What is Nanotechnology?
A Guide
Introduction

Nanotechnology is an exciting area of scientific development which promises ‘more for less’. It offers ways to create smaller, cheaper, lighter and faster devices that can do more and cleverer things, use less raw materials and consume less energy.

There are many examples of the application of nanotechnology from the simple to the complex. For example, there are nano coatings which can repel dirt and reduce the need for harmful cleaning agents, or prevent the spread of hospital-borne infections.

New-generation hip implants can be made more ‘body friendly’ because they have a nanoscale topography that encourages acceptance by the cells in their vicinity.

Moving on to more complex products, a good example of the application of nanotechnology is a mobile phone, which has changed dramatically in a few years – becoming smaller and smaller, while paradoxically, growing cleverer and faster – and cheaper!

'Nanotechnology is more for less'
Background

Nanotechnology originates from the Greek word meaning "dwarf". A nanometre is one billionth (10^{-9} m) of a metre, which is tiny, only the length of ten hydrogen atoms, or about one hundred thousandth of the width of a hair!

Although scientists have manipulated matter at the nanoscale for centuries, calling it physics or chemistry, it was not until a new generation of microscopes were invented in the nineteen eighties in IBM, Switzerland that the world of atoms and molecules could be visualized and managed.

In simple terms, nanotechnology can be defined as 'engineering at a very small scale', and this term can be applied to many areas of research and development – from medicine to manufacturing to computing, and even to textiles and cosmetics.

It can be difficult to imagine exactly by how much this greater understanding of the world of atoms and molecules has and will affect our lives and the everyday objects we see around us, but some of the areas where nanotechnologies are set to make a difference are described in the following pages.

From Micro to Nano

Nanotechnology, in one sense, is the natural continuation of the miniaturization revolution that we have witnessed over the last decade, where millionth of a metre (10^{-6} m) tolerances in engineered products have become commonplace, for example, in the automotive and aerospace industries enabling the construction of higher quality and safer vehicles and planes. It was the computer industry that kept on pushing the limits of miniaturization, and many devices we see today have nano features – such as cameras, DVD players, car airbag pressure sensors and inkjet printers.
New applications

Because of the opportunities nanotechnology offers in creating new features and functions, it is already providing the solutions to many long-standing medical, social and environmental problems. Also, because of its potential for business, nanotechnology is of global interest. It is attracting more public funding than any other area of technology, estimated at around 6 billion dollars worldwide in 2010 (nanoposts.com). It is also the one area of research that is truly multidisciplinary.

The contribution of nanotechnology to new products and processes requires a team effort, which may include life scientists – biologists and biochemists - working with physicists, chemists and information technology experts. Consider the development of a cochlear implant for example, and what that might require - at least a physiologist, an electronic engineer, a mechanical engineer and a biomaterials expert. This kind of teamwork is essential, not only for cochlear implants, but for any new, nano-based product whether it is a scratch-resistant lens or a new soap powder.

Nano scientists are now enthusiastically examining how the living world ‘works’ in order to find solutions to problems in the ‘non-living’ world. The way marine organisms build strength into their shells has lessons in how to engineer new lightweight, tough materials for cars; the way a leaf photosynthesizes can lead to techniques for efficiently generating renewable energy; even how a nettle delivers its sting can suggest better vaccination techniques.

These ideas are all leading to what is termed ‘disruptive’ solutions, when the old ways of making things are completely overtaken and discarded, in much the same way as a DVD has taken over from videotape, or a flat screen display from a cathode ray tube.
In the past, medical treatments were, rather like medieval architecture, the result of adopting those techniques that worked and discarding those that didn’t. Today, our improved knowledge of how the body functions at the cellular, or ‘nano’, level is leading to many new and better medical techniques. For example, we know that the earlier a disease can be detected, the easier it is to remedy. To achieve this, research is focussing on introducing into the body specially designed nanoparticles, which are composed of tiny fluorescent quantum dots that are bound to targeting antibodies. These antibodies can bind in turn to diseased cells, and when this happens, the quantum dots fluoresce brightly. This fluorescence can then be picked up by new, specially developed, advanced imaging systems, enabling the accurate pinpointing of a disease even at a very early stage.

Nanotechnology is also leading to faster diagnosis. Diagnosis can be a lengthy and stressful business, often with a test sample having to be sent away for analysis, with the results taking several days or even weeks to arrive. Nanotechnology is enabling much faster and more precise diagnosis, as many tests can be built into a single, often palm-sized device that only requires tiny quantities of sample. This device is sometimes called a ‘lab-on-a-chip’, and samples can be processed and analysed so rapidly that the results can be read out almost instantaneously.

People often complain that the cure for a disease can feel almost as bad as the disease itself, as prescription drugs may have unpleasant (and if we are very unlucky, sometimes even fatal!) side effects. This is because the body needs to be flooded with very high doses of a drug in order to ensure that a sufficient volume reaches the site of the disease. Accurate targeting of drugs can now be achieved, using specially designed drug-carrying nanoparticles. This means that much smaller quantities are necessary, so it is less toxic to the body. The drug is then activated only at the disease site (such as a tumour) by light or other means, and the progress of the cure can be monitored by the imaging techniques described above.
Nanotechnology offers some really exciting breakthroughs in environmentally friendly technologies from extracting renewable energy from the sun to the prevention of pollution. Geoffrey Sacks, the American Economist, in his 2007 BBC Reith lectures entitled ‘Bursting at the Seams’, famously commented: “The fate of the planet is not a spectator sport. We live in an interconnected world, where all parts of the world are affected by what happens in all other parts”.

There is no doubt that the pressures we are putting on the planet are leading to potentially catastrophic consequences. In the developed world, we have grown accustomed to using our car to go to the local shops, take weekend cruises and even day trips to far-flung places that might have taken three or more months to reach before air travel became commonplace. We like our vegetables and fruit out of season, and increasingly expect to eat meat at least once, if not twice a day. We haven’t thought about the effects of these activities on the planet, which in the past could absorb our excesses, but with the ongoing destruction of the rainforest (which is responsible for 25% of carbon emissions!) and the population of the world close to reaching 7 billion, the earth is showing signs of being unable to bounce back from the demands we are placing on it.

So what can we do to limit the damage and ensure a future for our children? Firstly, the bad news. The fossil fuel that oils our everyday lives is responsible for 44% of the carbon dioxide we emit annually – and rising! The good news is that the energy from sunlight is sufficient to meet our needs ten thousand times over. Today, more efficient and cheaper solar energy collectors are in the process of being developed using nanotechnology; these could be deployed as small units in our homes. They work particularly well in diffuse light, so would suit even less sunny climates. This would have the benefit of not sterilizing precious...
land (a diminishing resource for food), and quickly improve the quality of many people’s lives, especially in poorer housing or in the less developed world.

Not only do we need new ways of generating energy, we need better ways of storing it. Nanotechnology is leading to improved, environmentally-friendly batteries and supercapacitors. We also need to reduce damage to the environment. Particularly toxic are those chemicals we use as solvents. Nanotechnology is leading to their eradication through the development of new nanocoatings and nano structured surfaces that can effectively repel dirt and other contaminants. Coating metals to prevent corrosion also seriously affects the environment. Many anti-corrosion coatings involve chromium and cadmium, deadly substances, which the EU is seeking to limit. Of course, vehicle and component producers are keen to find alternatives, as recycling of toxic compounds is costly and unpleasant, and new smart nanocoatings are in the process of being developed that are non-toxic and highly effective. Serious contamination of the environment with heavy metals and other pollutants are thrown into the atmosphere from the fumes and smoke being emitted from industrial processes. It is encouraging to note that most of these of these particles and gases (including carbon dioxide) can be ‘scrubbed’ out - and even reclaimed and reused, using specially functionalised nanomaterials, placed in the waste gas stream.

Finally, given the old adage, if you can’t measure it, you can’t control it, fast, accurate, in-situ and online pollution monitoring is essential. New, cheap nanosensors are being developed from techniques used in medicine, that will enable us to do this quickly, effectively and cost effectively.
Nanomaterials

There are many fascinating examples of nanotechnology applications in new materials. For example, polymer coatings are notoriously easily damaged, and affected by heat. Adding only 2% of nanoparticulate clay minerals to a polymer coating makes a dramatic difference, resulting in coatings that are tough, durable and scratch resistant. This has implications for situations where a material fits a particular application in terms of its weight and strength, but needs protection from an external, potentially corrosive environment - which a reinforced polymer nanocoating can provide. Other nanocoatings can prevent the adherence of graffiti, enabling them to be easily removed by hosing with water once the coating has been applied. This has the important knock-on effect of improving urban environments, making them more attractive to bona fide citizens and less encouraging to criminals. These kinds of coatings, invented in Mexico, have been shown to work well in parts of Mexico City, transforming seedy crime-ridden neighbourhoods into increasingly respectable suburbs.

Nanoparticles

Particles at the nanoscale are below the wavelength of visible light, and therefore cannot be seen. Consequently, they can impart new properties while being invisible themselves! Fluorescent nanoparticles, or quantum dots (mentioned earlier) have a whole range of possible applications. They are invisible until ‘lit up’ by ultraviolet light, and can even be made to exhibit a range of colours, depending on their composition and size. Such nanoparticles are ideal for crime prevention, where goods can be invisibly ‘tagged’, preventing counterfeiting; stolen goods can be traced by their invisible ‘bar code’ and illicit drugs by the fact they have no legal identification. In some countries, cheap agricultural fuel is ‘laced’ with harmless nanoparticles, making it easy for police to identify a stolen consignment, merely by using ultraviolet light.

Nanoparticles can seem to be quite strange as they have new and unusual properties that are not obvious in the corresponding bulk material. This is because a nanoparticle has a large surface area in relation to its size, and is consequently highly reactive. This is exemplified by the fine grained materials that we use in our daily lives, such as flour, which can become explosive in some circumstances. Applications of nanoparticles include nanoparticulate titanium dioxide for sunscreens, and it also acts as a photocatalytic agent in coatings that can be applied to stay-clean windows, causing the dirt to be oxidized and easily washed away by rain.
Carbon nanotubes are a recently discovered unique material possessing amazing electronic, thermal, and structural properties. They are highly conductive both to electricity and heat, with an electrical conductivity as high as copper, and a thermal conductivity as great as diamond. They offer amazing possibilities for creating future nanoelectronic devices, circuits and computers. Carbon nanotubes also have extraordinary mechanical properties - they are 100 times stronger than steel, while only one sixth of the weight. These mechanical properties offer huge possibilities, for example, in the production of new stronger and lighter materials for military, aerospace and medical applications. Other applications include lubricants, coatings, catalysts and electro-optical devices.

The cost, purification, separation of nanotube types (Single Walled NanoTubes from Multi Walled NanoTubes), constraints in processing and scaling up and assembly methods are still hurdles for some applications. However, there are already products containing nanotubes on the market, for example, in some tennis racquets nanotubes are used to reinforce the frame and improve the racquet’s ability to absorb shocks. Carbon nanotubes can also be mixed with many different materials such as plastics and textiles, for example to produce lightweight bullet-proof vests.

According to engineers at the Frauenhofer Technology Development Group in Stuttgart the greatest potential for creating new products lies in harnessing the electrical properties of lightweight and robust nanotubes to generate heat. Applications range from electric blankets to heatable aircraft wings that no longer ice up, to ‘wallpaper’ heating for cold walls.
Textiles

The textile industry is an early adopter of new ideas and technologies. Textiles are not only for the fashion conscious - they have important applications in the aerospace, automotive, construction, healthcare and sportswear industries. Already on the market are socks and leisurewear with embedded silver nanoparticles that combat odour through killing bacteria – and this capability has been extended successfully to wound dressings. Several brands of clothing, including some designer labels, have incorporated self-cleaning and stain repellent nanotechnologies, very convenient for school clothes - and, of course, the less a garment needs to be washed, the more energy is saved! More glamorous applications include embedding gold nanoparticles into natural fabrics such as wool. The gold nanoparticles impart soft colours from pale soft greens, to browns and beiges, depending on the particle size and shape. These colours are stable, and may even provide some antibacterial properties to the fabrics, as an added bonus!

Across the globe a tremendous amount of research is taking place in electrospinning techniques. The spun, polymer-based nanofibres can be 'loaded' with different additives which could be nanoparticles, enzymes, drugs or catalysts. Some combinations can be antibacterial and sprayed on to wounds as a kind of healing ‘web’, others can be conductive or even form filters or membranes.

Scientists are also working on nanoelectronic devices that can be embedded into textiles to provide special support systems for individuals in dangerous professions or sports. Some garments can now provide life-signs monitoring, internal temperature monitoring, chemical sensing and also power generation and storage to enable communication with the outside world. Garments with this kind of technology can be vital for the safety of say firefighters working in dangerous situations in isolation from their colleagues, or even for skiers or their rescuers to give early warning signs of hypothermia.

In some establishments, research is ongoing into man-made nanofibres where clay minerals, carbon nanotubes or nanoparticulate metal oxides are used to impart new properties. These properties provide halogen-free, flame retardancy for a fabric, increased strength and shock-absorbency, heat and UV radiation stability, and even brighter colouration! Other work is ongoing in the very exciting area of inkjet printing onto textiles. This is opening up many possibilities, not just for the customised or localised printing of textiles to an individual design, but inkjet techniques can be used to create flexible electronic materials, sensing materials, and even the materials of the future with printed-on displays!
Food and Drink

Working at the nanoscale is not new to food companies. Many foods and beverages contain natural components that are nanoscale in size, and the manipulation of naturally occurring nanoparticles involved in the processing of, for example, dairy products, has been undertaken for some time under the name of ‘colloid science’! More recently, an improved understanding of mechanisms such as targeted delivery has enabled food companies to deliver scents, flavours, vitamins and minerals that offer health benefits or impart new physical, visual and sensory effects to foods. This has not only helped the exponential growth in the market for nutraceuticals and other functional foods but has enabled a wide range of new food products with new tastes, flavours and textures to be developed. Other applications of nanotechnology to food manufacturing include antibacterial work surfaces, filters that can extract toxins and packaging that provides a better barrier against contamination, or can signal when its contents are spoiling, by changing colour.

Scents and Flavours

A surprisingly interesting and lucrative field for the application of nanotechnology is in encapsulation and delivery technologies, especially for flavours and fragrances. These technologies were first developed for the delivery of pharmaceutical drugs, and have now found new applications in foods and household products. Encapsulation is an ideal way to improve the attributes and performance of a less-than-stable substance that might be affected by light or air, or have a tendency to sediment. Encapsulation gives active ingredients a longer shelf life, stability and protection from harsh processing environments so they can be delivered in a perfect state at ‘the moment of consumption’! For the food industry, it is a way of delivering enhanced taste, or ensuring that daily doses of vitamins and minerals are met – this is discussed in more detail below. In household products, nano encapsulation techniques can aid in the deposition of a cleaner or polish onto a surface such as a floor or counter; they can provide long lasting scents in household fragrances, and the slow release of enzymic and other agents in washing machines and dishwashers, helping reduce energy and water use.
The Car Industry

The automotive industry has appreciated for some time that nanotechnology can offer many benefits to this highly competitive and litigation-driven sector. Research is taking place into many applications of nanotechnology such as - improved lubricants, fuel cells for clean energy, lighter and stronger engine and body materials, better catalysts, nanoporous filters, self-cleaning windshields, self-healing and scratch-resistant coatings, environmentally friendly corrosion protection and colour-changing paints – to name but a few!

Major advances are also being made in the use of polymer nanocomposites for body panels as these can be made lightweight yet rugged, and in new metal nanocomposites to improve engine efficiency.

Specially designed nanoparticles are presently used as fuel additives to lower consumption in commercial vehicles and reduce toxic emissions.

Cars are notable for progressively increasing their high technology content, using smart nano-sensors for the prevention of possible problems from a tyre blow-out to brake failure, even to avoiding a collision!

Car manufacturers are keen to be more environmentally friendly in their manufacturing processes as well as in the final product. Investigations are underway in how nanotechnology may lead to a reduction in toxic wastes and by-products by substituting new nanomaterials for hazardous reactants and solvents or, better still, by using nanotechniques to eliminate their need altogether.
Are there risks from nanotechnology?

Some engineered nanoparticles, including carbon nanotubes, although offering tremendous opportunities also may pose risks which have to be addressed sensibly in order that the full benefits can be realized. We have all learned how to handle electricity, gas, steam and even cars, aeroplanes and mobile phones in a safe manner because we need their benefits. The same goes for engineered nanoparticles. Mostly they will be perfectly safe, embedded within other materials, such as polymers. There is some possibility that free nanoparticles of a specific length scales may pose health threats if inhaled, particularly at the manufacturing stage. Industry and government are very conscious of this, are funding research into identifying particles that may pose a hazard to health or the environment, and how these risks may be quantified, and minimised over the whole lifecycle of a given nanoparticle. There is no doubt that nanotechnology has great potential to bring benefits to society over a wide range of applications, but it is recognised that care has to be taken to ensure these advances come about in as safe a manner as possible.