Chapter 21
Nanotechnology: Applications and Markets, Present and Future

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Abstract The effects of nanotechnology, the application of nanoscience, which owes its early success to the IT industry, are already being felt across society. Because nanotechnology can now be applied so widely, it is called an *enabling* technology. There are few, if any, industries or products that could not benefit from the application of nanotechnology. It is not unreasonable to predict that nanotechnology will completely revolutionise industry and industrial processes within a decade. This chapter examines the economic and social potential of nanotechnology, and put figures on this potential, setting the scene for the remainder of the book which addresses how the most important issue of real time, non-destructive or invasive characterization at the nanoscale is being resolved.

21.1 Nanotechnology: Applications and Markets

21.1.1 Nanotechnology: Already of Global Economic Importance

Today we understand more and more about how the properties of everything in the world around us (including ourselves!) are defined by their component atoms and molecules. Already we are at the early stages of being able to manipulate these atoms and molecules in order to design new things with the features we want, improve medical treatments, the way we generate energy and process our food. This is nanoscience. The effects of nanotechnology, the application of nanoscience, which owes its early success to the IT industry, are already being felt across society. Because nanotechnology can now be applied so widely, it is called an *enabling* technology. For example, nanotech underpins many novel industrial developments, such as fabric treatments

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that repel stains, non-toxic paints that prevent rusting and biofouling, surface coatings that can kill bacteria and in more effective ways to deliver drugs.

We only need to think of the characteristics of a mobile phone, which today is in effect a mini computer, to appreciate just how many features can be incorporated into a product through micro and nanotechnology. A mobile phone can transmit sound, data, pictures, act as a video camera, a bank, a global positioning system, a health monitoring system, a teaching tool and an active (rather than passive) news provider. In essence, nano–enabled products are smaller, cheaper, lighter, faster, cleverer and often dramatically different to what they supercede. In theory, these new nano products should also use fewer raw materials and consume less energy to make. The developing countries are leapfrogging old technology and aiming to produce these new multifunctional products from the outset, in industries as diverse as aerospace, automotive, materials, foods, textiles and medicine, as well as in military, electronics and telecoms applications. There are few, if any, industries or products that could not benefit from the application of nanotechnology, and those that do not embrace the technology will be left behind by their competitors who do. It is not unreasonable to predict that nanotechnology will completely revolutionise industry and industrial processes within a decade.

As of March, 2011, the nanotechnology consumer products inventory contains 1317 products or product lines as shown in Fig. 21.1. Indeed, the inventory quoted suffers from the lack of a clear definition of what is a nanoproduct, and so is unlikely to be comprehensive, and should be considered only as a guide to the possible scale of market penetration.

Products were grouped according to relevant main categories (Fig. 21.2) that are loosely based on publicly available consumer product classification systems. The largest main category is Health and Fitness, with a total of 738 products. This includes products like cosmetics and sunscreens.

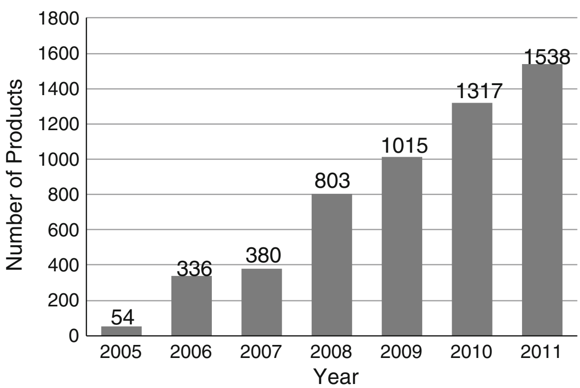

Fig. 21.1 Number of total products listed, by date of inventory update (*source* http://www.nanotechproject.org/inventories/consumer/analysis_draft/)

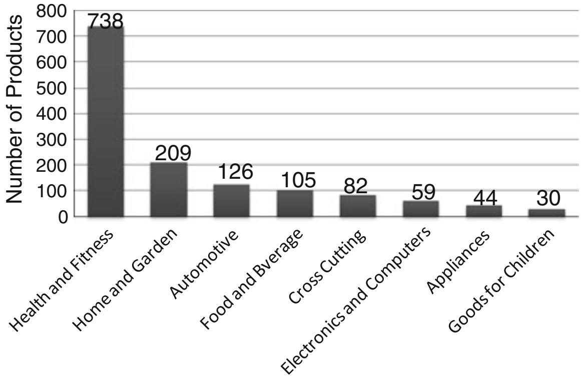

Fig. 21.2 Number of products, according to category on the market in 2011 (*source* http://www.nanotechproject.org/inventories/consumer/analysis)

The message is clear—the potential of nanotechnology is vast. However, there are some critically important sticking points that need to be quickly overcome before the benefits of nanotechnology are fully realized. These are: repeatability, stabilisation and characterization; latter being essential to establishing the first two.

These factors have determined so far the limited number of raw materials that constitute, so far, the main nanotechnology products on the market (see Fig. 21.3)

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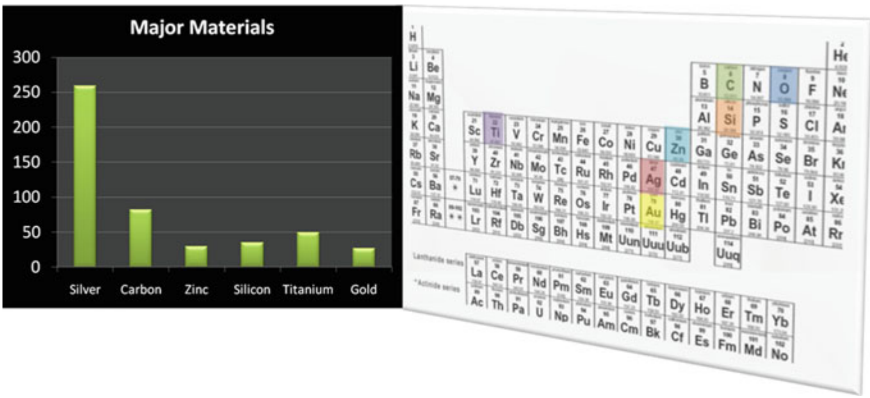

Fig. 21.3 Main elements constituting nanotechnology products on the market

21.1.2 Nano in the Home

If we take a whistle-stop tour of the nanotechnology products around us, we can usefully start in our homes. In a modern house, there could be stay-clean windows, solar collectors, dirt repellent carpets, curtains and chair coverings, anti-bacterial surfaces in the kitchen and toilet, stay-clean exterior paints, anti-corrosion coatings for radiators and gutterings, security lighting, lightweight and transparent wall and roof insulation and furniture treatments, all inside a structure made of environmentally friendly lightweight concrete.

If we examine the 'nano' behind some of these new products in a little more detail. To achieve a self-cleaning surface, there are two principal 'nano' techniques—one using super-hydrophobic and the other using super-hydrophilic materials. New structural paints can cleverly impart water and dirt repellency to whichever surface they are applied to. This is through emulating the Lotus effect, the way the leaves of the Lotus plant repel water through their special structure. Superhydrophilic surfaces on the other hand can be obtained by coating glass, ceramic tiles or plastics with nanoparticles of a semiconducting photocatalyst, titanium dioxide (TiO_2). If TiO_2 is illuminated by light, any grease, dirt and organic contaminants are decomposed and are easily swept away by rainwater. By definition, the size of a nanoparticle is below the wavelength of light, so the bonus is that the coating on the glass is therefore invisible.[1]

Even the technology for non-stick frying pans has switched to "nano" by using nanocomposites to provide heavy duty non sticking surface finishes. The idea of using silver for antimicrobial purposes has been adopted in many non-medical products. As well as in filters for air-conditioning, silver has also been introduced into washing machines and refrigerators for its antibacterial effect (Table. 21.1).

Nanoporous materials also offer superior thermal insulation. Although silica aerogels are the world champions in low thermal conductivity, their brittleness and high price have so far prevented a widespread use. Nevertheless, nanoporous materials have been developed in the form of flexible blankets or evacuated panels for better thermal management, vital in energy saving.

Table 21.1 Uses of nanotechnology products in the home

Dirt resistant facade paints
Self-cleaning coatings (windows etc)
Easy clean hygienic surfaces (in bathrooms, on food preparation surfaces)
Aerogels for lightweight insulation, and reduced flammability
Stay clean textiles (for carpets, furniture)

[1] http://www.nanoes.com/Reference/Self-Clean%20Materials.pdf

The Market for Nano-Enabled Homecare Products
According to Euromonitor, the sale of homecare products in the UK in 2010 was 3.7 billion UK£. Say the affluent world consists of only 1 billion people, then let's speculate that sales wolrdwide of homecare products to that community alone could be around 50 billion UK£, extrapolating the Euromonitor figures for the UK. If nano penetration is only 10 %, then the nano market worldwide for homecare products is already a not inconsiderable 5 billion UK£, or about 7.5 billion USD. As the world population increases, as wealth increases and the penetration of nano increases, it is not unreasonable to expect that nano influenced household products might reach 10 billion USD easily by 2015, and possibly much more.

Of course, nanotechnology represents not only a commercial opportunity but also to some, a considerable threat—and not just in product differentiation. For example, still in the area of household products, companies involved in manufacturing cleaning products could be threatened by self-cleaning coatings. Similarly detergent manufacturers might be disadvantaged by the development of dirt repellent textiles.

21.1.3 Up Close and Personal: A Nano Revolution in the Sunscreen and Cosmetic Industries

Nanoparticles serve many purposes in cosmetics: they enhance the properties and acceptability of cosmetics by providing softness, lustre, moisturizing and optical effects; they can protect the skin through sunscreens incorporating UV-filters. Most cosmetic manufacturers are extremely interested in the new properties nano brings to their formulations.

Ultra small capsules called liposomes were introduced into cosmetics as far back as 1986 by L'Oreal, a company that holds many nanotech patents. Liposomes are small containers or capsules ranging in size from below 100 nm to several micrometres. They are able to contain and deliver active ingredients such as drugs, vitamins and other cosmetic materials.

The same ingredients as found in common cosmetic formulations can be formulated in a variety of ways at the nanoscale—as nanospheres, nanocapsules, oleosomes and liposomes. These nano-based structures are important because they often improve the stability of the cosmetic and the active ingredients that they contain. Nano encapsulation techniques have led to many improvements in cosmetic products, such as the time-controlled release of scents, which means a more constant odour, as opposed to being overpowering immediately after application, but then the scent disappearing quickly.[2,3] Nanocapsules with a porous shell can release their content steadily over many months. If the capsule wall is rigid, it only releases the fragrance if it is ruptured (the release-on-demand principle). As only a few of the capsules burst at any one time, the effect can also last for months in this case. If not encapsulated, fragrance shelf life is short, with the scent altering or disappearing within a few weeks.

Ordinary cosmetic emulsions have droplet sizes between 100 and 100,000 nm. Nanoemulsions contain the same type of ingredients but their droplet dimensions may be as low as 10 nm. Given this small droplet size, nanoemulsions are transparent and have particular rheological properties, and because of their rheology and transparent properties, nanoemulsions are used in a number of cosmetics. When applied to skin or hair, nanoemulsions break down into their constituent ingredients.[4]

Some cosmetic products use mineral-based materials and their performance depends on particle size. In sunscreens, mineral nanoparticles (e.g. titanium dioxide and zinc oxide with particle sizes in the order of 20 nm) are efficient UV-filters. They transmit, reflect and scatter the visible part of the sun's rays while strongly absorbing in the UV region. These UV-filters consist of micron-sized aggregates, which are composed of nanosized primary particles.[5] The surface of these nanoparticles may be treated with an inert coating to improve their dispersion in the formulation and to prevent photocatalytic activity. The advantage of mineral UV-filters is that they provide broad UV-protection and usually do not cause adverse health effects.

The Market for Nano in Cosmetics.
According to Global Industry Analysts (GIA), the global cosmetics market is predicted to reach $41.4 billion by 2014.[6] Nano offers many advantages for new formulations, and few successful companies will have a range of cosmetics that do not have some kind of nano aspect to their formulation. So penetration is likely to be high, at the very least 20 %, and growing. So by 2015, nano enhanced cosmetics could be worth at least 8–10 billion USD.

21.1.4 NanoTextiles for Fashion, Work, Sport and Industry

Nano is having a major impact in textiles, an industry that is remarkable for being an early adopter of new ideas and technologies. Textiles are not only for the fashion

2 http://www.salvona.com/19-nanosal-

3 http://www.cosmeticsdesign.com/news/ng.asp?n=80466-naturalnano-nanotechnology-license-agreement-nanotubes

4 http://www.pharmainfo.net/pharma-student-magazine/nanoemulsions

5 Nanotechnology and Sunscreens, http://www.foe.org/nano_sunscreens_guide/Nano_Sunscreens.pdf

6 http://www.cosmeticsdesign.com/Market-Trends/Global-market-for-color-cosmetics-set-to-reach-41.4billion.

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 designer labels, have incorporated self-cleaning and stain repellent nanotechnologies, very convenient for school clothes and military wear,—and, of course, the less a garment needs to be washed, the more energy and money is saved.

More glamorous applications include embedding gold and other precious metal 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.

Currently, considerable research is focused on developing electrospinning techniques which produce long fibres of polymer, only nanometres in width, originally developed in an effort to emulate spider silk. 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. There are many exciting applications of the ability to spray-on a textile.

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 monitoring for several life signs, including temperature, chemical sensing and they can be used for 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.

Research is also 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, increased strength and shock-absorbency, heat and UV radiation stability, and even brighter colouration. Other work is focused on 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 display capabilities.

The Market for Nano in Textiles

Textiles include materials with an almost unimaginable spectrum of applications, and nanotechnology is further widening that spectrum. Given the many varieties and uses of textiles, and considering figures from various bodies involved in the industry, it is not unreasonable to suggest that in 2010, the global textile market was worth around 100 billion USD. It is likely that a high percentage of textile manufacturers are not taking advantage of nano, as much clothing is being produced in time-honoured ways. If the penetration of nano is only 1 % for high end applications, this still represents a 1 billion USD market, possibly 1.5 billion USD by 2015, as nano becomes more accepted and desirable, offering product differentiation opportunities.

21.1.5 Nano for Security: Anti-Counterfeit Protection and Discouraging Thieves

In a study undertaken in 2010, and reported in The Enquirer,[7] US Congress decided it was almost impossible to quantify the cost of counterfeit goods to industry, and surprisingly, that the effect was not necessarily all bad, and in the long run counterfeit goods can benefit consumers, mostly because counterfeit products are cheaper than the alternatives.

Although Congress in the US may dismiss counterfeiting as not all 'bad', this is not how commercial companies, who have built up their brands embodying quality and value over possibly many decades, view it. Most companies with known brands will fight tooth and nail to protect their brand rights and their investment in product development and promotion. Counterfeiting can also be dangerous, as in an extreme situation where aeroplane parts are replaced by counterfeit ones that are not fit for purpose.

The latest developments in nano for brand security and packaging offer what is called "smart protection", where often invisible, nano-enabled taggants provide not only an authentication of products, but can also assist in identifying the provenance of stolen goods. This security technique depends on the fact that nanoparticles are invisible. Consequently, they can impart new, unseen properties.

Quantum dots, which are fluorescent nanoparticles, have a whole range of possible applications in this industry. 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 and non-destructively 'tagged'. Stolen goods can be traced by this invisible 'bar code'

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[7] The Inquirer (http://s.tt/14vqR).

Table 21.2 Nanotech in brand and product security

Nanoparticles for security printing (e.g. invisible bar codes)
Unique recognition systems
Paper-like electronic displays which can be used to display information on a given product (history of manufacture and transport)
Magnetic nanoparticle tagging
Nanoparticle chemical markers
Ambient atmosphere nanoparticulate indicators (anti-tamper)

and also illict drugs by the fact they possess no legal nano identification. In some countries, cheap agricultural fuel can be 'laced' with harmless nanoparticles, making it easy for police to identify a stolen consignment, merely by using ultraviolet light.

Some taggants contain unique magnetic 'fingerprints' and can be used on a wide range of articles, including pharmaceutical packaging, luxury goods (such as watches and handbags), and automotive and aviation spare parts. Other, invisible, nano scale identification tags can be added to products and, using special equipment, field testers can immediately spot the real from the fake. A number of nano-based products have already been introduced including intelligent inks and nanoparticle coatings for product security (Table 21.2).

To illustrate the importance of the problem. Nanotechnology has been a key priority in the Sixth EU framework programme for RTD (FP6, 2002–2006) and this remains the case in the Seventh Framework programme (FP7, 2007–2013), with a budget of € 3475 Million for the NMP programme. Key areas include security and the prevention of identity theft, counterfeiting, with especial resonance for the financial services industry, in relation to credit cards, personal identification techniques, authentication, forensics, quantum cryptography and the market for counterfeit and grey goods.

The Market for Nano in Brand and Product Security Applications. According to a 2009 Observatory Nano report,[8] the size of the global market for brand and product security applications is estimated at between 40 and 60 billion USD. Nanotech offers an innovative approach in this technologically advanced market, so even if penetration is only 10–15 % now, it is likely to rise to at least 20 % by 2015, representing a possible market size of 8–12 billion USD.

[8] http://www.observatorynano.eu/project/filesystem/files/Economics_Security_final.pdf

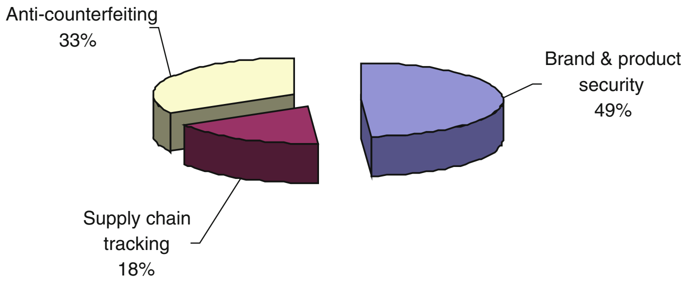

Fig. 21.4 Global brand and product security: nanotechnology implementation

21.1.6 Food for the Family: Nanotech in Food Processing, Improved Shelf Life, Flavour Enhancement, Vitamin Encapsulation and Fat Reduction

Working at the nanoscale is not new to food companies. The properties of all foods and beverages relate to their constituent components that are nanoscale in size. The manipulation of naturally occurring nanoparticles involved in the processing of dairy products, for example, has been undertaken for some time under the name of 'colloid science'. More recently, an improved understanding of techniques 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 perishable contents are spoiling, by changing colour.

Whether a product is a food, a drink, a pharmaceutical drug or a cosmetic, whether it is ingested or applied, so long as it enters the bloodstream, it will produce an effect on the human organism. The line between these different groups is hard to draw. It is interesting to note that while hospitals are focused on the treatment of patients using prescription drugs, very few consider that treatment may be possible by monitoring/selecting appropriate foodstuffs—although everything we ingest is a chemical to some degree or other, as it is made up of molecules that are absorbed in the body. In fact, treatment through a professional nutritional analysis is an area that has been almost entirely ignored until now, in preference to treatment by drugs which, because of their concentration of a single chemical, are often highly toxic.

Food companies themselves are increasingly aware of the medical component of their products, and the implementation of scientific knowledge in commercial foodstuff production could have much wider implications for the health of the population than is presently acknowledged. Table 21.3 below lists some of the applications of nanotechnology in foods, from production to ingestion.

It is only in relatively recent times that novel technologies have come under investigation as offering new functionalities and benefits as well as efficient delivery mechanisms for the food and beverage industries. For example, food researchers are gaining a greater understanding of the mechanisms of targeted delivery, with a view to optimizing the delivery of vitamins and minerals in food to benefit health; technologies related to the creation of novel physical, visual and sensory effects for competitive advantage.

The Market for Nano in the Processed Food, Beverage and Related Packaging Industries

There are many figures for the world market for processed foods. Whatever figure is used, the numbers are extraordinary. In 2005, this market was estimated at 3.2 trillion USD.[9] So for the world giants in food processing, the competition is cut throat, with everything to play for in terms of market share through increased food stability, shelf life, safety, and a better consumer experience. It is estimated that the market for alcoholic, soft and hot drinks is about 50 % of that for processed foods. So the total market, given an annual growth rate of 7.5 % can be estimated at around 7.5 trillion USD in 2010 and up to 10 trillion dollars in 2015.

If nano has a penetration of even 1 % in this market, and it may be more as the market is dominated by around 100 companies who can afford to (and need to!) adopt new technologies, then nano in the food and beverage industries could be worth at least 100 billion USD by 2015. Not an insignificant number by any means. Regarding smart, active packaging for the food and beverage industries, this has been estimated at 11.7 billion USD in 2011.[10] It is likely that nano will have an important impact in most of this market sector, because of its dependence on technology. Even estimating only a 20 % penetration, this represents over 2 billion USD now, and probably twice as much by 2015 as nano applications become increasingly important to the sector. So again, more large numbers for nano here.

Potential applications of nanotechnology includes nano-encapsulation of flavours or nutrients to suit consumer preference or health requirements; nanofilters that can remove toxins; food constituents that can be made to alter their colour; flavour modifications that can be created by using differently-'twisted' molecules (for example, the direction of chirality of a molecule may determine whether the flavour imparted is 'lemon' or 'orange'); packaging that can keep perishable contents fresher for longer, or detect when contents are spoiling and changing colour to warn consumers. In

[9] http://www.ers.usda.gov/AmberWaves/February05/Features/ProcessedFood.htm

[10] http://www.visiongain.com/Report/574/The-Active-Intelligent-and-Smart-Food-Drink-Packaging-Market-2011-2021

essence, the understanding of food materials and food processing at the nanoscale is increasingly recognized as vital in the creation of new and better food products, and also to minimizing waste from increasing shelf life and visual indicators of freshness. No more sell-by dates! (Table 21.3).

Table 21.3 Applications of nanoproducts in food related areas

Market sub sector	Nano applications
Food production	- Anti-bacterial food preparation surface coatings
	- Colloid stability improvements
Conservation	- Preservatives, antioxidants etc
	- Optimal environment emulation
	- Lifespan extension
	- Fridge food freshness maintenance
Packaging	- Anti-counterfeit (tracking systems, smart packaging)
	- Contamination prevention, freshness maintenance
	- Novel, brand-oriented packaging
	- Freshness/shelf life indicators
	- Speed check out enhancements
	- Improved flexibility, durability, temperature/ moisture stability, barrier, anti-microbial properties
Novel and 'Fashion' Foods	- Colour, scent, flavour, taste and texture enhancement
Health foods	- Supplement encapsulation (vitamins, minerals etc)
	- Enhanced bioavailability
	- Reduction in salts, fats and sugars
	- 'Delivery systems' (scents, flavours etc)
	- Sprays
Agriculture	- Soil remediation
	- Water purification
	- Pesticides
	- Nanosensors

Source International Nano Markets

Table 21.4 Areas where applications of nanotechnology for health foods are currently close to market or already available

Enhanced delivery of nutraceuticals and bioactive compounds in functional foods
Enhanced flavours, texture and delivery of bioactive functional ingredients
Enhanced solubility—the smaller the component particle, the more soluble
Controlled release for in-situ flavour and colour modification of products
Improved bioavailability of vitamins and minerals for medical and sporting applications
Protection of the stability of micronutrients and bioactive compounds during processing, storage and distribution
Encapsulation of fats and oils for reduced calorie products
Nano particulate salt for more flavour with less salt content

21.1.7 *Getting Around: Nano in Cars, Aeroplanes, Ships, Trains etc*

The automotive industry has appreciated for some time that nanotechnology can offer many benefits in this highly competitive and litigious sector. Research is taking place into applications of nanotechnology to improved safety systems from tyre blow out and brake failure warning systems to collision avoidance (Table 21.4).

Other nano benefits include improved lubricants, lighter and stronger materials for engine blocks, nanoporous filters, self-cleaning windshields, self-healing and scratch-resistant coatings, environmentally friendly corrosion protection and colour-changing paints. 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 (Table 21.5).

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 use altogether (Table 21.6).

The Market for Nano in the Automotive Sector.
According to Wikipedia (which cites the "2008 Global Market Data Book", Automotive News, p. 5), 71.9 million new cars were sold worldwide in 2007. This figure is probably quite similar in scale to today's sales, given the downturn, balanced by the increase in population. The sale of new trucks is about one third that of cars, making total industry sales of about 96 million new vehicles a year. The automotive sector has always been an early adopter of new technology for competitive and liability reasons. If the size of the automotive industry is estimated at a reasonable average value of 4500 USD per car, and the truck industry at twice that, namely 9000 USD per vehicle, then the value of the total industry (trucks and cars) is around 650 billion USD/yr. If the penetration of nano into automotive components is about 15 % by value, possibly more, then the worth of nano to that industry can be estimated today at about 100 billion USD, and by 2015, given a market penetration of at least 20 %, would be about 130–150 billion USD—the latter given some increased growth also in the sector value.

Table 21.5 Nanotechnologies in the food and beverage processing and related packaging industries

Organic nanoadditives
Inorganic nanoadditives
Addition of nanoparticles offering specific additional functionalities or novelty
Nanosensors for food quality control and smart packaging
Nanoparticles for toxin scrubbing and to slow down ripening
Nanocoatings and nanofilms for protecting kitchenware and foodstuffs against pathogenic bacteria
Packaging for ambient temperature maintenance
Nanosprays of bioluminescent indicators in antibacterial defence systems
Incorporation of nanosized ingredients and additives
Processing of food at the nanoscale
Nanoencapsulation of ingredients, additives and supplements (based on micelles and liposomes)
Manufactured mineral nanoparticles as additives and supplements
Incorporation of nano sunscreens and other modifications in food packaging

Table 21.6 Areas of application of nanotechnology in the automotive sector

Fuel cells
Power systems
Tyres
Heat transfer
Lighting and displays
Sensors
Coatings
Smart materials
Interiors
Structural and functional materials

21.1.8 When We Get Ill: Nanomedicine, High Speed Diagnostics, Drug Delivery and Medical Devices

In the past, medical treatments have been, rather like medieval architecture, the result of adopting those techniques that worked and discarding those that didn't. Today, our improving knowledge of how the body functions at the molecular, 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, but until now, early detection has been very difficult (Table 21.7).

Today we can introduce into the body specially designed nanoparticles, which are composed of tiny fluorescent quantum dots that are chemically bound to antibodies, which in turn 'bind' to diseased cells. 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 indeed.

Table 21.7 Applications of nanotechnology in the life sciences and healthcare sector

Market area	Nanomaterials application
Diagnostics	- Diagnostic imaging, with the use of targeted imaging agents that signal the site of disease
	- In-vivo monitoring of the body's physiology using a variety of nanotechnology-based probes and sensors
	- In-vitro diagnosis that is faster, more precise and informative, building hundreds of diagnostic tests into a single device
Drug delivery	- Nanoparticles for the delivery of minute doses of highly-active drugs, or of novel theranostic products to specific sites that can be tracked and activated by conventional radiological devices
	- Nanodevices that could be used to deliver substances or drugs to specific target areas in the body, e.g. oxygen to poorly vascularized tissues
	- New "smart" nanoengineered materials that can impart new levels of performance to "conventional" medical devices and drugs
Implants and medical supplies/devices	- Biocompatible nanostructured implant surfaces and coated stents
	- Easy-clean and self-cleaning nanocoatings and antibacterial surfaces
	- Better performing and cheaper to produce artificial retinas and cochlear implants that mimic more closely nature's light/sound receptor and transmission systems
	- Novel implantable devices allowing treatment of hitherto incurable degenerative or congenital diseases
	- Nanodevices for minimally invasive surgery
	- Design of surgical and diagnostic tools with cheaper manufacturing facilitated by nanotechnology and offering improved performance, e.g. ultra-sharp nano-diamond coated scalpels for microsurgery
Tissue engineering	- Biomimetic scaffolds as pattern for tissues and organ regeneration

Source International Nano Markets

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 at least. Ultra miniaturisation is enabling many tests to be speedily undertaken on 'lab-on-a-chip' devices, using tiny samples which 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, 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 the drug can now be achieved, using specially designed drug-carrying nanoparticles. This also means that much smaller quantities of a drug 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 also be monitored by imaging the location and movement of the specially designed nanoparticles, which usually have a fluorescent component.

The Market for Nano in Pharmaceutical Drugs

Most commentators seem to have a figure of around a trillion dollars for the value of pharma sales worldwide. IMS Health estimate 1.1 trillion USD sales by 2014; PRLog estimate a trillion USD sales by 2012. As the pipeline for new drugs has faltered over the last decade, balanced by new opportunities in targeted drug delivery, which offers reduces toxicity while improving outcomes, the importance of nano to the pharma industry has increased dramatically. Designer nanoparticles carry drugs and release them to the therapeutic target, and the benefit to drug companies from using innovative techniques with existing drugs is that no further expensive testing is required. Furthermore, protein-based drugs, which have hitherto been difficult to deliver, are now experiencing a huge resurgence of therapeutic interest as at the nanoscale their solubility properties change dramatically.

If nano only has 5 % penetration of the pharma market, this still means a market size of around 50 billion USD—and definitely growing.

The Market for Nano in Medical Devices

According to Espigen, the US market for medical devices (the largest in the world) is estimated at 105.8 billion USD in 2011, though CIMS, the Center for Integrated Manufacturing Studies placed it at 336 billion USD in 2008. The CIMS estimate includes: implantable devices (such as pacemakers, drug pumps, stents, and joint replacements); diagnostic testing devices, including clinical blood, urine, and tissue testing; and home healthcare products and electronic monitoring devices. Speculatively, if the rest of the world together equals the size of the US market, then the total size could be around 600–700 billion USD. Devices increasingly need to be smart, in some instances, vanishingly small and body friendly, so nano has an increasing role in new developments. Estimating a penetration today of nano in devices of about 10 %, probably rising to 15 % in 2015—within a fast growing market, driven by demographic trends of an increasing ageing and wealthy population, to about 1 trillion USD in 2015, gives a modest estimate of market size of about 100 billion USD for nano-enabled devices.

21.1.9 Nano for the Environment

Nanotechnology offers some really exciting breakthrough opportunities 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'**, 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 also want to hoard our assets in the form of gold and diamonds. 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 reaching an unsustainable 7 billion, the earth is showing clear 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 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 for people living in in poor quality housing or in the less developed world, where energy is hard or expensive to access.

Not only do we need new ways of generating energy, we need better ways of storing it, and 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, and nanotechnology is leading to their eradication through the development new nanocoatings and nano structured surfaces that can effectively repel dirt and other contaminants. Most coatings used to prevent corrosion are toxic and seriously affect the environment. Many anti-corrosion coatings involve chromium and cadmium, deadly substances, the use of which is being limited by the EU. Of course, vehicle and component producers are keen to find alternatives, as recycling of toxic compounds is costly and unpleasant, so 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.

There is a raft of potential applications enabled by nanotechnology, short and long-term, offering environmental benefits. Some of these are listed below, but it is a vast area.

- water purification and filtration;
- new materials offering 'more for less';
- more efficient use of material and energy and therefore reduced environmental impact;
- sensors for improved monitoring and detection capabilities;
- treatment and remediation techniques for cost-effective and specific site cleanup;
- green manufacturing to eliminate the generation of waste products;
- green energy technology for the creation of commercially viable clean energy sources;
- paints using less or water based solvent;
- more efficient fuel cells and batteries;
- fuel additives to improve fuel economy.

Nanotechnology offers opportunities in reducing and saving energy; some applications under investigation include:

- Thermoelectric nanomaterials that enable the generation of electricity from waste heat in consumer appliances, automobiles, and industrial processes;
- Higher efficiency photovoltaic cells using quantum dots connected by carbon nanotubes;
- Gases flowing over carbon nanotubes that have been shown to convert to an electrical current, a discovery with implications for novel distributed wind power;
- Multi-walled nanotubes that increase the performance of hydrogen fuel cells.

Advanced nanotechnology projects relating to energy are in storage and conversion, and in manufacturing improvements by reducing materials and process rates in energy saving e.g. by better thermal insulation, and in enhancing renewable energies sources. Specifically, this includes products such as batteries, manufacturing catalysts, fuel cells, solar cells, and strong lightweight materials.

Global Market for Nano in Environmental Applications
This is a huge market with several important sectors. Perhaps the largest is renewable energy generation, energy storage and energy saving.

Wind. The market for wind turbines is estimated to be 100 billion USD by 2013.[11] Nano composites have an increasingly important role to play in the development of stronger, tougher and lighterweight turbine blades. If the market penetration for nano composites is only 10 %, that is still a market of 10 billion USD.

Solar Energy. Recent figures[12] from the USA's leading solar trade group, the Solar Energy Industries Association (SEIA), show that in 2010, solar energy is America's fastest growing energy sector stock, growing in total market value by 67 % from 3.6 billion USD in 2009 to 6.0 billion USD in 2010, compared to the overall US GDP growth rate of only 3 percent. Nano has an increasing impact on solar energy collection. If penetration of nano in solar collectors is only 5 %, then that represents a market of about 0.3 billion USD in the United States alone, and around 0.75–1 billion USD worldwide, in a fast growing market.

Energy Storage. Energy storage technologies where nano is impacting include[13]: batteries, fuel cells (fuel cell development has increased in recent years due to an attempt to increase conversion efficiency of chemical energy stored in hydrocarbon or hydrogen fuels into electricity). Research is being conducted on harnessing the quantum effects of nanoscale capacitors to create digital quantum batteries. Although this technology is still in the experimental stage, it theoretically has the potential to provide dramatic increases in energy storage capacity.[14] According to a BCC Research 2009 report,[15] nano for environmental applications, including protection, maintenance, enhancement and remediation is predicted to be worth 21.8 billion USD by 2014.

21.1.10 Nanomaterials

Nanomaterials, and their associated manufacturing and processing technologies, are the key enablers of the nanotechnology industry, and encompass a wide range of materials. Nanoparticles serve as the "building blocks" for nanomaterials and devices. They include nanocrystalline materials such as ceramic, metal and metal

[11] http://windharvest.com/windmarket
[12] http://www.seia.org/cs/news_detail?pressrelease.id=1292
[13] http://en.wikipedia.org/wiki/Energy_storage
[14] http://www.technologyreview.com/computing/24265/?a=f
[15] http://www.bccresearch.com/report/nanotechnology-environmental-applications-nan039b.html

oxide nanoparticles; fullerenes, nanotubes and related structures. By virtue of their structure, nanomaterials exhibit different physical, chemical, electrical, and magnetic properties from conventional materials, which can be exploited for a variety of structural and non-structural applications. The following are the core nanomaterials offering the main market opportunities:

- Nanoparticles
- Nanocoatings
- Nanocomposites
- Carbon nanotubes
- Graphene
- Nanoporous materials
- Quantum dots
- Nanofibres
- Fullerenes
- Nanowires
- Nanocapsules.

There are many 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 grafitti, 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.

Novel nanocomposites have applications in many industries, including the aerospace and automotive industries. Carbon nanotubes are increasingly applied where toughness, electrical conductivity and flexibility are required, combined with light weight. Nanoporous materials have applications in purification techniques including blood and water and pure liquids for the electronics industries; quantum dots have applications in security, electrics and medical diagnostics; nanofibres have many applications in reinforcing; fullerenes have medical and other applications; nanowires for the electronics industries, and nanocapsules for the delivery of drugs, scents and flavours and the stabilisations of foods and perishable materials.

Scents and flavours are a surprisingly interesting and lucrative field for the application of nano encapsulation and delivery technologies. 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.

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 and separation of nanotube types, constraints in processing and scaling up and assembly methods are hurdles that are now being overcome. Already there are several consumer products containing nanotubes on the market, for example, in sports equipment including tennis racquets, golf clubs and skis, where nanotubes improve the strength of the equipment but at less weight and also the ability to absorb shocks. Carbon nanotubes can also be mixed with many different materials such as polymers and included in textiles for example in the production of lighterweight bullet-proof vests, and in several military applications.

Graphene is the new nanomaterial that is generating huge excitement. It is an allotrope of carbon that can be produced in thin sheets of only one atom in thickness. Applications include commercial, aerospace and military. As graphene is currently the 'material of the moment' some space is given to potential applications are currently being explored:

Composites with higher strength to weight ratios. By adding graphene to thermosetting and other polymer composites, a stronger/stiffer composite may be possible compared with a similar weight of carbon nanotubes, with applications in wind turbine blades or aircraft components, for example.

Transistors that operate at higher frequency. Electrons in graphene move at higher speed compared to electrons in silicon, offering the potential to build high frequency transistors. Researchers are also working on lithography techniques for fabricating integrated circuits based on graphene.

Lower cost of display screens in mobile devices. Graphene is capable of replacing indium-based electrodes in organic light emitting diodes (OLEDs). These diodes are used in electronic device display screens which require low power consumption. The use of graphene instead of indium not only reduces the cost but eliminates the use of metals in OLEDs, which may also make devices easier to recycle.

Storing hydrogen for fuel cell powered cars. It has been found that graphene layers in a fuel tank increase the binding energy of hydrogen to the graphene surface, resulting in a higher amount of hydrogen storage and therefore a lighter weight fuel tank. This could help in the development of hydrogen fueled cars.

Sensors to diagnose diseases. Graphene, strands of DNA, and fluorescent molecules can be combined to diagnose diseases. Graphene has a large surface area and molecules sensitive to particular diseases can attach to the carbon atoms in the graphene. When an identical single strand DNA combines with the strand on the graphene a double strand DNA is formed that floats off from the graphene, increasing the fluorescence level, thus detecting the same DNA for a particular disease in a sample.

Ultracapacitors with better performance than batteries. These ultracapacitiors store electrons on graphene sheets, as the large surface of graphene provides an increase in the electrical power that can be stored in the capacitor. It is possible that these ultracapacitors will have as much electrical storage capacity as lithium ion batteries, but can be recharged in minutes instead of hours

Global Market for Nanomaterials

Nanoparticles	Nanoparticles are available as dry powders or liquid dispersions. Important nanoparticulate materials are simple metal oxides, such as silica, alumina, titania, zinc oxide, iron oxide, ceria, and zirconia. Silica and iron oxide nanoparticles have been in the market for about a half-century or more. Nanocrystalline titania, zinc oxide, ceria, and other oxides have entered the market more recently. The nanoparticles market is an important one, worth around 1.6 billion USD in 2007, and predicted to rise to over 20.5 billion USD by 2015.[a] In the last few years, clay nanoparticles have made their way into composites in cars and packaging materials, and this makes up a significant percentage of the current market; however, new applications are coming onto the market. For example, casings for electronic devices such as computers containing nanoparticles also offer improved shielding against electromagnetic intrusion.[b]

[a]Nanomaterials. Applications and Markets to 2015. International Nano Markets

[b]Nanomaterials, Applications and Markets to 2015. International Nano Markets

Nanocoatings	Nanocoatings such as thin films and engineered surfaces have been developed and applied across a wide range of industries for decades. The ability of controlling surface coatings at the nanoscale is of paramount importance for a large-scale industrial development of nanotechnology. Highly sophisticated surface-related properties, such as optical, magnetic, electronic and catalytic can be obtained via nanostructured coatings. For example, in the silicon-integrated circuit industry many devices rely on thin films for their operation, and control of film thicknesses approaching the atomic level is routine. Other applications on the market are "self-cleaning" coatings and optical-functional surfaces for facades, vehicles, solar cells etc. (e.g. for anti-reflective surfaces, sunshade glazing, anti-reflective coatings for instrument panels). At present, many physical and chemical methods are available for the nanofabrication of layers and coatings with nanometric control of the structural and functional features; however, the scale-up of these methods remains a major challenge. "One way" coating systems based on nanomaterials make up the bulk of this market, for example in anti-bacterial; protective and conductive coatings. However under development are "two way" systems such as shape-memory materials, hydrophobic/hydrophilic switching and thermochromic pigmented coatings that will come onto the market in the next 4–5 years. The fastest growing markets to 2015 is expected to be in interior and exterior household protection, textiles and medical markets, driven by the increased demands for protective and repellent coatings. Conductive carbon nanotube coatings are also finding market traction in the electronics and automotive sectors and this will continue to be a strong growth area. Continuing to hold the biggest market share will be military applications such as anti-corrosion coatings which also find application in the gas and oil markets. According to new study[c], global consumption of paints and coatings in 2012 is projected to be worth 120 billion USD. If a modest 10% of this market can be ascribed to nano-influenced coatings, then that market alone in 2012 is worth 6 billion USD. Given a year-on-year increase in market share of 15%, then the market for nanopaints and coatings in 2015 can be estimated at around 10 billion USD. It is likely that including other nano coatings could increase this market estimate by at least 50%.
Nanocomposites	The nanocomposites market was worth around 437 million USD in 2007, increasing to approximately 2 billion USD by 2010, and 7 billion USD by 2015. Applications in automotive, aerospace, packaging (food and drink), electronics and consumer goods is expected to account for the largest percentage of revenue by 2015

[c] Global Paint & Coatings, 2013–2018, Kusumgar, Nerlfi, & Growney

Nanoporous materials	Nanoporous materials possess unique surface, structural, and bulk properties that underline their important uses in various fields such as ion exchange, separation, catalysis, sensor, biological molecular isolation and purifications. Nanoporous materials are also of scientific and technological importance because of their vast ability to adsorb and interact with atoms, ions and molecules on their large interior surfaces and in the nanometer sized pore space. They offer new opportunities in areas of inclusion chemistry, guest-host synthesis and molecular manipulations and reaction in the nanoscale for making nanoparticles, nanowires and other quantum nanostructures.[d] According to a 2009 report[e] published by GIA, Global Market for Nanoporous/Microporous Materials Expect to Reach 3.75 billion USD by 2015
Quantum dots	The global market for quantum dots, which in 2010 was estimated to generate 67 million USD in revenues, is projected to grow over the next 5 years at a compound annual growth rate (CAGR) of 58.3 %, reaching almost 670 million USD by 2015, representing a tenfold increase.[f]
Nanofibres	Nanofibres have a variety of applications, in the electronics, energy, medical and aerospace sectors. Several types of nanofibres have been developed: polymeric, carbon, ceramic, glass, metallic and composite. Nanofibres are being developed for conductive and reinforcement applications in composites. The main revenue generating application in 2007 for nanofibres was in filtration and separation media. The nanofibres sector is expected to grow from 10.4 million USD in 2007 to 1193 million USD in 2015. The fastest growing sector is expected to be in ITC, increasing from 7 million USD in 2007 to 480 million USD by 2015. Inorganic nanowire light-emitting diodes (LEDs) have held promise as inexpensive and tiny light sources, but fabrication has been challenging. Nanofibre technology has been shown to enable on-chip light sources smaller and cheaper than LEDs, and easier to fabricate.[g] Thermoplastics play a vital role in protecting electronic devices from electromagnetic interference (EMI) and a variety of additives can be used to provide this protection, with carbon nanofibres the most promising application area. The energy sector will also benefit from carbon nanofibres growing from 7 million USD in 2007 to 480 million USD in 2015. Lithium-ion batteries incorporating nanofibres will come onto the market in the next 2–3 years. Carbon filaments are covered with platinum nanoparticles and can be made into nonwoven fabrics and used as electrode layers in a hydrogen fuel cell. The platinum acts as a catalyst, separating electrons from hydrogen atoms so they can be discharged as electricity. The carbon nanofibres transport the electrons out of the fuel cell with their large surface area of the nanofibres providing a base for the chemical reaction to occur. Also under development are thin film nanofibre sensors that can be made of polyaniline nanofibres having superior performance in both sensitivity and time response to a variety of gas vapours including, acids, bases, redox active vapors, alcohols and volatile organic chemicals.

[d] http://www.icpress.co.uk/etextbook/p181/p181_chap1.pdf
[e] http://www.strategyr.com/Nanoporous_Microporous_Materials_Market_Report.asp
[f] http://bccresearch.blogspot.com/2011/06/global-market-for-quantum-dots-to-grow.html
[g] **NANO OPTICS: Electrospun light-emitting nanofibers could replace LEDs,** http://www.laserfocusworld.com/display_article/311576/12/ARTCL/none/News/NANO-OPTICS:-Electrospun-light-emitting-nanofibers-could-replace-LED

Fullerenes	A fullerene is any molecule composed entirely of carbon, in the form of a hollow sphere, ellipsoid or tube. The fullerenes market is worth around 58.5 million USD in 2007. The energy sector is the most prominent with fullerenes used in fuel cells, solar cells and batteries. This market is expected to grow, with significant growth also expected in the ITC and automotive sectors, reaching approx. 1.8 billion USD by 2015
Nanowires	Nanowires are ultrafine wires or linear arrays of dots, formed by self-assembly, which can be manufactured from a wide range of materials. Semiconductor nanowires made of silicon, gallium nitride and indium phosphides have demonstrated remarkable optical, electronic and magnetic characteristics. For example, silica nanowires can bend light around very tight corners. The market for nanowires is worth approximately 34 million USD in 2007. The main market is in ITC, and this will continue to be the case with an estimated market worth 1.227 billion USD in 2015. Nanowires are finding application in electronic devices (including field-effect transistors, sensors, detectors. light-emitting diodes, and for metallic interconnects of quantum devices and nanodevices, allowing replacement of copper in computers and electronics); high-density data storage (as magnetic read heads or patterned storage media); and superconducting wires that can make electrical generators lighter and more efficient. Other applications are as bio and chemical sensors. Nanowires comprised of '1-dimensional' semiconducting materials have the greatest potential as biosensors because they can easily be incorporated into electronic circuits that allow continuous readout. Nanowires can be 'functionalized' to detect virtually any form of bi-molecular interaction that involves proteins (including antibodies, receptors and enzymes) or nucleic acids.[h]
Nanocapsules	The nanocapsules market is worth around 32 million USD in 2007. Applications in healthcare especially in the area of drug delivery, cosmetics and homecare are expected to account for the largest percentage of revenue by 2015, which is predicted to reach over 1.4 billion USD by then
Carbon nanotubes	The market for carbon nanotubes was approximately 168.5 million USD in 2008. The ITC market is likely to see the biggest penetration to 2015, with the performance enhancing properties allowing electronics manufacturers to meet demanding market needs. The incorporation of CNTs into the displays market will increase demand by 2010, with a revenue forecast in the ITC market of 1.1 billion USD approx. by 2015. While in the longer run, electronics will continue to dominate nanotube applications as broader use in semiconductors occurs, strong opportunities are also expected in CNT-based products.[i]
Graphene	According to a new technical market research report by BCC, the global market value for graphene-based products will be worth an estimated 67 million USD in 2015 and is expected to increase to 675.1 million USD in 2020, for a five-year compound annual growth rate (CAGR) of 58.7 %.[j]

[h] Nanomaterials. Applications and Markets 2008-2015. International Nano Markets

[i] Global Market for Carbon Nanotubes, International Nano Markets

[j] http://www.electronics.ca/publications/products/Graphene%3A-Technologies%2C-Applications%2C-and-Markets.html

21.1.11 Finally, What are the 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 of new nanomaterials 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.