This is what Levi's character says:

'We don't have those tweezers we often dream of at night, the way a thirsty man dreams of springs, that would allow us to pick up a segment, hold it firm and straight, and paste it in the right direction on the segment that has already been assembled. If we had those tweezers (and it's possible that, one day, we will), we would have managed to create some lovely things that so far only the Almighty has made, for example, to assemble – perhaps not a frog or a dragonfly – but at least a microbe or the spore of a mold.'

This sounds like Feynman's dream, doesn't it? But it is different in an important way. Feynman's building blocks are atoms. He's a physicist, and his instinct is to build things up from the most fundamental level. But Levi is talking about constructing with molecules: groups of atoms already joined together into certain stable shapes and structures. If you try to build with atoms, the force of chemistry – the making and breaking of chemical bonds – may become a problem. If you build with molecules, you can use those forces to your advantage.

And that is what many chemists are now doing. They have become molecular engineers, designing and building molecules that can be put together in all kinds of clever ways to make nanoscale structures and, yes, even machines. Some of these have moving parts, like motors. Some act like the electronic devices on silicon chips, conducting electrical currents or switching them on and off. And the truly revolutionary thing about molecular engineering is that, if you're clever enough, you can design your molecular building blocks so that they assemble themselves. That's to say, you don't even need a scanning tunnelling microscope, or Primo Levi's tweezers, to push or lift them into a particular arrangement. You just shake them up together in a beaker of water and – hey presto! –

they *self-assemble* into your nanoscale device. It's like making a watch by putting all the cogs and springs and so forth into a jar, rattling them around, and pulling out the fully assembled device. That sounds miraculous, perhaps, but chemistry lets you do it, because molecules *like* to stick together, and with a little foresight we can control how they do it.

The great attraction of the molecular engineering approach to nanotechnology is that we already know it works. We know for sure that it is capable of producing the most remarkable computers in the world, that it can make nanoscale machines that harness the energy of sunlight or that move and repair themselves and sense and adapt to their environment. I have one right here; in fact, I have millions of them right here. Devices like this are at work in every cell in our bodies. Every living organism is a product of a kind of molecular nanotechnology.

If you think it is stretching a metaphor to regard ourselves in this light, let's just consider what does go on inside our cells. There is a molecular data bank: our DNA, our genes, which store the information needed to build the molecular machines – the enzymes and other proteins – that are responsible for assembling and maintaining our cells. There is a set of molecular machinery for reading this information and converting it into functioning protein molecules. Some of these molecules are like motors, which step along the walkways and the scaffolding of the cell. Some of them generate the fuel, the energy, that drives them all. Some send and read signals to and from other molecules or cells. In the brain, this cell-to-cell signalling happens across a vast network of interconnections, and it gives us the power of thought. Some protein devices monitor the temperature, the pressure, the saltiness of their surroundings. Some are like doorways that open and close in our cell walls. We are communities of cooperating molecular machines.

So in essence biology provides what mathematicians call an existence proof for nanotechnology: evidence that something is possible by its very existence as an example.

Thanks to the discoveries of biochemists and molecular biologists over the past several decades, we are starting to understand how some of these molecular machines of the cell work. We know, for example, that some of the so-called motor proteins, responsible for moving things around inside cells or for causing large-scale motions such as the flexing of our muscles, are two-legged walkers with legs that bend and step along tracks constituted from other protein molecules. And this enables us to think about how we might design artificial molecular machines that take advantage of some of these same chemical and mechanical principles.

There's one very striking feature of these protein devices: they are *soft* machines. Remember the idea of making nanoscale devices from hard, strong diamond? [pic] That's our usual instinct, based on the experience of human-scale engineering: we cast engines and turbines and camshafts and cogs from steel and rigid ceramic materials. But at the molecular scale you don't need that rigidity; in fact it can be a hindrance. Proteins are relatively loose, floppy structures, just as our protein-based tissues like skin are soft. They generally *need* a certain bendiness in order to function properly. When a motor protein takes a step, it is not like a door hinge pivoting around an axle, but more like an inchworm.

And biological machines don't need to be kept scrupulously clean and dry – they are designed to work in the dirty, salty fluid of our cells. So far, most attempts to shrink mechanical engineering down to microscopic scales have simply scaled down the flywheels and gears and levers of everyday machinery. But I think that, based on what we find in biology, truly nanotechnological machinery will look utterly different.

So then, we can try to make molecular machines from scratch, based perhaps on some of the clever designs that we see in nature. There are already some spectacular artificial molecular devices of this sort: for example, molecules that contract or expand by sliding over one another, which mimic the molecular mechanism of muscle movement. Or hoop-shaped molecules threaded on an axle, that can slide up and down and store information like the beads of an abacus. Some researchers have even made molecules that can perform rudimentary arithmetic, adding 1+1 and telling us the answer. OK, it's not exactly a computer, but it's a start.

Yet molecular nanotechnology isn't just learning lessons from the molecules of biology; it is using those molecules themselves. Think about it. It is an awesomely difficult task to design and build a molecular motor from scratch, even if we use the tips suggested by a biological motor protein. Why do that at all, when the motor protein itself already exists? Why not just appropriate this molecular machine from a cell and adapt it to do what we want it to do? I think this is where we are going to see some of the most exciting developments in this field: from a nanoscale synthesis of engineering and biology.

Here's an example. Researchers at the University of Washington have figured out how to use motor proteins to move nanoscale objects around on a surface, shunting them like railway carriages along pre-defined tracks and channels [pic]. They stick the motor proteins in rows to the surface, and the nanoscale cargo is then passed along the row in the same way that a bucket brigade hands down buckets of water to extinguish a fire. You can imagine how this idea might be used to create a sort of nanoscale building site on which materials get delivered to wherever they are required.

Some motor proteins don't generate this kind of motion in a straight line, but act more like the motors we're familiar with: they rotate a spindle. A team at Cornell University has modified these rotary motors by attaching a tiny metal propeller to the spindle so that it spins round and round [pic]. They've even found a way to add a switch so that they can turn the rotation on and off. Might this be the way to propel a nanoscale submarine?

Just think for a moment about how difficult this is. The researchers had to make all these little posts on a sheet of nickel, each of them just a few nanometres wide. They had to figure out how to glue the protein to the post without damaging the molecule. And they had to cut out each of the metal propellers and work out how to fix them to the spindle of the motor protein. Apart from anything else, it's a stunning piece of materials science.

Other groups are trying to make molecular-scale structures and devices that can replicate. This might sound worryingly like Drexler's grey goo, but in fact it is based on a very different idea and it is very hard to see how this kind of replication could ever get out of hand. Our cells replicate by dividing in two, and before they do that they must make copies of all the chromosomes – all the little bundles of DNA – so that the two daughter cells both end up with the same DNA content as the original parent cell. So cells contain molecular protein machines – enzymes – for replicating DNA. Well then, if DNA can replicate, why not make replicating nanoscale devices from DNA itself? This is precisely what the researchers are trying to do.

The DNA in our chromosomes doesn't exactly replicate autonomously – as I say, there are special enzymes that assist this process. But chemists have figured out how to make short stretches of DNA replicate without the help of these enzymes. This means that it becomes possible to make copies without having to recruit all that complicated protein machinery.

But making nanostructures whose very fabric is DNA itself might sound odd. We don't generally think of DNA as a construction material. For the molecular engineer, however, it is in many ways an ideal construction material. Short stretches of DNA are rather like molecular-scale rods, and what is particularly marvellous about DNA rods is that they can be chemically designed to self-assemble in very complex ways. For example, researchers have made DNA rods that come together to form the sides of a nanoscale cube. [pic] The challenge now is to make DNA rods that will not only self-assemble into a nanoscale structure but will also, if fed with the right chemical ingredients, produce copies of themselves. Then that structure itself could be made to replicate. It's a truly monumental challenge, but the basic procedures needed to achieve this have already been demonstrated; now we have to figure out how to put those elements together.

Nanotechnology has been promising great things for at least the past ten years, and the US government clearly believes it has great potential. Last year around $600 million was invested in nanotechnology research and development in the United States, while in Japan the spending has leapt from $120 million in 1997 to $750 million in 2002. The European Union has recently allocated a billion pounds for nanotechnological research, and there are laboratories working in this field all over the world. But it is still a fledgling science, and the first fruits of all this effort are going to be nothing like as dramatic as cell-sized robots. You may not have realised this, but there are some nanotechnological products already on the market, mostly making use of nanoscale chunks of material called nanoparticles or nanocrystals. Scientists have developed a range of methods for making these particles, which are typically a few dozen to a few hundred nanometres in size, like a very fine powder. It's possible to make them from metals, from semiconductors, from plastics, even from drugs.

Nanoparticles can have useful properties that coarser powders do not. For instance, they are too small to block light, so a thin layer of nanoparticles looks transparent where larger particles look chalky. Nanocrystals of titanium dioxide – the material used, in larger grains, as the white pigment in paint – are now added to sunscreens, where they absorb ultraviolet light and protect our skin without leaving a whitish film when they are applied. The same kind of particles are coated onto glass or ceramic tiles to make them self-cleaning: here they use the energy of the sun's ultraviolet rays to burn up dirt on the glass surface, as well as helping rain water to spread evenly on the surface and wash the remains away. Scientists at BASF in Germany are developing a spray-on coating that repels both water and dirt, which could be used to make clothing and shoes both waterproof and self-cleaning. They have used an idea borrowed from the way lotus leaves keep clean [pic]. The surface of a lotus leaf is covered with lots of tiny bumps of wax. These bumps prevent water droplets from sticking to the surface, so they roll straight off and pick up particles of dirt as they do so. This is called the lotus effect. The BASF scientists have mimicked this microscopically bumpy surface in their spray, which contains nanoparticles of mineral-like substances such as silica or alumina held within some kind of resin. A German paint company has also used the idea to make a self-cleaning paint – here it is in action. Put this on a building or a car, and you'll almost never have to wash it down.

Nanoparticles of the alkali calcium hydroxide are being developed for preserving ancient manuscripts. They can be sprayed onto paper and parchment, where they neutralize acids in the fabric and stop them from making the documents brittle and discoloured, but without altering the appearance of the manuscripts. Metals that are composed of a patchwork of nanoscale grains may become harder and tougher than ordinary metals. Conversely, ceramic materials made of nanocrystal grains can become soft and mouldable at high temperatures, so that they can be shaped into engineering components. Some nanoparticles acquire an ability to glow – to emit visible light – a property that bigger chunks of the same material don't possess. These fluorescent nanoparticles are being used as tags in medical research to label and track molecules such as proteins as they move around our cells.

Well, you can see from all of this that nanotechnology is not a single area of science with a single or unified objective. Rather, it is almost a new kind of technological philosophy, a new way of doing things. We don't, after all, speak of 'macrotechnology' – that would be too vague a word to carry much meaning, embracing everything from making automobiles and vacuum cleaners to developing medical scanners, milk cartons, dams and suspension bridges. Nanotechnology means nothing more or less than the expression of this creative diversity at scales smaller than engineers of a hundred years ago, such as Thomas Edison the inventor of the light bulb, would ever have dared dream of. This must surely mean that nanotechnology is not intrinsically good or bad. Like all technologies, it is shaped by our own inventiveness and imagination, and it will therefore reflect our own preoccupations, strengths and failings. It is for us to choose how we wish to use it.

Grey goo may be a myth, but there are certainly other ethical questions about nanotechnology. You'll be hearing more and more about these questions in the next year – you may have seen this article in yesterday's Observer newspaper which talks about them, for example. Experience in other disciplines, particularly biotechnology, has made scientists aware that they need to anticipate ethical issues early. Very recently, some specialists in biological ethics in Canada have warned that, although nanotechnology offers tremendous potential benefits to humankind, for example in medicine, environmental engineering and clean energy generation, fears driven by a lack of information and understanding are already creating a backlash. They say that the suggestions of a ban on putting nanoscale materials into commercial products should be a wake-up call for nanotechnology developers. It says that “there is a danger of derailing nanotechnology if the study of ethical, legal and social implications does not catch up with the speed of scientific development.”

And so perhaps we need to ask what nanotechnology implies for issues such as equity (who will benefit?), privacy and security (will we be increasingly monitored by invisible devices?), the environment (are nanoparticles toxic?) and military and weapons research. None of these concerns is unique to nanotechnology; but perhaps if nanotechnology were to become a focus for an ethical debate on technological advances in general, that may be no bad thing. But it is then vital that we direct our attention to real concerns, and not use up our energy worrying about dangers that exist only in the minds of thriller writers and movie makers. When you go to see *Prey*, enjoy it for what it is. But if you really want to know what is going on in nanotechnology, places like this are where you can find out.