

How is nanotechnology helping Australian lifeguards? See page 5.



SPL

Nanobot: Fact or fantasy? Find out on page 5.

Small is beautiful.

Nanotechnologies are fast becoming the 'next big thing' (only not big at all).

Dealing with things smaller than 100 nanometres (for comparison, a human hair is 80 000 nm wide), nanotechnologies are poised to provide fantastically light and strong materials and revolutionise medicine. They are the future, say the nano-enthusiasts.

Hang on, say nano-sceptics, didn't you say the same thing about nuclear power, gene therapy and genetically modified animals? Where's the jetpack and flying car you promised? Where are the flocks of sheep making life-saving medicines in their milk? How do we know nanoparticles aren't going to trigger the next CJD? And what if self-replicating nanobots turn everything into grey goo?

From nano-hype to nano-nonsense, this issue in the *Big Picture* series sifts sense from speculation. What are nanotechnologies and what might they do for us? What (if anything) do we need to worry about?

More broadly, though, it looks at how new technologies move from the lab to the high street and hospital, how potential benefits are weighed against possible downsides, and what role the public should play in the process.

FIND OUT MORE →

FAST FACT

German scientists have created a nanoparticle-containing polymer that both repels and kills bacteria.

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NAVIGATING THE NANOWORLD

The buzz about nanotechnologies in the media reflects both the possibilities and the uncertainties of this cutting-edge area of science.

The potential of nanotechnology is **apparently endless**: we are promised everything from the mundane (better paints, self-cleaning windows) to the bizarre (tiny submarines that will glide through our veins destroying bacteria).

NANOSCIENCE IS THE SCIENCE OF THE EXTREMELY TINY.

As a result, nanoscience and technologies are attracting considerable **investment** from governments and industry hoping to drive economic development.

So what exactly is nanoscience? And why the excitement? In a nutshell, nanoscience is the science of the extremely tiny. Nano (from the Greek for 'dwarf') is the prefix for units of 10^{-9} . So one nanometre is a billionth of a metre or a millionth of a millimetre.

The nano size range is usually defined as smaller than 100 nm. But why is nanoscience so special? The key point is that, **at nanoscales, materials have strikingly different properties** (see box, right).

Nanoscience is concerned with understanding these effects; **nanotechnologies aim to exploit them to create novel structures, devices and systems** for a variety of different industries. Because the range of applications is so diverse, it's helpful to think of **nanotechnologies** in the plural.

Nanosystems in biology
Ironically, the most complex and highly functional nanoscale materials and machines have already been invented – by **nature**. Proteins and other naturally occurring molecules regulate and control biological systems with incredible precision. Ultrastrong or other clever materials

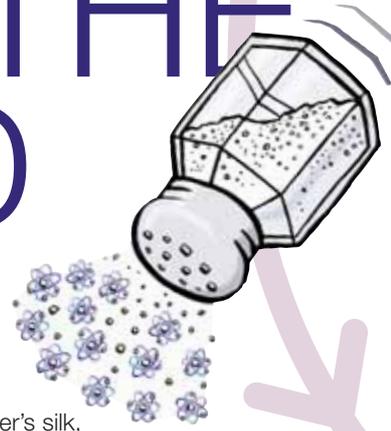
are commonplace – from mussel glue, through spider's silk, to water-repelling lotus leaves.

Many nanotechnologists are drawing inspiration from biology to create new synthetic materials and devices.

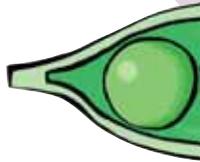
So why the worry?

Some people suggest that the **unusual properties that make the nano-world so exciting also require us to proceed with caution.**

Because they act so differently, nanomaterials cannot be thought of as the same substance, only smaller. Their properties, and their effects on people or the environment, may be quite different from those of their macro-forms.



...an atom would be the size of a grain of salt...



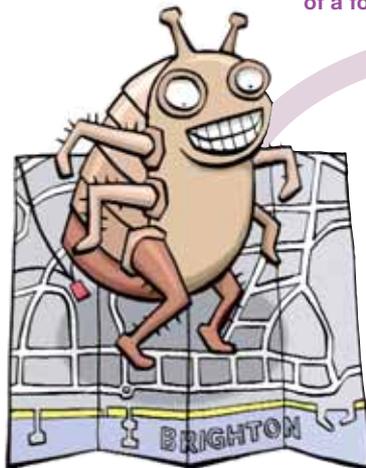
...a virus would be as big as a person...



...a red blood cell would be the size of a football pitch...



...a hair would be as wide as a river...



...a flea would be the size of Brighton...



...a doughnut would be the size of the UK...

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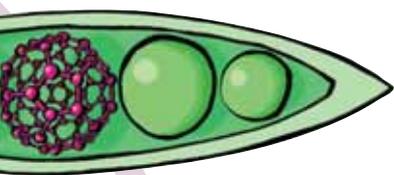
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Are nanotechnologies really that new?

We've used nanotechnologies for centuries – we just never knew it.

Some people talk about a nanotechnology revolution as if this were the start of something radically new.

Others point out that nanotechnologies have not yet produced any new products – merely enhanced existing products such as tennis racquets and trousers. Also, nanotech has been used for decades without a great deal of excitement. In this sense,



...a carbon C60 molecule would be the size of a pea...



IMAGINE...

...if a nanoparticle was the size of a football

...how big would you be?

Find out at our interactive nanoconverter at www.wellcome.ac.uk/bigpicture/nano

...a chicken would be as big as the Earth...



nanotechnology is a 'rebranding' of older science, and its influence is evolutionary rather than revolutionary.

In the longer term, though, nanotechnologies do have the potential to affect manufacturing processes across a wide range of industries. This will lead not just to 'the same but better' but to genuinely new products.

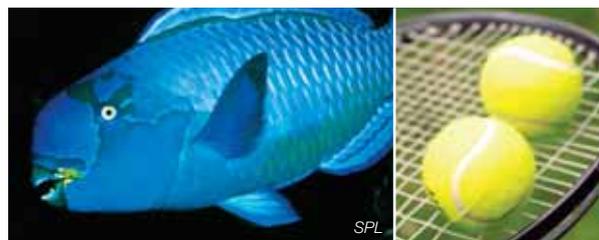
Old nano

Nanoparticles are not new: they have existed widely in the natural world, for millions of years, created by living things or volcanic activity.

Nano-effects are astonishingly common in nature – from non-reflective moths' eyes to extraordinarily efficient nano-lenses in crystalline sponges. The enamel of our teeth is constructed, in part, by use of natural nanotechnology.

Indeed, people have exploited the properties of nanoparticles for centuries. Gold and silver nanoparticles are responsible for some coloured pigments, used in stained glass and ceramics since the 10th century (depending on their size, gold particles can appear red, blue or gold).

Computer chips have been made using nanotechnologies for the last 20 years, and chemists have been making polymers – large molecules made up of nanoscale subunits – for decades.



LEFT: This coral-grazing parrotfish has particularly strong, durable teeth made up of bundles of nanofibres. RIGHT: Tennis balls made of nano-based materials remain pressurised for longer.

New nano

Today, there are two approaches to manufacturing nanomaterials: 'bottom-up' and 'top-down'.

In the 'bottom-up' approach, structures are built up atom by atom using sophisticated tools such as the scanning tunnelling microscope or atomic force microscope. You can find out more about these technologies on the *Big Picture* website. These can pick up, slide or drag atoms or molecules around to build simple nanostructures.

Molecules can also be assembled by chemical synthesis – or by self-assembly, whereby atoms and molecules arrange themselves into ordered structures.

In 'top-down' approaches, traditional engineering techniques such as machining and etching are used at very small scales. Products therefore tend to be refinements of existing products, such as electronic chips with ever more components crammed onto them.



...the London Eye would just about fit between the Earth and the Moon.

LIFE AT NANOSCALES

If you dive into a swimming pool, your inertia will keep you moving through the water for several metres. If you were nano-sized, however, the water would be like treacle – its viscosity would soon bring you to a gloopy halt.

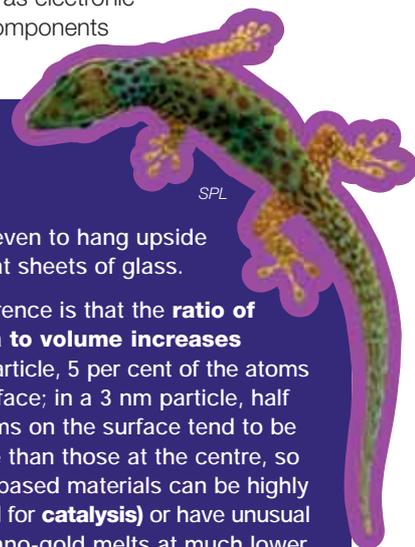
Nanoscale objects show markedly different behaviour to large objects. For a nanoparticle in a swimming pool, inertia is negligible and viscosity dominates. The water molecules would also bombard the particle because of Brownian motion – throwing it around like an aeroplane in constant turbulence.

At nanoscales, forces that hold surfaces together become very strong. For a 'nanobot' (see page 5), this could be a bad thing – it would tend to stick to the first surface it met. For geckos, this is extremely useful: nano-forces created by the extremely fine hair on their feet allow them to walk on

ceilings and even to hang upside down from flat sheets of glass.

Another difference is that the ratio of surface area to volume increases (in a 30 nm particle, 5 per cent of the atoms are on its surface; in a 3 nm particle, half are). The atoms on the surface tend to be more reactive than those at the centre, so nanoparticle-based materials can be highly reactive (good for catalysis) or have unusual properties (nano-gold melts at much lower temperatures than the solid metal).

At nanoscales, the behaviour of individual atoms and electrons becomes important, and interesting quantum effects come into play. These fundamentally alter the optical, electrical and magnetic behaviour of materials. You can find out more about the peculiar quantum world in *Big Picture Online* (www.wellcome.ac.uk/bigpicture/nano).



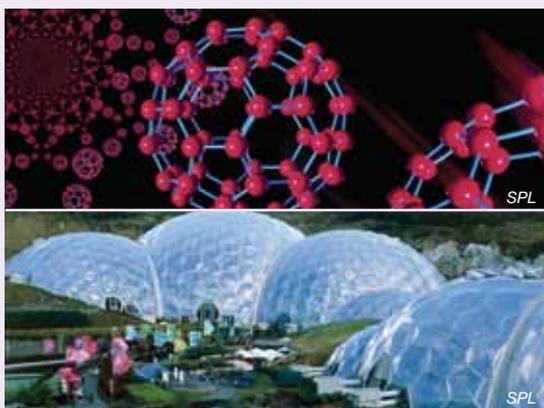
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NANOSCIENCE POTENTIAL

FAST FACT

A team of German and Swiss scientists has calculated that nano-forces allow spiders to carry more than 170 times their own body weight.

Nanotechnologies have the potential to touch almost every aspect of our lives. What are they based on and what might they do for us?

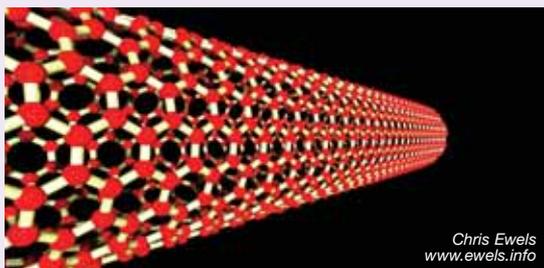


C60/fullerenes

In 1996, Sir Harry Kroto, Rick Smalley and Robert Curl won a Nobel Prize for their synthesis of a new form of carbon, C₆₀, which they named **buckminsterfullerene** in honour of Buckminster Fuller, the architect who pioneered the geodesic dome (as seen at the Eden Project in Cornwall, left). C₆₀ molecules are also called **buckyballs**.

In architecture, geodesic domes are known for their strength and lightness. The same is true of buckyballs. When fired at a stainless steel plate at 15 000 mph, they just bounce off it. And when compressed to 70 per cent of their original size, they become twice as hard as diamond.

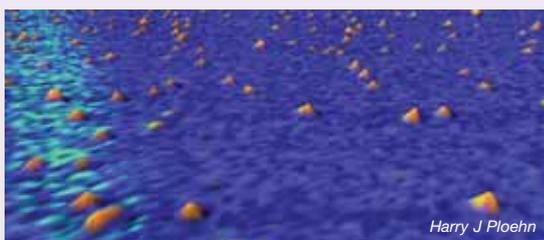
Their chemistry can also be manipulated. A version in which all of the carbon atoms are combined with hydrogen (a 'fuzzyball') is more slippery than Teflon – just right for coating bowling balls.



Carbon nanotubes

The discovery of carbon nanotubes in 1991 opened up a new era in materials science. These incredible molecules have an array of fascinating electronic, magnetic and mechanical properties. They are at least 100 times stronger than steel, but only one-sixth as heavy – so nanotube fibres could strengthen just about any material.

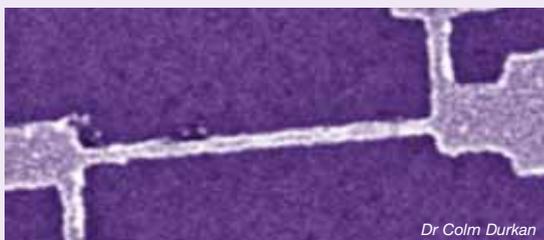
Also, nanotubes can conduct heat and electricity far better than copper, and are already being used in polymers to control or enhance conductivity, and in antistatic packaging.



Nanoparticles

The term **nanoparticles** covers a diverse range of chemical and other entities. They can be metallic, mineral, polymer-based or a combination of materials.

They have multiple uses: as catalysts, drug delivery mechanisms, dyes, sunscreens, filters and much more (see opposite).



Nanowires

Nanowires are extremely narrow threads (less than 50 nm wide). They have potential to be used in **nanoscale electrical devices**. The vision is of electronic chips so small and cheap that they could be used in almost any way.

In biology, they could form the heart of extremely sensitive **biosensors**, identifying molecules associated with disease or the binding of chemicals to a drug target.



Self-assembled nanostructures

If nature can be persuaded to build structures, manufacturing becomes much easier. Fortunately, self-assembly is widespread in nature (think crystal growth or blood clotting).

Many very clever routes are taking advantage of self-assembly. This includes use of chemical monomers that naturally polymerise, creating a **polymer mesh** whose properties can be modified by tweaking the original monomer (see box on page 15).

NANOBOTS: FACT OR FANTASY?

Nanobots were the vision of researcher Eric Drexler. He envisaged tiny robots (hence the term 'nanobots') that could make nanomaterials, atom by atom. The nanobots would replicate themselves by taking raw materials, plucking out the atoms they needed one by one, then assembling a new copy of themselves.

Are they really dangerous?

He thought so. In his *Engines of Creation* (1986), which introduced nanotechnology to the public, Drexler suggested that if a few nanobots were to multiply out of control, they could form a swarm of tiny, precisely engineered yet lethal machines that together pull apart every living thing in their path, atom by atom.

He imagined that this rampaging swarm might look like 'grey goo'. According to one estimate, it would take replicating nanobots just three or four hours to transform all living things on Earth to grey goo. In April 2003, the grey goo scenario apparently prompted Prince

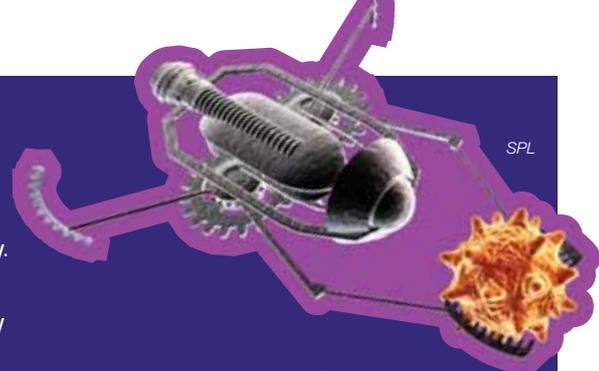
Charles to enter the nano-debate. He called a meeting of leading scientists to discuss nanotechnology.

A closer look

Nanobots are nanofiction – and likely to remain so for decades to come. Drexler himself has disowned the grey goo scenario, and Prince Charles has acknowledged it is not an issue.

The practical challenges would be immense, and there seems little need for self-replication anyway. Even physics is against the idea. Nanosubs, inside blood vessels, would be smashed to bits in the nanoworld (see page 3).

We also tend to think about 'manufacturing' in terms of production lines, but these are not easy to apply at the nanoscale. Many nano-engineers argue that we should be looking to chemistry and biology for inspiration, taking advantage of Brownian motion, the 'stickiness' of molecules and



molecular recognition ('lock and key' interactions) to build things.

Other futuristic prophecies distinguish 'hard' nanotechnologies – nanofactories, in which products are built by mechanical processes – and 'soft' nanotechnologies, those based on biological systems.

Soft nanotechnologies merge into biotechnology. They can be seen in projects that combine biological and physical systems, and those that are attempting to create 'minimal viable cells', building up simple cells from scratch. As biological systems are known for their powers of self-replication, this has led to fears that the 'grey goo' may in fact be a 'green goo'.

HOW THEY ARE USED

Medical applications

The medical potential of nanotechnologies is huge. Already on the market in the USA are **wound dressings** that exploit the antimicrobial properties of nanocrystalline silver.

Nanomaterials could make good **implants**. Nanoparticles such as nanocrystalline zirconium oxide (zirconia) and nanocrystalline silicon carbide are strong, lightweight, resistant to wear and corrosion and (unlike many other nanoparticles) inert.

For the future, **there is potential for nanoparticles to be used as vehicles for gene and drug delivery.**

Environmental applications

There are environmental concerns about nanoparticles, but they could also play an important role in protecting the environment.

A typical application would be based on a column containing nanoparticles that bound to a particular contaminant. As water passed through the column, the contaminant would be absorbed onto the nanoparticles. The nanoparticles could then be retrieved (e.g. by removing them magnetically) and the contaminant washed out.



Discover more applications of nano – from medicating contact lenses to new vaccine delivery technologies – at **Big Picture Online**.

www.wellcome.ac.uk/bigpicture/nano

Military applications

New classes of nanopolymers are being developed that can be sprayed on to a soldier, to form a suit without seams. The fabric is planned to contain embedded enzymes that detect and break down chemical and biological warfare agents, various biosensors to monitor a soldier's health, and nanosized silicon carbide particles for physical protection.

The nano-battlesuit is being developed at Massachusetts Institute of Technology's Institute for Soldier Nanotechnologies.

Cosmetics

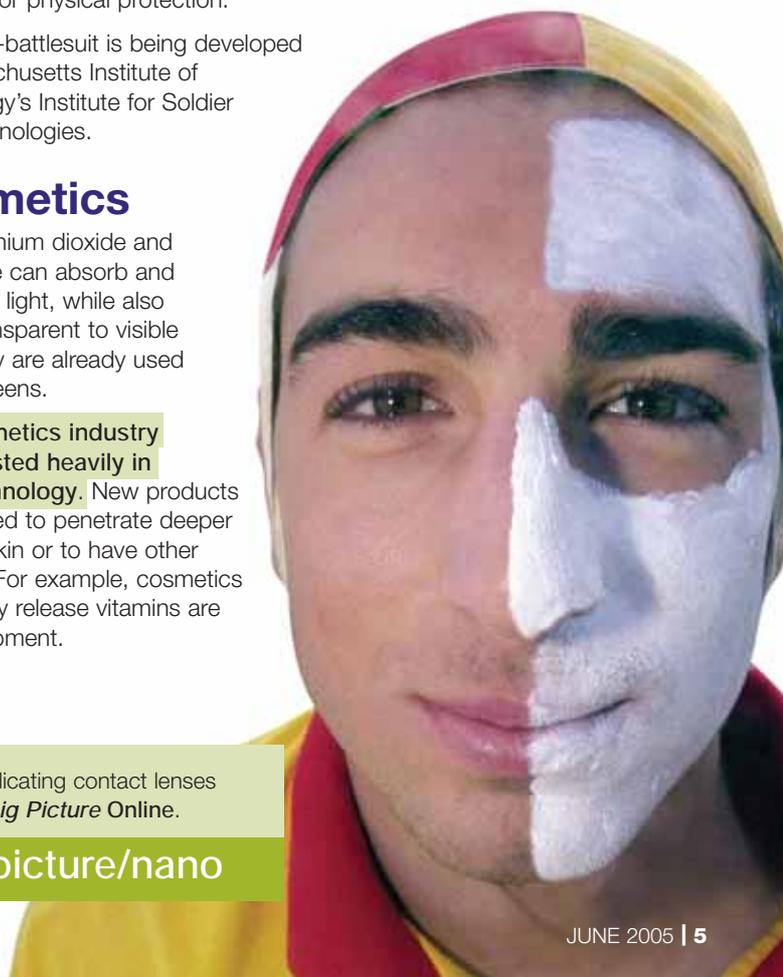
Nano-titanium dioxide and zinc oxide can absorb and reflect UV light, while also being transparent to visible light. They are already used in sunscreens.

The cosmetics industry has invested heavily in nanotechnology. New products are claimed to penetrate deeper into the skin or to have other benefits. For example, cosmetics that slowly release vitamins are in development.

BELOW

Nanoparticles of titanium dioxide are being used to create transparent sunscreens.

Newspix/Jody D'arcy



THE DOWNSIDE

FAST FACT

Japanese scientists have used nano-needles 100 nm wide to deliver materials to very specific points in the cell.

Nanotechnologies offer the potential for huge benefits. But we shouldn't be blinded by dazzling nano-promises, say concerned nanosceptics: there may be hidden costs and are the benefits ones we really want?

Sometimes a piece of technology seems very likely to be mainly good or mainly bad. Usually, though, especially in an area as broad as nanotechnology, there will be a range of possibilities for use and abuse, a mix of good and bad effects.

To maximise the benefits, it helps to think about the possible downside of new technologies early on and to realise that some impacts may be unpredictable. In a complex world, taking this job seriously includes exposing disagreements about what count as good applications, and considering who benefits and who bears the costs.

Introducing our heroine, 'Nan O'...

Better fishing rods, but fewer fish?



FAST FACT

Researchers in Florida, USA, have devised a nanoparticle-based bioassay that can detect a single bacterium within 20 minutes.

Green or black?

Despite the potential for nano-clean-up, one of the biggest fears is the possibility of environmental damage. Given their small size, the worry is that nanoparticles will easily become airborne and spread through the atmosphere, or will contaminate aquatic environments. Once in the environment, they could accumulate in living organisms, as many harmful substances do, or damage ecosystems.

Very little is known about the fate of nanoparticles in the environment, or their impact on living systems. Some preliminary research suggests that carbon nanoparticles – buckyballs – can harm fish. But this was at very high concentrations and involved only a few fish.

VERY LITTLE IS KNOWN ABOUT THE FATE OF NANOPARTICLES IN THE ENVIRONMENT

Also, the impact of nanoparticles is going to depend on their composition and their surface chemistry. Changing the chemical groups on the outside of buckyballs makes a big difference to their properties. So it will not be easy to make generalisations.

Safety first

Nanoparticles and nanotubes may be harmful. But we don't really know.

Nanotechnologies are partly about crafting new materials, and these may need safety testing. But are there new hazards arising from the kinds of material on offer?

UNFORTUNATELY, THERE IS A LOT OF SPECULATION BUT LITTLE HARD INFORMATION.

The main concern is about nanoparticles. Because their properties differ from larger forms of the same substance – nano-gold, for example, is not like solid gold – there are fears that existing safety measures may not be adequate. Unfortunately, there is a lot of speculation but little hard information.

Some forms of nanoparticle appear to be able to pass through the skin. This has its advantages – for example, it is a way to get vitamins into the body using cosmetics. But, given their size, they could interfere with the function of proteins on the surface of cells, or be taken up into cells and bind to intracellular molecules. This has been seen in the lab, but it is not clear how harmful it is.

Take a deep breath...

A second possible route of exposure is through the lungs, if people breathe in nanoparticles present in the atmosphere. Again, very little is known about how nanoparticles behave in our lungs, but it is clear that they can be taken up by cells in the lung, triggering inflammation. They can also get into the bloodstream, and transport of nanoparticles through nerve tissue to the brain has also been seen.

Carbon nanotubes may be an especial cause for concern, as they resemble asbestos fibres, which caused cancers in workers who breathed an asbestos-laden atmosphere. As with nanoparticles, new research is needed on their possible effects, but again early signs are that they might pose a threat to health.

There will also be puzzles to solve in measuring and monitoring. Nanoparticles are often too small to show up with standard instruments.



Until more is known about environmental impacts of nanoparticles and nanotubes, we recommend that the release of manufactured nanoparticles and nanotubes into the environment is avoided as far as possible.

Royal Society/Royal Academy of Engineering report.



New drugs or new toxins?



Safer lives or more surveillance?

Civil liberties

Information, information everywhere: will it become even harder to keep personal information to ourselves?



These days everyone, from governments and health workers to banks and supermarkets, seems to want more personal information. One set of applications of nanotechnologies will offer lots of possibilities for collecting new data. Tiny sensors, embedded in clothes, products or even bodies, could monitor the movement of people or products, or record health information. It might mean we are observed, sorted, profiled and classified wherever we go, and whatever we do.

This can be harmless, if it helps service providers or companies give us what we need. But it may also make it harder to protect privacy, or keep personal information confidential.

These concerns are not new, and are already discussed in relation to barcodes, ID cards, computer databases and CCTV cameras. So nanotechnologies may not give rise to any new issues, but they are likely to intensify existing debates.

Who benefits?

Will nanotechnologies lead to a nano-divide between rich and poor?

Many people fear that nanotechnologies will further increase the gap between the 'haves' and the 'have nots'. Certainly, early examples of nano-products have been driven by a rich-world agenda: suncreams, tennis balls, tennis racquets, laptop computers and so on. And millions of pounds are being spent on sensor-laden 'smartsuits' for 21st-century infantry.

But it is not inevitable that nanotechnologies will heighten global inequalities. Applied the right way, they could provide many benefits (e.g. renewable energy from solar power, medical diagnostic kits, cheap water purification or waste clean-up). Nano-based technologies may also allow countries to 'leapfrog' outdated technologies.

As usual, the issue depends on the priority we wish to give to problems affecting the developing world. There has been little sign so far that the needs of poor countries are shaping the nano-revolution. An alternative is for countries to seize the initiative for themselves. And some emerging economies, such as China and Mexico, have made moves to develop local nano-capacity.

But there is always a fear that new technologies can be too seductive, being pursued more for their own interest than because they offer the best prospect for solving existing problems. Many (probably most) of the world's biggest problems could be tackled with tools we already possess.

This issue is explored further at www.wellcome.ac.uk/bigpicture/nano.

Nanotechnology is likely to be particularly important in the developing world, because it involves little labour, land or maintenance; it is highly productive and inexpensive; and it requires only modest amounts of materials and energy. UN Millennium Project.

Wonderful opportunities – but only for some?

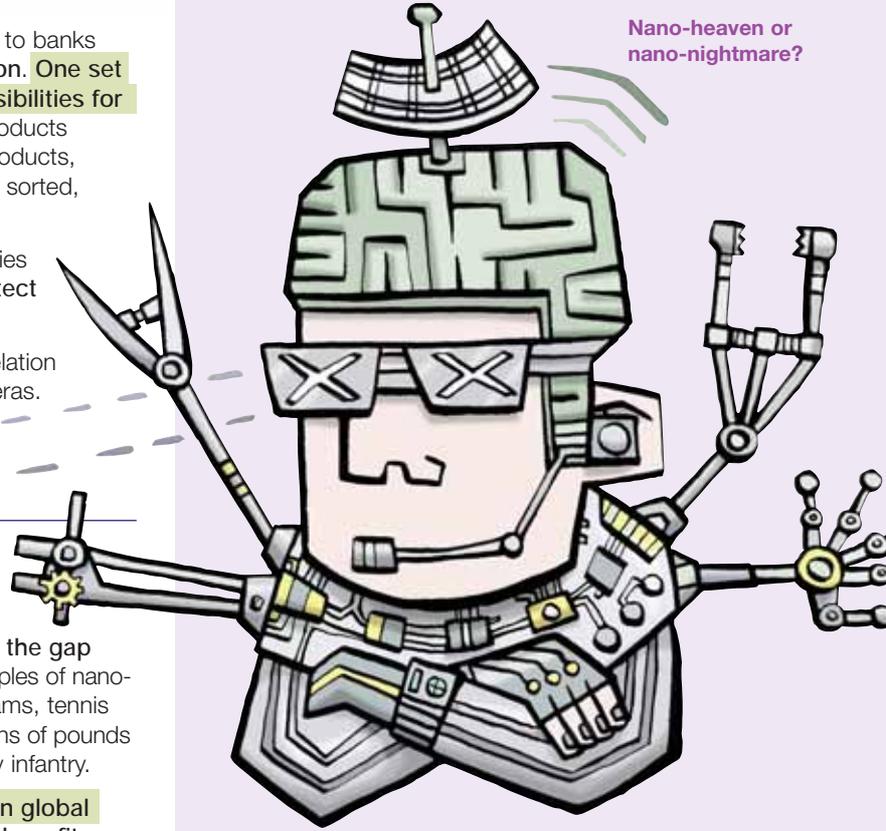


Hello, post-humans

The coming together of biology, nanotechnologies, information technologies and possibly even neuroscience may blur the boundaries between human and machine.

If some of the grander nano-promises come true, then nanotechnologies could help bring about a fusion between people and technology never seen before.

Nano-heaven or nano-nightmare?



The machinery of the living cell is one kind of nanotechnology. Adapting it, or combining it with new nano-devices could, in theory, give future humans new capabilities such as enhanced senses or control of computers connected to their own nervous systems.

This is all a fair way off. Current work is mostly medical, like better artificial ear implants for the profoundly deaf.

Better by design

A key issue will be whether enhancement is simply a new twist to an old story, or a new stage in evolution. From flints and fire to computers and fast food, we humans have always made and remade our environment and our culture through our tools.

We are currently free to adapt ourselves, by education, exercise or cosmetic surgery, for example. Does there come a point when broader social concerns require us to impose restrictions? Why? Should nano-enhancement be treated differently from other forms of human betterment?

Are we likely to widen further the gap between the 'haves' and the 'have-nots'? Could we even be heading for separate evolution – 'organic' humans versus 'enhanced' humans?

These are difficult questions to answer, and will depend on how nanotechnologies develop over the next few years. But they are worth thinking about if we wish to shape a future we want.

RISKY BUSINESS

As well as having many benefits, new nanotechnologies could backfire. How do we tackle risks and the unknown?

The first human who made fire was obviously a great hero. Having light, heat and hot food beats freezing in the dark every time. But fire can burn fingers, homes and forests. Today, we worry that the fuel we burn is changing the atmosphere of the whole planet.

Technologies have improved our lives immeasurably, but we now know that they can bite back. From cars and chemicals to medicines and microchips, new things bring costs as well as benefits. But how do we balance potential gains against possible drawbacks? This is a complex situation that now involves governments, industry, universities, consumer and campaign groups and ordinary people.

Escaping genies

Do we need new approaches to handle nanotechnologies?

Is existing regulation suitable for new technologies? Do nanotechnologies require special treatment? One argument used in the GM crop debate was that, once 'out there', they could not be recalled, as cars with a faulty component could be.

This is true of biological technologies in general. Living things have a survive-and-spread potential that most chemical or mechanical products do not.

The self-replicating nanobot concept (see page 5) raised the nightmare scenario of the planet being reduced to 'grey goo', but few believe this is a credible scenario.

What about nanoparticles? Certainly, they would be difficult to retrieve once out in the environment. But then so are caffeine, Viagra and sex hormones from contraceptive pills, all of which can be detected in rivers and seas.

PEOPLE POWER

Is there any point involving 'ordinary' people when complex technical issues are being discussed?



- There is a **democratic argument** that the voice of the people should be heard. If politicians are there to serve the people, should they not occasionally **listen to people's views**? Some feel that industry or other groups have the ear of government, and popular views are ignored.
- '**Ordinary people**' bring a useful perspective to bear, more able to tell what the actual impact of a technology will be.
- Society has changed dramatically. We are now more willing to **challenge authority**. We have lost trust in many authority figures, particularly politicians. We now have many more ways in which we can get our voices heard. We have a **vocal, powerful, challenging media**. Information can be shared more easily, on the web and by email.



- Very **technical issues** are being discussed. Can non-specialists really get up to speed to be able to contribute constructively? (In fact the evidence to date is that, given the opportunity, they can.)
- Where do we **draw the line**? Can the public really be involved in every decision, scientific and otherwise, and shouldn't politicians be representing our interests anyway?
- **Who** would be included? What happens, for example, if there are lots of people who have been personally affected? Is this right, or does it introduce bias?

The final decision

Ultimately, decisions have to be made, balancing scientific, social and political considerations, long-term potential against short-term impact, and individual freedoms against the collective good.

FAST FACT

Lux Research says that sales of products incorporating emerging nanotechnology will rise to \$2.6 trillion in 2014.



ON THE WEB

'The public' is made up of a very large number of people with a broad range of experiences and interests. Who should be involved and how would it be done? This issue is considered in more detail at *Big Picture Online*.

www.wellcome.ac.uk/bigpicture/nano



Phone for help

In a risky world, how do we work out what is safe?

We don't appear to be very logical when it comes to risk. We sometimes seem to go to extreme lengths to avoid tiny risks, while ignoring much bigger ones.

Often, the way we get information makes it hard for us to make sense of it. **Relative versus absolute** risk is a typical cause of confusion. A doubling or 100 per cent increase in risk sounds scary, but a change from one in ten million to two in ten million would be little cause for concern.

Actually, most of us manage risk pretty well. **We are bombarded with so much information that to survive we actually need to ignore most of it.**

So we tend to draw rapid conclusions from bits of information – what some psychologists call **'thin slicing'**. We make rapid, semi-automatic decisions based on many factors: our past experience, current state of mind, understanding of the risks, personality, what our friends think and so on. Most of the time it's a pretty successful strategy, but it is 'quick and dirty' and can go wrong, of course.

As well as benefits, individuals are likely to be affected by their **sense of control** over a situation – or lack of it. **In the GM crop scenario, it was clear that people felt they had little control over what was going on.** Reaction was also influenced by a widespread **loss of trust** in authority figures after BSE (mad cow disease).

As a society, we continue to view science and technology, in general, as **good things**. Our concerns tend to be more specific, or about issues such as **regulation or who gets to benefit**. What some fear, however, is that **our belief in science and technology means we often rely on scientific or technological solutions rather than social ones.**



FIELD STUDY: With GM crops, the only beneficiaries seemed to be agri-business: is that worth an environmental risk? This could change, if foods became much cheaper, or helped poor farmers. *Rex Features*



CALLING FOR CHANGE: Mobile phones appear to carry some risk, but the advantages are obvious. People seem more concerned about mobile phone masts: they appear to pose a lesser threat, but the personal benefits are not so obvious. *Rex Features*

Assessing risk

In an uncertain world, working out what risk is acceptable is very hard.

An awareness of possible drawbacks leads us to consider risk. Broadly speaking, **risk analysis** makes us think about:

- the **likelihood** that something bad will happen
- the **consequences** of the bad thing happening.

We then weigh these against the benefits, real or potential.

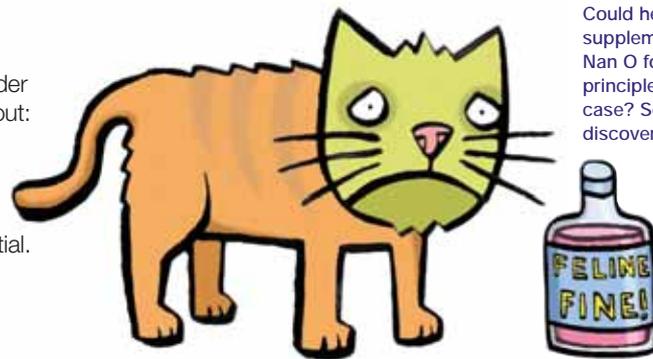
Industry and governments need to make more formal assessments of risk. But that is far from easy with a new technology.

It is in industry's interest to drive forward, to get products to market as rapidly as possible. **The Government has to walk a tightrope, supporting industry to generate wealth but maintaining a bigger picture** to ensure that any negative consequences don't outweigh the benefits. This is where **regulation** comes in.

The UK has many regulatory structures: health and safety, employment law, environmental protection and others.

Better safe than sorry?

Nowadays, many groups argue that we should adopt a 'safety-first' approach, following the **precautionary principle**. This states that, when it is theoretically



Nan O's cat, Tibbs, is poorly. Could her new 'FelineFine' vitamin supplement be to blame? Should Nan O follow the precautionary principle and stop using it, just in case? See *Big Picture Online* to discover Tibbs's fate.

As Nobel Prize-winning physicist Niels Bohr put it,

// **Prediction is very difficult, particularly about the future.** //

possible that technologies might cause serious problems, they should not be introduced, even if there is no firm proof of harmful effects. They must first be shown to be absolutely safe.

This all sounds fine in principle, but **what do we actually mean by 'safe'?** How safe is safe enough? Proving a negative – that something does not do harm – is difficult, if not impossible.

And caution may have its own cost. In **medicine**, it may lead to the later introduction of drugs, or to promising drugs being abandoned if side-effects are thought to be too severe.

Scientists have also pointed out that **many historic scientific achievements would not have happened had the precautionary principle been applied** – ranging from vaccination and the contraceptive pill to the internet.

Just because we take our time to check out the options carefully doesn't mean everyone will. Less cautious companies or countries may feel the risks are worth taking.

We can try to adopt the moral high ground, and push for 'higher standards' in other countries. But that can easily sound like rich countries trying to hold back poorer ones.



TRICKY INNOVATION

Will nanotechnologies take the world by storm? The road from idea to application is long and rocky – many factors will influence whether a product ever sees the light of day.

Science and technology offer a huge range of possibilities for feeding, clothing, mending, defending or just amusing ourselves. Only some ever become part of our lives, however. This is partly because time and money are always limited. If you spend all your cash on heart transplants, for instance, then cholesterol testing to prevent heart disease may lose out.

But there are a host of other things that influence technological futures, such as politics, economics, and social, environmental and technological issues.

THE IPOD:
a 'must-have' product – and it's based on nanotech too.

Rex Features

Primary school children go mad for 'NanoGum', your nano-based biodegradable chewing gum.
MOVE ON FOUR SPACES.

Politics...

Politicians in democratic countries promise to do things on our behalf, such as manage the economy, improve public health and maintain effective defence. And they pay attention to safety issues, and must heed public opinion – not least because they want to get re-elected.

When it comes to technology, the **economy** tends to come first. Science is now increasingly supported not because new knowledge is valued in itself but because it is a good 'investment'.

We are now supposed to be living in a '**knowledge economy**' – we cannot compete with the low wages of, say, the Far East, so we need to concentrate on high-tech industries and jobs requiring special skills, education and a strong research capability.

Governments try to imagine future technological possibilities, to help guide spending choices. The UK Government, like others, has a strong commitment to biotechnology and genetics. Nanotechnology looks to be getting the same treatment, with special research programmes and dedicated institutes.

Beliefs also play an important role. It is easier to do research on stem cells derived from human embryos in the UK than the USA, for example, because of the US Government's opposition on religious grounds.

Economics...

In the end, someone has to pay for all this stuff. By and large it is left to the **commercial sector** to develop products. So what actually gets made depends on what can be sold.

All this makes innovation – bringing a genuinely new product to market – a different type of risky business. Many products fail the test of consumer demand. At one time Digital Audiotape (DAT) promised a listening revolution, but it never got picked up in a big way. MP3s and iPods, however, caught the public imagination.

On the other hand, particular demands can shape the technology on offer. Personal computers have astonishingly good graphics because that is what game-players want, even though the mass of email and word-processor users may never see them in action.

Because of the way that health products are used, the situation here is slightly different. Consumer demand plays less of a role (though that may change) and there is a growing trend to assess cost-effectiveness of new treatments. Bodies such as the **National Institute for Clinical Excellence** carry out detailed studies to find out which treatments should be recommended.

But economic realities still dictate what happens. Pharmaceutical companies constantly search for **blockbuster drugs** – ideally tackling a widespread problem for many years. Less common problems, or those affecting the developing world, hardly get a look in.

Financial opportunities can also create incentives for companies to develop medical products of dubious value, to be marketed at the general population.

FAST FACT

Up to 2000 workers could be exposed to nanoparticles in universities and new companies, the UK's Health and Safety Executive estimated in 2004.

The Government decides your 'nano-oncotox' cancer treatment is the bee's knees and invests £50 million.
LEAP FORWARD 5 SPACES.

Social influences...

Consumers make or break a new product. But social influence can go further, from creating fashions that increase demand to active opposition to certain products. Mobile phones have been massively popular; the Segway (below, right) has not caught on. Sometimes it is simply successful marketing that makes all the difference.

Some technologies attract controversy, which brings them to a shuddering halt – GM food in the UK, for example.

Public attitudes to nanoscience appear fairly positive at the moment. But this is probably a poor predictor of future responses. Few people have heard much about nanotechnology, so this positive outlook may derive from a general feeling that science and technology do more good than harm.

But the recent history of GM shows how public opinion can be swayed and can distinguish between different uses of the same technology. So genetic alteration for medical benefit seems to be more widely accepted than altering genes of crop plants.

Nano-oncotox gets through phase 1 clinical trials.
MOVE FORWARD FOUR SPACES.

Nano-protestors blockade your lab.
GO BACK THREE SPACES.

BARE-FACED CHEEK: Protestors reference Richard Feynman, who highlighted the possibilities of nanoscience in his classic talk 'There's plenty of room at the bottom'.
T.H.O.N.G.

Technological...

Another problem for the would-be entrepreneur is knowing when the time is ripe to invest in a particular technology. There is a big gap between the visions of nano-manufacture and what is now possible in the lab. Even if something works in the lab, it may take much more work to scale it up for wider use.

The whole process of technological development can take decades, and it is often evolutionary rather than revolutionary. There have been bold predictions about **gene therapy**, but hardly any patients have seen the benefit yet – mostly because it has proven so technologically demanding.

A discharge of nanoparticles affects local streams.
MISS A GO WHILE YOU FIX THE PROBLEM.

DAM THE ENVIRONMENT: New projects are supposed to assess environmental impacts. *Rex Features*

IT'LL NEVER CATCH ON: A rare sighting of a Segway. *Rex Features*

Environment...

In the past, environmental impacts were rarely thought about. Environmental harms are easy to pass on to someone else – air and water often shift pollutants far away from the source. And they're often 'invisible' – until fish start dying or winter disappears.

Environmental impact assessment is now routine for big projects like dams, factories or airports. For products, new methods can assess **costs over the whole life-cycle**, not just manufacture. So the cost of a nuclear power station will eventually include paying to dismantle it and store the waste. But whether all relevant costs (and non-financial social impacts) get factored in is open to debate.

Even simple things, like a styrofoam cup in Starbucks, can be analysed for environmental costs and benefits.

Catastrophe!
Nano-oncotox is found to increase the risk of stroke.
GO BACK TO START.

SEARCH AND DESTROY: Nanoparticles are being used to destroy cancer cells such as these. *Paul Andrews, University of Dundee*

FINISH

ART



REAL VOICES

Where are we now with nano, and where are we going?

We asked people from two quite different backgrounds to give us their views.

Dr Doug Parr (DP) is the Chief Scientific Advisor of Greenpeace, an independent non-profit global campaigning organisation.

Professor Mark Welland (MW), Professor of Nanotechnology, is the Director of the Interdisciplinary Research Centre for Nanotechnology and the Nanoscience Centre at the University of Cambridge.

How will nanotechnologies change our lives over the next 20 years?

Mark Welland By definition the amount of funding going into nanotechnologies (in the USA, the money invested in nanotechnologies is more than the budget for NASA) means that there will be significant differences in our lives. We'll see huge impacts in lots of areas.

Doug Parr It's very difficult to say. It's hard to see 20 years ahead. We do need to stay a bit sceptical about how likely technologies are to change our lives, because a lot of predictions are wrong.

Is opposition to nanotechnologies just a fear of change?

DP There isn't big public opposition to nanotechnologies. Greenpeace isn't opposed to them either: I hope some good things will come out of them. But we do have some scepticism about how they will be shaped.

MW No, it's fear of unknown consequences. Because physical properties set at the atomic- and molecular-length scales can lead to other unplanned properties and consequences.

Will nanotechnologies widen the gap between the world's rich and poor?

DP If the current model of technology development is followed, the divide will increase because investment in nanoscience will largely be made by, and for the benefit of, richer countries. At best they will have no impact on the divide and won't increase it.

MW There's always that danger. But nanotechnologies are unique in that – unlike other industries, which require levels of investment that are impossible for developing countries – you can make new materials and devices very cheaply with them. This could shrink the gap between rich and poor countries.

Should the public be involved in decisions about the future direction of nanotechnologies?

MW As in all technologies, yes. The question is, how do you go about it? We're running a citizens' jury with the *Guardian* and Greenpeace, which will bring out issues in a public way. But it's still limited: it may involve around 20 people.

DP Yes, we should be involved. This is everyone's future we're talking about. The blockage is that decision makers don't involve the public in debates. Unlike most areas of policy making or public services, in science there are no intermediate mechanisms to ensure the decision makers are accountable to the public about how or what research is funded.



ARE NANOTECHNOLOGIES BEING OVERHYPED?

DP Time will tell. Maybe, maybe not.

MW Absolutely. No question.

ON THE WEB

You can find longer versions of these interviews at *Big Picture Online*.

www.wellcome.ac.uk/bigpicture/nano

ABOVE

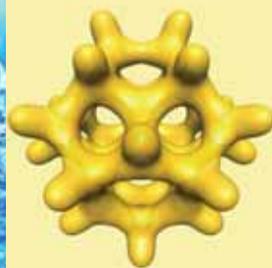
A flying 'barberbot', designed to provide automatic haircuts. Nanotechnology has stimulated feverish speculation (and artistic creativity).

Tim Fonseca

WILL NANOTECHNOLOGIES AFFECT THE ENVIRONMENT?

MW Technologies in general do. Nanoparticles could potentially have a toxic effect. We need to understand the pathways through which they move into the environment. At the moment, the quantities being made are tiny, but they could be greater in the future as people start to scale-up production.

DP They definitely will. But at present it's hard to tell whether the effect will be good or bad. Solar cells would be a good effect.



Are there enough controls in place?

MW Controls can be put in place either because we know of negative outcomes or consequences, which we must stop, or because we are uncertain about the outcome of certain technologies. Once an uncertainty or negative certainty is recognised, we must do something.

Are there enough controls? I think we need a balance. If you control everything in the interests of safety, you end up restricting all development so it will never happen. We need to allow technology to develop and be useful.

DP Regulatory frameworks are clearly not suitable yet. A broader point is: are regulatory frameworks that determine science and technology delivering what we want for society? They're generally not up to it, which is why we still have huge centralised electricity plants, rather than cheap, energy-efficient solar cells.

What excites and scares you most about nanoscience?

DP I'm excited about the possibility of clean energy.

What scares me... is the fusion of nanotech and biotech if – and it is an if – it uses biological tools to produce self-replicating objects. I'm talking cyborgs, rather than grey goo. But it's ten years from being a serious prospect and might never happen.

MW I'm excited by the fact that such small beautiful structures have consequences on sizes 1000 million times bigger and offer such an enormous potential for new applications.

I don't think anything particularly scares me. I'm concerned we're not doing enough research into some of the uncertainties.



LEFT AND RIGHT
'Nano-flowers' produced by growth of silicon carbide nanowires on gallium catalyst particles.
Ghim Wei Ho and Mark Welland

CENTRE
A model of electron density in a silicon nanocrystal.
Zack Helms

BACKGROUND
Vin Crespi, Penn State Physics

Democs

The game to play to have your say

Excited about the nano-future?

Worried about the fish?

Here's your chance to make your voice heard – while also having fun.

This issue's online activity is based on the 'Democs' (Deliberative Meeting of Citizens) format – a card game developed by **nef** (the New Economics Foundation).

Democs enables people to find out more about and express their views on complex topical issues such as nanotechnologies, stem cell research and GM food. It can also record public opinion, which can inform policy makers.

In this game, specially adapted for post-16 students, students work in groups to find

out more about nanoscience and nanotechnologies, think about a selection of case studies – from a transhumanist's enthusiasm for human enhancement to a physicist's fears about environmental impacts – and mull over some key issues.

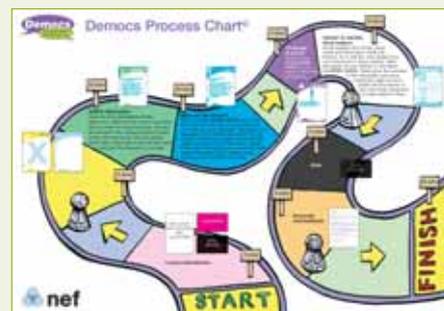
At the beginning and end of the activity, students vote on how nanotechnologies should be regulated. Final opinions can be submitted to **nef** and may be used to influence local or national decision making.

Collated results will also appear on the Wellcome Trust website, so students can compare their views with those from other schools and colleges.

Full details can be found at www.wellcome.ac.uk/bigpicture/nano.

Democs is produced by the New Economics Foundation (www.neweconomics.org/gen), an independent 'think-and-do tank'.

The development of Democs has been supported by two Wellcome Trust Society Award grants.



ONLINE ACTIVITY

WHERE NOW FOR NANO?

Nanotechnologies are finding a huge range of applications, as these case studies illustrate. How do you think they will be affected by the factors discussed in this issue? Which would you back for success?



LIGHT FANTASTIC

Quantum dots...

Just a few thousands of atoms each, **quantum dots** are being used as tiny beacons or markers that can be used to watch and track cells, genes, proteins and other small molecules.

When a beam of light is shone upon a quantum dot, the electrons in its core become excited and re-emit light – at a wavelength that depends on the size of the core. By altering the size of the core, researchers can fine-tune quantum dots to emit light

at a variety of wavelengths, producing a set of multicoloured markers.

The dots can be a thousand times brighter and last much longer than conventional dyes. In one study, scientists used quantum dots to watch blood flow in the tissues of living mice. The images were so detailed they showed blood vessel walls rippling with each heartbeat.

Adding antibodies or other molecules to the dots can be used to target them very specifically. Whole cells can be labelled and tracked –

more than 100 different cells simultaneously. Proteins on the surface of cells, such as cancer cells, can be identified. Even the movements of individual proteins can be followed inside a cell.



THE FUTURE

Currently big in the lab, where they look assured of a bright future. Companies are already selling quantum dot-based products for use in the lab. Very long-term possibility of quantum dot-based computers – won't be in PC World for a few decades yet.

DETECTIVE AGENCIES

Diagnostics...

A highly promising use of nanotechnologies is in diagnosis of disease. The key principles are the specific **recognition** of a molecule linked to a disease state and **detection** of this recognition. Nanotechnologies offer the prospect of very sensitive recognition and very quick detection.

Early-warning test kits for disease are being developed using quantum dots and **gold nanoshells**. Gold nanoshells are like tiny Maltesers, but have a crunchy core of glass and an outer case of gold rather than chocolate; unlike quantum dots, which re-emit

light energy, gold nanoshells absorb or scatter the energy.

Quick blood tests are being developed using nanoshells coupled to molecules that detect disease-associated proteins. Changes to the nanoshells' optical properties when they bind to the target can easily be detected.

Nanoparticles are being developed that recognise proteins produced only by **cancer cells**. A longer-term plan is to produce a cocktail of different coloured quantum dots (see above) to help doctors spot early indications of cancer, or identify different types of tumour.

A technique called **bio-barcode amplification** has been used to identify tiny amounts of a protein that may be an early hallmark of Alzheimer's disease.



THE FUTURE

Great potential: some examples of clinical research applications. Medical products have to undergo careful testing, so it will be several years before any products hit the market. Practical issues will have to be resolved, so that the devices can be used by health professionals. Healthcare services will then have to decide whether to use them – often a political and economic decision.

GREAT STRIDES FORWARD

Nanopants...

Probably the most visible nanotech products to date are the **stain- and wrinkle-resistant trousers** developed by Greensboro, North Carolina-based Nano-Tex LLC and sold by Eddie Bauer, Lee Jeans and several other retailers.

Nanopants (or nanotrousers) are garments whose fabric has been treated with a product containing polymer chains to improve their resistance to staining. Quite simply, hydrophobic bits of the chain will arrange themselves away from the textile surface, presenting a water- and stain-resistant surface to the outside world.

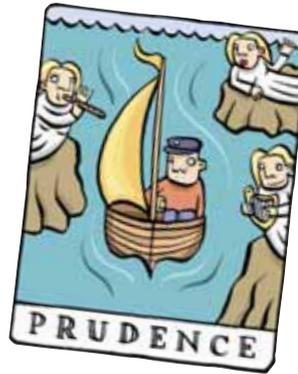
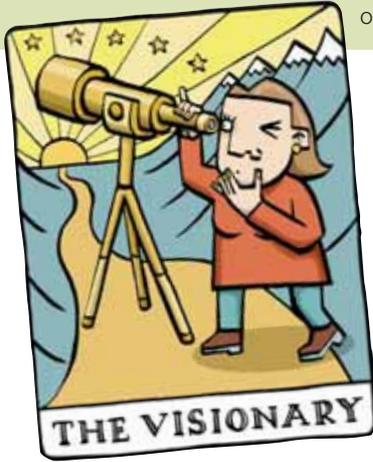
If you happen to spill coffee or orange juice on your 'nanopants' the liquid simply beads off and falls harmlessly to the floor, rather than leaving a stubborn stain.

Handy.



THE FUTURE

No regulatory worries – the products are already on the shelves. Key question is: will the public want them?



BIONANO – OR NANOBIO?

FAST FACT

A Japanese company has developed 10 nm-diameter particles that coat pollen and stop it releasing hay-fever-causing allergens.

Molecular machines...

Nanotechnology may be a new human activity, but nature has been at it for millions of years. Every cell contains thousands, even millions, of machines and factories that can build remarkable structures with an efficiency that today's scientists can only marvel at.

For example, the enzyme ATP synthase, which makes ATP, the chemical energy source for nearly all living organisms, is actually a tiny **rotary motor**. It has been attached to a nanoscale bar magnet made of nickel: this hybrid device could be a potential **nanomolecular motor** of the future, although the biological component is not very robust.

Others are combining components from different organisms, such as

the light-detection system from plants and energy-generating enzymes from mitochondria, to create biologically based **solar cells**.



THE FUTURE

Still at the lab phase. Many technological obstacles to overcome (e.g. how stable will biocomponents be?). Society may not be keen on the 'bio' bit – may raise fears of a cyborg world.

WHAT'S GOOD FOR THE GOOSE

Nanoscience and nanotechnologies are truly interdisciplinary, weaving together physics, chemistry and biology.

Interestingly, benefits flow both ways: engineers are looking to biologists to help produce better products, while life scientists are drawing on chemistry and physics to deliver medical benefits.

One US group, for example, is using a technique common in molecular biology to generate proteins that bind to particular metals – things that don't exist in the natural world. These can then be used to create nanoscale-ordered structures,

such as components of chips, nanowires and even a virus-based LCD screen.

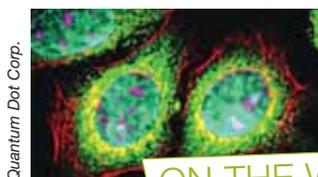
On the other hand, the ability of engineered chemicals to self-assemble is creating new therapeutic opportunities. By finely controlling the chemical composition of monomers, for example, researchers can create polymers with very specific properties. These can be woven into a very fine mesh.

Excitingly, proteins with particular biological properties can be attached, so the mesh becomes bioactive. The mesh is being tested as a possible way of healing

severed nerves: the proteins promote the growth of useful cell types and inhibit those that get in the way of repair.

This kind of approach opens up enormous possibilities for regenerative medicine and repair.

On the other hand, rarely do new applications not have some kind of unexpected impact. The trick is to go into new research areas with our eyes open to the amazing possibilities but not blinded by them, so we can make a sensible assessment of possible risks and drawbacks.



Quantum Dot Corp.

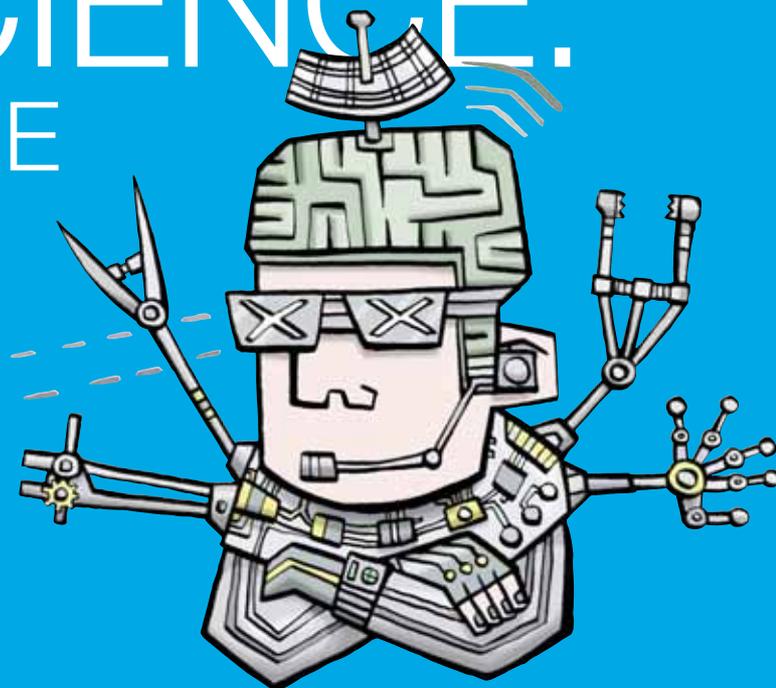
See a selection of quantum dots and other beautiful images and animations at our online nano-gallery. *Big Picture Online* also illustrates how the 'biobarcode' technique and nanoparticle-based cancer treatments work.

ON THE WEB

www.wellcome.ac.uk/bigpicture/nano

NANOSCIENCE: THE BIG PICTURE

- Nanoscience is the science of the **extremely small** – objects smaller than 100 nanometres (0.00001 cm).
- At these scales, the **properties of materials** change dramatically. Factors such as Brownian motion, surface stickiness and quantum effects become important.
- Nanotechnologies are based on a **range of new materials**, including carbon C60, carbon nanotubes, nanoparticles, nanowires, and polymers based on nano-size subunits.
- A huge **range of applications** are possible, based on stronger, lighter or smaller materials, or compounds with unusual optical or electrical properties.
- Early applications are **enhancing existing products** – tennis racquets, golf clubs, sunscreens.
- Possible **medical applications** include better implants, wound dressings, diagnostics and cancer treatments.
- Combining biological molecules with nano-mechanical components is creating **radically new materials**; these are at an early stage of development.
- The public currently has little input into **policy making** in science and technology.



- **Environmental concerns** focus mainly on **nanoparticles** but very little is known about their impact on living things.
- **Self-replicating nanobots** are extremely unlikely.
- Nanotechnologies could increase the divide between **rich and poor**, but could also provide products useful to the developing world and may be easier for poorer countries to take up.
- Several groups advocate **greater public involvement**. Others doubt it is feasible (or even desirable).

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