OPPORTUNITIES FOR INDUSTRY IN THE APPLICATION OF NANOTECHNOLOGY

Ottilia Saxl - The Institute of Nanotechnology

Foreword

As a member both of the Foresight Materials panel with special responsibility for nanotechnology, and a Board member of the Institute of Nanotechnology, I welcome this new publication which aims to give a flavour of how nanotechnology will affect industry in the foreseeable future.

It is doubly welcome in the light of the fact that the term 'nanotechnology' was notably absent from earlier Foresight exercises, although its importance is implicit in the creation of many of the new technologies identified by Foresight as being crucial to UK industry in the next 10-20 years.

Even armed with the knowledge that we are entering the nanotechnology era may not prepare us completely for the imminent cascade of 'disruptive' technologies that will forever alter the way industry works, and how new products will be made.

If investment in nanotechnology in America, Japan and Europe as stated at the end of this report is a yardstick of potential, it is reasonable to accept that nanotechnology will be of major importance to all industrial nations in the near future. There are great opportunities here for the UK. Our forte is innovation; our best asset our Universities. Nanotechnology offers us the chance to build a solid economy, that offers quality employment if we focus on the development of UK-owned business, focussing on high added value niche market products.

Some major questions that need to be answered now, in order that the UK can respond to this imminent challenge effectively and quickly are:

- *Where should UK money be invested?*
- *Which technologies, industries and academic research should the UK support?*
- *Is there a benefit in a new Institute devoted to nanotechnology?*
- *What would a network of infrastructure providers look like?*
- *Would it comprise instrument manufacturers, clean room designers, training providers?*
- *Should there be a radical rethink of the compartmentalisation of scientific teaching and research?*

and finally

- *Can we afford to ignore this opportunity?*

Professor Graham J Davies, General Manager, Technology Acquisition, BT Group Technology

'Imagine a technology so powerful that it will allow such feats as desktop manufacturing, cellular repair, artificial intelligence, inexpensive space travel, clean and abundant energy, and environmental restoration; a technology so portable that everyone can reap its benefits; a technology so fundamental that it will radically change our economic and political systems; a technology so imminent that most of us will see its impact within our lifetimes. Such is the promise of Nanotechnology'.
Kai Wu

1. Background Introduction

Nanotechnology has not quite reached the full extent of the vision of Dr Wu, though we are already experiencing its effects, particularly in applications resulting from nanoelectronics and semiconductor technologies. The present trend towards miniaturisation - the competitive quest for ever smaller machines and components that use less resources (e.g. energy, materials) - while offering the potential for the cheap mass-production of increasingly complex goods is rapidly pushing industry into the nanometre realms.

The coming era of nanotechnology is being made possible by the remarkable convergence of many technological advances in this decade that include

- hugely powerful computers that allow the design of new materials and the simulation of their properties
- a new generation of microscopes that can provide images at the nanometre scale, as well as measure and manipulate atoms and molecules
- the advent of virtual reality that enables us to visit and experience the wonders of this new and hitherto unimaginable nanoworld

As the work of scientists tends increasingly towards the size domains of molecules and atoms, the very nature of matter is increasingly close to being controlled and manipulated. The possibilities this opens up are endless: from the production of new, lighter and stronger materials which have applications in areas as diverse as space travel to bone implants, to the creation of therapeutic drugs with individual-specific properties.

The aim of this publication is to highlight the potential applications of nanotechnology to industry, and discuss how the challenges of this new industrial revolution can be successfully met.

Nanotechnology - What is it?

Nanotechnology can best be considered as a 'catch-all' description of activities at an almost vanishingly small scale that have applications in the real world. A nanometre is a billionth of a metre, that is, about 1/80,000 of the diameter of a human hair, or 10 times the diameter of a hydrogen atom.

An early promoter of the industrial applications of nanotechnology in the UK, Professor Albert Franks, defined it as 'that area of science and technology where dimensions and tolerances in the range of 0.1nm to 100 nm play a critical role'. This definition neatly allows for both the 'bottom up' and 'top down' approaches* to nanotechnology (see below). It encompasses precision engineering as well as electronics, electromechanical systems (such as the development of 'lab-on-a-chip' devices) and mainstream biomedical research and development in areas as diverse as gene therapy, drug delivery and novel drug discovery techniques.

** 'Top-down' refers to the fabrication of nanoscale structures by machining and etching techniques, whereas 'bottom-up', often referred to as molecular nanotechnology, applies to the creation of organic and inorganic structures, atom-by-atom, or molecule-by-molecule. 'Top-down' or 'bottom-up' can be a measure of the level of advancement of nanotechnology, and nanotechnology, as applied today, is still in the main at the 'top-down' stage.*

Why nanotechnology is important

The role of nanotechnology as a major driver of technological change and its consequent importance in the shaping of world economies in the next millennium is undisputed, as evidenced by the commitment to nanoscale research by the US and Japan (see Appendix 2 - Nanotechnology Funding). It is crucial that the UK also identifies those technologies that may offer the most economic benefits.

A recent survey (Nexus, 1998) has demonstrated that the market for microengineered products is greatest in electronics and biomedicine. These conclusions can in very general terms be extrapolated to nanotechnology. The UK is not an owner of electronics or semiconductor technology in the main, but tremendous opportunities exist in integrating these technologies into systems or components in high added value niche market products for biomedical and related applications. These applications include medical and environmental sensors, diagnostic and analytical devices, and range of equipment for minimally invasive surgery. There may be also be some potential for low cost, high volume applications in these areas.

2. Key Manufacturing Infrastructure Requirements

Infrastructure Requirements

A wide range of production capabilities, training and facilities are required as part of the creation of an infrastructure that will nurture nanotechnology and provide the basis for industrial development. For example, mathematics, computer modelling and simulation skills will be essential as well as an understanding of tools and standards. Frontier research requires advanced instrumentation to be available across the board; from the level of individual laboratories to national facilities. There is also a need for research on state-of-the-art instruments and their deployment

Key issues are:

1. *the production of, or access to specialist materials ii)*
2. *the adoption of advanced manufacturing processes*
3. *access to specialist tools needed for manufacturing, test, assembly and inspection*
4. *the installation of ultra-clean manufacturing facilities*
5. *the provision of adequate training facilities for the development of skilled manpower*

It is worth noting that business opportunities will exist at all stages of development of the new technology, including the provision of the basic requirements.

Materials for the Nanoindustrial Revolution

Materials science and technology is fundamental to the majority of the applications of nanotechnology. 'Raw' materials such as semiconductors, oxides and specialist organic and inorganic chemicals, will need to meet new specifications and parameters. For example.

Nanoparticles: Controlled production of particles in the 1 - 100 nm size range is crucial, and handling of these fine particles will be a key issue.

Quantum structures: Material purity is of the highest importance here, and research into production methodology is required.

Multilayer thin films: These require clean deposition equipment and environment (impurities and defects will ruin the properties of the films) with fast turn-around and high throughput.. Also, very high purity materials will be needed for sputtering and evaporation sources.

Nanomechanical devices: The physical integrity of the material used to produce the devices will be of key importance, given the strains and stresses to which it will be subject.

Nanoprobe materials: These are the materials required for the manufacture of tips for scanning probe microscopes, the basic tools of nanotechnology. These need to be chemically inert, physically stable materials capable of being fashioned reproducibly into atomic sharp tips.

Biosensors and transducers: The capability of synthesising ultra high purity specialist organic chemicals having a range of terminating groups for these applications is required, as well as ways of bonding these molecules reproducibly to the surfaces of semiconductors and oxide materials

Advanced Manufacturing Processes:

Manufacturing processes at the nanoscale can involve accretion or removal of material, or changes to the shape or form of material already present. Each of these processes provides new challenges and opportunities, as follows
Accretion of powders: New generations of processing equipment will be needed to deal with nanopowders in the manufacture of nanocrystalline materials.
Quantum structures and devices: The problem of producing devices with critical dimensions below 100nm, using 'top-down' techniques, is one that the electronics industry is currently wrestling with. Currently, commercial lithography is based on optical methods, but the wavelengths of visible and near ultraviolet light are too long to be usable on the nanometre scale. A range of alternatives is available, but parallel rather than serial writing techniques are needed for scale-up to commercial manufacturing levels, though this may not be a realistic goal for European companies.
Deposition: Recent breakthroughs in the UK are making deposition on selected areas possible, in high transmission mode. Until now, this has been achieved only through focused ion beam sources operated in droplet mode - an approach which is restrictive in terms of the range of materials that can be handled.
Cutting, milling: Only focused ion beam (FIB) techniques provide a means for selective cutting or removal of material with sub-100nm accuracy. Although these techniques were largely pioneered in Europe - and the UK in particular - the present suppliers of such equipment are almost exclusively American or Japanese companies.

Machine Tools and Instrumentation for Manufacture, Assembly, Test and Inspection

As structures become ever smaller, the necessity for on-line quality assurance test systems for certification duties, becomes more important and demanding. In the future, the nanometre scale will be the precision standard for material analysis, control purposes and also for material treatment. Already nano-analytical methods are used routinely for testing in the manufacture of:

- Magnetic storage disks
- Electronic multilayer systems
- Industrial polishing processes

New magnetoresistive multilayer systems offer drastically better positioning and controlling properties of sensors for application in the automotive industry and as measuring systems for velocity, strain or work piece positioning
Key areas of instrumentation and characterisation include

- Scanning probe techniques: observation + operation
- Some aspects of electron microscopy
- Some aspects of surface analysis
- Field emission + field ion microscopy + atomic probe analysis
- Nanomanipulators
- using principles of mechanical / optical / electric / magnetic / piezo techniques
- Test, calibration and measurement: Standards, benchmarks, procedures
- Nanotools, nanomotors, nanomachines
- Nanoprobes: production, characterisation, multiprobes
- Equipment to characterise magnetic / optical / electrical / mechanical properties of nanostructures with high spatial resolution
- Microfluidics
- Focussed ion beam technology
- Computer software for data analysis and representation, simulation, modelling

An essential stage in the development of a large scale nanotechnology industry is the creation of machine tools for the production of nanodevices, and test, measurement and inspection techniques to aid manufacturers and provide quality control of nano products. It is also an area where knowledge has been, and continues to be transferred from research institutions to industry. It is the first nano area to become economically active, including the creation on numerous small and medium-sized companies.
Machine tools for nanotechnology are already being developed in Japan, the USA and (to a limited extent) in the UK. Not only is it already an economically viable aspect of nanotechnology, but its strategic significance is very high. These machines will have to underpin all future production of nanodevices, and it is very important that the UK should play a key role in their development.

Ultra-clean manufacturing facilities

Some aspects of nanoscale manufacturing may require clean room technology - either full scale facilities or 'table top' scale; but this will depend on the particular process or industry. Refer to S2C2 - the Scottish Society for Contamination Control - as the repository of all knowledge on the subject in an international context. email: S2C2@mech.gla.ac.uk

Training

Academic institutions and funding bodies in the UK are beginning to recognise the need for courses in nanotechnology; and new modular and full-time Masters courses are in the process of being developed by more than one institution - see http:// www.epsrc.ac.uk Consideration now needs to be given to the contents of undergraduate science courses, in the light of fundamental knowledge required for nanoscale science; as well as the current philosophy of single-discipline research projects for PhD students in this multidisciplinary era.
However, there is no truly multidisciplinary centre for nanotechnology R&D.
In summary, industry needs suitable production methods for low cost manufacture of a whole range of materials such as nanomaterials, nanoporous systems, corrosion inhibitors, polymers, molecular sieves, ceramics, light absorbers and emitters, magnetic nanomaterials, pigments, colloids and so on. For end products, like catalysts or adhesive layers, a competitive market position can only be maintained if the analytical equipment necessary for material characterisation on an atomic or molecular level is available. Also essential to the equation are people who are trained to understand the new production methods, tools, analytical and testing techniques.
Finally, as materials at the nanometre scale may have unpredictable effects on living matter, the possible toxic and other hazardous properties of various nanomaterials need careful and sensitive investigation.
If government accepts that there is a case for a national strategy in nanotechnology, in areas where the UK wishes to retain or gain and internationally competitive presence, it is essential that the infrastructure requirements are put in place now.

3. Sensors

Car airbags provide a good example of how the cost of technology is decreasing, while functionality is increasing. In the USA airbags were once a major target for thieves because the accelerometer trigger they contain is so expensive. They are now becoming too cheap to steal, as an accelerometer on a single chip can be built for the equivalent of about $2.50, that is not only cheaper but also 'smarter' and more reliable. Future systems will incorporate sensors manufactured using nanotechniques that are capable of identifying not only the presence of a passenger, but their weight and size as well, and making adjustments accordingly. Sensors presently utilise a range of technologies including MEMS (microelectromechanical systems), piezo-materials, micromachines and very large scale integration (VLSI) video:

- MEMS are created through machining, etching, cutting or milling to nanometre tolerances. In time, MEMS-based sensors will be overtaken for complexity, speed and cheapness of production by the thin film and self-assembly techniques discussed in Chapter 7. Whatever applies now to the marketability and complexity of sensors based on MEMS will be hugely extended by these nanotechniques.
- Piezo-electric materials are materials that develop an electrical charge when deformed and, conversely, deform when in the presence of an electrical field. Piezo-electrics are particularly useful as surface-mount sensors for measuring physical movement and stress in materials. Like MEMS, piezo-electric materials have been around for some time, but new research is leading to the creation of new classes of piezo-based "smart materials" - materials that both actively sense and respond to the surrounding environment.
- Micro-machines are created using semiconductor manufacturing techniques, but are more complex in design than MEMS, incorporating in some instances micrometre-scale gears and other moving parts machined to nanometre-scale precision. Micromachines exploit the often overlooked structural qualities of silicon: a low coefficient of thermal expansion, high thermal conductivity, a strength-to-weight ratio more favourable than aluminum, and an elasticity comparable to that of steel.

Applications of ultra small machine technology are manifold - in microfabricated sensor arrays and neural networks; microelectronic noses; medical diagnostic breathalysers, and microfabricated terahertz electronic circuits and waveguides for medical imaging.

- VLSI Video. Today, a video camera with all the attendant circuitry required to attach it to a computer costs approximately £6 a unit to produce. This cost is dropping dramatically as all the components - the charge-coupled device (CCD), the circuitry and even the lens can now be packaged on a single chip which can be translated into a myriad of applications, including surveillance, security, and games.

The combination of cheap video and laser-based web bandwidth is already delivering a hint of what the future will really hold. The world of video is not a world of people looking at each other via videoconferencing. Rather, it is a world of cameras aimed at everything everywhere, watched over by machines, and only occasionally examined by people.

Global Positioning System Sensors - Some Predictions

Global positioning system (GPS) sensors are being produced at lower and lower costs but with increasing performance. Systems once costing tens of thousands of £'s can now be bought in a handheld package for under £400. Nanotechnology means that in the not-too-distant future, integrated sensor / GPS modules will be small and inexpensive enough to integrate into packages in order to track the location and treatment of valuable goods they may contain. Laser technology is also rapidly changing gyroscopic technology as ring laser gyros (RLGs) displace traditional spinning-mass systems in aircraft, also delivering hugely increased performance and reliability at a lower cost. In the long run, it is likely that advanced MEMS accelerometer arrays will in turn displace RLG technology.

From Sensors to Effectors
The impact of sensors will not stop at mere sensing. Sensing devices will be required also to respond to what they 'see'. The sensor era will then become a sensor / effector era, where devices will not only observe the world around them, but will also be able to react to, manipulate and change what they 'see'.

Market Predictions
Some world market predictions for the sensor technologies described above, in the year 2002 compared with 1996 are as follows:

1996			2002	
	Units	Market	Units	Market
Anti Collision Sensors	0.01m	$0.5 million	2m	$20 million
Pressure Sensors	115m	$600 million	300m	$1.3 billion
Chemical Sensors	100m	$300 million	400m	$8 billion
Magnetoresistive Sensors	15m	$20 million	60m	$60 million

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Source: Nexus: MST Market study, 1996 - 2002
Predictions for an application such anti-collision sensing in the automotive industry show that a technology almost coming from nowhere can quickly generate large revenues as a result of offering high benefits for low cost, like many sensor technologies under development.

4. Virtual Reality

Virtual reality offers us the means of observing and understanding how things work and enable us to interact with this new and previously unimaginable domain inhabited by molecules and atoms.
The term Virtual Reality (VR) is applied to a collection of technologies which together form an interface between humans and computers which is more intuitive to use. Typically (but not exclusively) this is achieved by real-time interaction with three-dimensional computer generated imagery (CGI). In some cases, exploring

and interacting with the CGI requires the use of special peripheral devices to create a sense of 'presence' or 'immersion' within the virtual environment.

VR is a convergence of technologies from a much wider range of disciplines - human factors, telerobotics / telepresence, multimedia, computer-aided design (CAD), process simulation, ergonomics simulation (including mannequin tools) and computer-generated imagery (CGI - games, animation). One of the emerging strengths of VR is that it enables objects and their behaviour to be more accessible and understandable to the human user. This is particularly in cases where objects or processes exist in reality, but are not visible to the naked eye, as is the case with nanotechnology.

Using VR to visualise objects at micro-/ nano-scales is not a new idea. As long ago as 1992 VR was being used to visualise the output of a scanning tunnelling microscope (STM), effectively giving surface engineers the means to witness - and measure - atomic changes brought about by chemical and radioactive processes. The data produced by the STM are ideal for conversion into a VR model, which is typically made up of hundreds of individual polygons or facets. Instantaneous records from the location of a mechanical boom supporting the microscopes probe provide x and z coordinates of each surface point during the scan. Data relating to the y coordinates (surface relief) are obtained from tiny boom deflections, which occur as the system attempts to maintain a fixed current between the probe tip and the sample surface.

One company, Philips, has been evaluating Virtual Reality for some time, and late in 1996, the company used VR to 'miniaturise' employees so that they could experience the microscopic nature of the semiconductors they were employed to manufacture. This had been performed once before, using a miniature optical switching assembly. However, in the Philips example, the requirement was to miniaturise the users (virtually) to the level of the surface of the chip concerned. The demonstration starts when the VR user dons a head-mounted display equipped with a small electromagnetic tracking sensor which relays position and orientation information to the host computer, updating the images in the headset as the user's head turns. Once in the headset, the user finds herself in a simple office environment. The user is also provided with a handgrip, which is used to control her movements around the office. On a desk in front of the user is a printed circuit board, lying next to a PC.

As the VR user approaches the desk, she is shrunk to a height of around 1cm and is then free to move amongst the resistors, capacitors, microprocessors and the TrenchMOS semiconductors themselves. On approaching one of the semiconductors, the plastic cap automatically lifts off, exposing the TrenchMOS itself. The user is then shrunk again, this time to a height of around 1mm, and can move around the very reflective surface of the chip. The final shrinkage takes the user to a height of some 20-30 microns, and as the smooth aluminium substrate is removed, the regular hexagonal patterns of the chip surface are exposed, extending as far as the eye can see.

The implications of using VR for non-destructive testing and inspection of materials in the offshore, aerospace, electronics and medical industry are enormous, as is its use in assisting humans in the assembly of future micro-devices, such as motors, pumps and actuators. Add to this recent developments in the haptics interface arena (systems capable of providing the sense of touch and force using VR), and suddenly one begins to see the dawning of a new and exciting era in interface specifications for allowing micro- and nano-designers perform real design and assembly tasks.

5. Catalysis

Catalysis could arguably be the most important technology in our modern society since it enables the production of a wide range of materials and fuels. Catalysis is also fundamental to the control of polluting emissions from industry and cars. However, the full extent of the nature of the surface of nanoparticles used in catalysis is not completely understood; and when this happens, existing catalytic processes will be improved, and new processes designed and developed.

How catalysis works

Most of the catalysts used are known as 'heterogeneous catalysts', highly porous materials with a large surface area. Because catalytic reactions take place at the surface of the material, therefore the more surface there is, the better. Many of these catalysts consist of an active phase and a passive phase, the latter being made of a chemically and thermally stable material (such as alumina). This support, or passive phase, enables the active phase to exist as nanoparticles that are resistant to sintering. The size range for such nanoparticles is from the atomically dispersed through to micron size, though commonly they are in the range of 1-10 nm. Such materials have been in existence long before it was realised they belonged to the realms of nanotechnology!

Areas of Major Impact of Catalysis

Fuel Production: Catalysis is crucial to reforming oil distillates to the appropriate chemical mix for use in cars, trucks, planes etc., (all fuels have been through several catalytic plants in their production). High levels of sulphur in fuels are removed to very low levels in some countries (many more in the future) by catalytic desulphurisation.

- *Materials Production*: All polymers are produced using catalysis; some undergoing a large number of different processes (e.g. nylon requires more than 12 different large-scale catalytic processes).
- *Environmental Protection*: Catalysis is used in the clean-up of emissions from cars and industry, solving both atmospheric and aqueous pollution problems.
- *Health*: Many drugs and pharmaceuticals are produced using catalysis. It could be said that chemistry, not medicine, drives modern healthcare!
- *Agriculture*: Catalysis is used to produce fertilisers and crop protection chemicals.
- *Food:* There are many applications here - for instance all margarine has passed through a Ni/SiO2 catalyst to hydrogenate the double bonds on vegetable oil to give 'spreadability'.
- *Commodities:* A huge range of basic chemicals are produced from oil and gas, using catalysis. One example is ethylene oxide used for antifreeze and for washing powder additives.

Properties of Nanoparticulate Catalysts

It is known that a variety of phenomena affect the reactivity of nanoparticulate catalysts. Pinning down the nature of the active sites has proved to be very elusive and it is very rare to know even their surface morphology or how they work at the atomic level, partly because the techniques to enable such studies was not available. However, the advent of scanning probe microscopy (SPM) and other techniques is beginning to shed light on the nanoscale behaviour in this field. A full understanding of the forces at work will enable better and more effective catalysts to be designed.

The Future

1. Model Studies

Studies are concentrating on correlating the structure of nanoparticles with their reactivity. The Scanning Tunnelling Microscope (STM) will have a crucial role to play in unravelling this behaviour. The techniques of nanotechnology are also being applied to the fabrication of ordered arrays of nanoparticles, but so far these have mainly used electron beam lithography which is only capable of low resolution (producing large particles of ca.100nm). Nevertheless this provides an ideal route to study effects such as particle spacing and particle size on sintering and reactivity. Unisized clusters of smaller particles can be produced, but in a random arrangement. Methods to routinely produce ordered, unisized arrays of 1nm would be a huge advance in this field and could produce a stepchange in the technology.

2. Catalyst Fabrication.

One limitation on catalyst invention and application has been the slowness of individual catalyst preparation and reactivity characterisation. Moves are afoot to explore ways of enhancing this process by using the kinds of combinatorial methods that have been a success in organic synthesis. However, it is a complex process for heterogeneous catalysis, requiring novel methods for enhanced and rapid catalyst screening that will result in more rapid and selective catalyst invention / scale-up. New methods are slow to percolate to the actual manufacturing process which is presently conducted on a grand scale (a single plant often uses 50 tonnes of catalyst). Nevertheless, it is possible that nanotechnology will evolve methods for producing specialist materials. The pharmaceutical sector uses catalysis on a much smaller scale, producing high added value molecules, and here it is most likely that new methodology will make the greatest impact.

6. Coatings

Coating technology is now being strongly influenced by nanotechnology. Nano-scale materials, characterised by grain sizes of less than 100nm are being investigated, and significant advances are being made in the synthesis of high quality nanocrystalline powders, and several methods such as vapour condensation and solution precipitation have been scaled up for industrial use. Metallic stainless steel coatings sprayed using nano-crystalline powders have been shown to possess increased hardness when compared with conventional coatings, although the porosity is increased. Also, the reaction kinetics involving small scale particles during spraying are notably different. Novel tungsten carbide - cobalt coatings produced from nanostructured powders have also shown promising results in terms of bond strength, but to date little work has been conducted to assess their durability.

Nano-composite coatings comprising a ceramic/polymer mix have also been applied by High Velocity Oxy-Fuel (HVOF) spraying. These nanoparticle reinforced polymer composites have advantages in applications where the polymer strength is less important than the ductility of the coating. The HVOF process has also been shown to cause little polymer degradation. More studies are still required in this new area to improve the understanding of the interfacial properties at the polymer/ceramic junction, and how this affects the coating properties.

In addition to being able to apply coatings made from nano-phase powders, techniques themselves are being developed in which the processing parameters involved in the spraying actually produce the nano-crystalline structure. This has been experimentally achieved using a hypersonic plasma particle deposition (HPPD) process to apply SiC coatings. Coatings were successfully applied and the properties showed great promise.

7. Chemistry

'Self Assembly and Self Organisation'

What follows is a discussion of self-assembly in organic molecules, but it is worth mentioning briefly an inorganic example of self assembly - the Stranski-Krastonov method for growing of self assembly quantum dots (SAQD) which has rendered the lithographic approach to semiconductor quantum dot fabrication virtually obsolete. This method has been the catalyst of intense research, and UK groups are already working to develop SAQD lasers.

The study of the self-assembling nature of molecules, enabled by the tools of nanotechnology, is proving to be the foundation of an enormous explosion of applications in science and technology. The combination of being able to define structures on a 10 nm scale, produce nanoparticles with almost any desired radius, use new microscope technology and derived measurement techniques to 'see' surfaces and structures on a 0.1 nm length scale and also manipulate these structures, allows us to observe and harness new material properties that are a consequence of this self-assembly property

The physical properties of matter are highly size dependent. Given that for spherical particles in the nanometre range, the electronic energy level of separation is proportional to the square of the inverse radius of the particle, it is obvious that nanoparticles will exhibit many new and exciting phenomena that can be used in new applications.

In materials that in bulk form exhibit phase transitions phenomena associated with size will have major implications. The phase transition properties of, for example magnetic, superconductive and ferroelectric nanocomposites can be designed in such a way that devices can be created that operate just below those threshold fields or temperatures or currents required to switch the system from the collectively ordered into the disordered state. In this way, small perturbations can be made to give rise to large responses; and this feature can be incorporated in new types of detectors and sensors.

The behaviour of a small quantity of self-assembling molecules is strongly influenced by the way they are attached to a surface. Surface forces predominate in small or ultra thin assemblies, and in practice this means that the behavior of nano-assemblies can be more readily manipulated by the choice of surfaces.

It is even possible to envisage the possibility of programming self-assembling systems! A particular type of ordering may for example only be achieved if the system is subjected to a specific sequence of external signals and stresses. At present, any 'information' generated, in the form of a local change in structure, can be stored in organic and inorganic glasses, including self-assembling polymers, or by burning an electronic 'hole' in a molecule, using specific light signals. To create more advanced memories, it may be possible to harness the versatile organisational properties of small quantities of self-assembling molecular systems. Charged and dipole-carrying self-assembling systems have been shown to have a very large number of distinct configurations, some of which can only be achieved by specific and deliberate triggers. These can be manipulated to store, and perhaps later process intelligent information.

New materials

It is also possible to make new types of nanocomposites or organic/inorganic hybrid structures by depositing or attaching organic molecules to ultra-small particles or ultra-thin man made layered structures (superlattices). There are many applications for these new materials in different products and processes, some of which are described below:

Application	***Improvements using new attached molecules***
Colloids	New structural, optical and thermodynamic properties.
Pigments	Better thermal stability without loss of absorption characteristics.
Dispersions	Nanoparticle size, and molecular structures can be tailored.
Emulsions	Engineering of viscosity and particle size.
Anti corrosion Coatings	Improved surface mechanical properties and stability in air.
Ferrofluids	Creation of 'fluid magnets', which can be externally manipulated using a magnetic field. As a consequence, the magnetic fluid can also be made to exhibit different rheological properties and structure.
Magnetic particles	Below a critical size, magnetic particles are superparamagnetic and the collective magnetic response is fluid. Superparamagnets adjust to weak external magnetic forces.
Passivated magnetic particles	Magnetic particles can be covered with insulators or molecular overlayers, and the surface made resistant to oxidation or insulated to electrical conduction.
Ceramic processing technology	'Customised' ceramics for one-off applications; particularly using stabilised zirconia
Nano-emulsion	Nanoparticle size and composition selected to produce required viscosity and absorption characteristics
Lubricants	Tailored viscosity and thermal expansion properties.
Drug delivery systems:	Nanoparticles can determine the chemical reactivity rate, the location and the timing of drug delivery.
Bio-receptors fo energy transfer	Nanocomposites can be designed to exhibit well defined singlet or triplet excitonic absorption spectra. These localised bundles of light energy can be transferred over long distances to a 'receptor' and used for example for photochemistry or charge generation (the photoelectric cell).
Cosmetics	The addition of nanoparticles can influence the flow characteristics and mechanical properties of cosmetics, as well as the absorption of harmful radiation.
UV protection gels	Same as above.
Sol-gel technology	In the design of different types of materials.

Finally, nanoparticles can be alloyed to engineer surface bonding properties, and used for the fabrication of sticking, non sticking or selectively sticking surfaces.

New Devices
New depositional techniques offer a myriad of industrial applications, from the

production of new chemical and gas sensors, optical sensors, solar panels and other energy conversion devices to bio-implants and in-vivo monitoring.
The basis of these techniques is an organic film (the responsive layer) which can be deposited on a hard, active electronic chip substrate. The solid state chip receives signals from the organic overlayer as it reacts to changes in its environment, and processes them. The innovatory techniques involved are

- making of the hybrid interface
- addressing the organic film from below (i.e. from the substrate side) using state-of-the-art superlattice and nano-engineering technology.

Some applications are as follows:

- Molecular films can be combined with optical waveguides and resonators to make evanescent field sensing devices with applications to biosensing and optical switching devices
- Molecules and bio molecules can be used to absorb and transfer photonic energy to chemical energy; with applications for solar energy conversion and photochemistry
- Surfaces of liquid crystals or thin membranes and other organic compounds can be used to detect molecules via structural, dielectric or conductive changes, with applications in gas and chemical sensing
- Semiconducting (or metallic) circuits and tunnel devices can be fabricated incorporating organic or biological materials with applications for imaging biomolecules and molecular motion, chemical reactions, growth, local temperature fluctuations and environmental changes.

Also, using these depositional techniques, new biocompatible materials can be designed for use in teeth or bone replacement.

8. Nanometrology

Fundamental to commercial nanotechnology is repeatability, and fundamental to repeatability is measurement. Many of the processes and production procedures envisaged in nanotechnology take place at the atomic level. In order to achieve adequate control of the movement of systems that might be used in such processes, for example for atomic manipulation, dimensions need to be known at the atomic level and beyond.
Moreover, a knowledge of the perfection of the texture at the nanometre and sub-nanometre level is an essential requirement if highly specialised applications of nanotechnology are to operate correctly, for example x-ray optical components and mirrors used in laser gyroscopes. Thus dimensional metrology plays a key role in the success and efficient implementation of many developments in nanotechnology. Ultimately all the measurements of length must be referred back to the national standards of length which are held at the National Physical Laboratory in Teddington.
How can the accuracy of position, size and displacement be achieved at the atomic level? There are basically two methods:
First, by using a laser interferometer as an ultra-sensitive displacement transducer and sub-dividing the fringes to an extremely fine level. In this way displacements of the order of fractions of a nanometre can be measured which can be traced to the national standard of length. However, one problem with laser interferometer-based systems is that the components of the interferometer are not completely perfect and do introduce small uncertainties in the way the optical fringes are sub-divided. Nevertheless, such interferometers can be used for measuring over an extremely wide range (from nanometres to several metres) and are therefore extremely valuable measuring tools.

The problem in the uncertainties of sub-division of optical fringes can be overcome by using an interferometer using x-rays. Using the diffractive properties of x-rays in the silicon crystal an interferometer can be constructed that has a fringe spacing of about 0.3 nm. Because much work has been undertaken to determine the lattice spacing in silicon with exceptional accuracy, this method provides a very powerful method for measuring ultra-small displacements. But such interferometers can only perform measurements very slowly.
At NPL the two types of interferometer are combined to take advantage of the extreme resolution of the x-ray system which is coupled to the range of an optical interferometer. For measurements up to 10 micrometres the measurement uncertainty of the instrument is less than 40 picometres

In order to meet the requirements of visualising surfaces at the atomic level a wide range of probes (scanning tunnelling microscopes and atomic force microscopes being the best known examples) are capable of revealing the positions of atoms. Whilst, such probes can generate very impressive pictures of atoms on a surface, however, it is only relatively recently that such probing systems have been able to be used for measurement. By fitting laser interferometers to the microscope the tip of the microscope can be tracked accurately in space. NPL has a system which can measure components, mostly surface texture reference standards, to an accuracy in the order of nanometres.

9. Nanoelectronics

Nanoelectronics and UK Industry

In the following discussion of the future of nanoelectronics, it needs to be borne in mind that the UK is a relatively small player in an electronics world dominated by American, Japanese and some European companies. It is not a player at all in the semiconductor, computer and software industries. UK companies are users of semiconductor and electronic technology, and although some research organisations may see themselves as innovators, exploitation of the technology is so capital intensive that most ideas can only be taken into production by existing large companies.

Nanoelectronics - Present and Future

Since the transistor was invented some 50 years ago, the trend in electronics has been to create smaller and smaller products using fewer chips of greater complexity and smaller 'feature' sizes. The development of integrated circuits and storage devices have continued to progress at an exponential rate; at present it takes two or three years for each successive halving of component size.
However, the technologies used for data processing and storage have fundamental limits below which the devices no longer function in a predictable manner. For instance, oxide layers used in Complimentary Metal Oxide Semiconductors (CMOS) devices are becoming so thin that leakage currents are conducted quantum mechanically by electron tunnelling. According to recent estimates, microelectronics and magnetic storage technologies only have another 10 to 12 more years to go before reaching their ultimate limits. Using present microelectronic technology, it is predicted that by the year 2005 a chip will contain 190 million transistors and have feature sizes of 100nm with a clock speed of up to 3.5 GHz.
The lithographically defined dimensions of commercial semiconductor devices are already close to the 100 nm range, with minimum layer thicknesses in the 10nm

range, and a replacement technology to advance miniaturisation even further down, eventually to the dimensions of single atoms and molecules, is keenly sought.
We have now reached a stage where totally new approaches to nanoelectronics are in evidence, such as DNA computing (proposed in 1994 and now becoming a reality), and quantum computing where a universal computer could operate using quantum mechanical effects. Both of these novel concepts also rely on being able to control of the properties of individual atoms or molecules.
In the US between 1988 and 1994, $45 billion alone was spent by the semiconductor industry on microelectronics research. Nanoelectronics, based on quantum effects, is foreseen as the successor to microelectronics, and is already involving even larger sums. It is expected that the first applications will probably be in the military sector, with the transition from microelectronics to nanoelectronics ultimately being determined purely by economic factors.
A major barrier to the introduction of nanoelectronics, is that there are no established mass production techniques for creating devices on a commercial basis. Whereas the transistor is a basic building block for microelectronic devices, it is not clear what the basic (three-terminal) element of a nanoelectronic device will be. Likewise, a well-defined architecture required to process data has yet to be established.
The evolution of electronics is interesting in that it has been characterised by a series of fundamental paradigm changes 'disruptive technologies'. For instance, the mechanical relay was replaced by the vacuum tube, which in turn was replaced by the transistor. The large mainframes of the past that used power greedy bipolar devices have been now been replaced by the CMOS devices used in home PC's. Nanoelectronics is currently not only looking for the successor to CMOS processing but to a replacement for the transistor device itself. The two possible routes to the future fabrication of nanoelectronic devices loosely termed 'top down' or 'bottom up' techniques referred to earlier.
The 'top down' approach is basically an extension of the established method of engineering and microelectronics processing, using controlled damage by photons, ions and even grinding techniques. This process is often described in terms of the deposition, patterning and etching of layers of material, with typically a planarisation step using chemical-mechanical polishing to create layers of wiring. There is a whole range of potential obstacles for this approach because, as the technologies are pushed to smaller sizes, the cost shoots up, the tolerances are more difficult to maintain.
To be scaleable to the atomic and molecular scale, softer methods with atomic tolerances will be eventually be essential.

10. The Automotive Industry

The automotive industry, although not specifically identified by Foresight as an industrial sector, is of interest insofar as UK companies are players in the components market. It is a major user of sensors and components for the new integrated miniaturised systems. To quote some interesting statistics from 'Materials Foresight on the Electronics Industry', published by the IoM and IEE in 1998:

- In 1986 there were some 12M electronic units in cars worldwide
- In 1995 that figure had increased to 100M units By 2000 it will have doubled to 200M units
- In 1995 the worldwide automotive electronics industry was worth $100BN and was growing faster than telecommunications

- A modern high value car today has 25 - 50 microprocessors and a local area network (LAN)
- In 1995 the automotive electronics content was less than 5% of the vehicles cost. By 2000 the figure could approach 15-20%
- In 1997, 13M cars (1/3 of the world's output) were produced in Western Europe, each containing on average of 5 or 6 electronic systems worth several hundred pounds
- Top of the range models have more than 20 separate electronic systems.
- Forecasts suggest that the number and value of automotive electronic systems will grow at 10% pa, so that early in the next century electronic systems will account for at least 15% of the vehicle value, and electronics content will be 30-35% of the total system cost
- In 1995 Motorola estimated that semiconductor use in the world automotive market was $6.6 BN. By 2000 it is expected to rise to $13.5 BN · Sensor use is expected to rise to 24 per vehicle by 2002

Car manufacturers are also hungry users of technologies that relate to cost-effective improvements in vehicle performance, convenience and safety. Better performance is related to improved engine efficiency (see section on catalysis above) and the use of lightweight, high strength materials, all of which will be affected by nanotechnology. Convenience and safety are behind the quick adoption by the car industry of a new technology that relies on miniaturisation, such as the increasing use of global positioning systems (GPS) in cars.

GPS systems began to be installed in Japanese cars more than a decade ago as the roads there are notorious for being unmarked and many buildings are unnumbered. The technology is now a standard option for all new cars, and can include additional facilities such as a computer, CD-ROM, display monitor, and the opportunity to add peripherals, such as a cellular phone system or other in-vehicle electronic modules. Increasingly GPS technology will find applications worldwide, in vehicle tracking, security, fleet management, and automatic locator systems. Sales of GPS units are projected to grow from 1.1 million units in 1996 to more than 11 million by 2001.

Apart from the benefits of 'wireless' technology, nanotechnology has many applications in the automotive industry which have been outlined separately in preceeding chapters. These include the development of new lighter and stronger materials, on-line sensors that can measure wear and abrasion, and additives to improve the adhesion of parts and layers.

Nanotechnology is underpinning further developments in the automotive industry in:

- the avoidance of lubricants by using thin layers on bearings and gliding elements
- new electrostatic filters
- high power switches in ignition devices via field emission principles at sharp tips
- new catalysts using highly porous and chemically selective surfaces

Nanoparticles with a different size can also be used as paint additives to get new colour effects, better hardness or durability properties. Future applications may include motor parts made from new ceramics, plastics with a higher strength, and better vibration dampers based on magnetic nanofluids.

11. Energy

Nanotechnology has an important part to play in the generation of renewable energy particularly through the enhancement of photovoltaic (PV) cell technology.

The conversion of sunlight directly to electricity offers an inexhaustible and environmentally benign energy source. If the efficiency of PV cells were enhanced and costs reduced, they would make a very significant contribution to the energy needs of the developed and developing world.
Current concerns over CO2 emissions are presently driving an increased interest in PV. Although total PV power output remains relatively low, the industry is growing rapidly - the production of PV modules expanded 40% worldwide in 1997. Although most current PV production is based upon crystalline and amorphous silicon technologies, research is now focusing upon new technologies which may result in significant reductions in PV costs, and / or improvements in efficiency. The two areas in particular where nanotechnology is playing a key role in achieving these aims are:

Quantum well solar cells
The cost of PV devices can be reduced directly by the use of light concentrating systems, and indirectly by using narrow-band gap cells to convert waste radiant energy from conventional power sources. The latter is a novel, fast growing area known as thermophotovoltaics (TPV).
The incorporation of quantum wells (QW's) is being studied to produce higher efficiency photovoltaic cells for concentrator and TPV applications. QW's are ultra-thin layers (nanostructures) of narrower band-gap semiconductor (the well) grown between regions of higher band-gap material (the barrier) by modern crystal growth technologies such as molecular beam epitaxy (MBE) and metal-organic vapour phase epitaxy (MOVPE). These techniques are already being extensively researched for information technology applications. In photo-diodes and modulators they will be the basis of the all-optical computer of the future.

Dye sensitised nanocrystalline devices
The second example of nano-structured materials for PV applications concerns the use of nanoporous metal oxide films. In 1991, Michael Grätzel developed a novel photoelectric cell that closely mimicked the principles of photosynthesis. Light is captured by an intensely coloured dye; the energy of the light is then used to inject an electron from the dye into an semiconductor such as titanium dioxide (TiO2). This remarkably efficient charge separation reaction initiates current flow and the output of electrical energy by the cell
These novel photoelectrical solar cells have attracted considerable interest because of their potential as low cost solar cells. In contrast to conventional solid state solar cells, which depend on advanced processing of very high purity semiconductors and are therefore relatively expensive to make, the Grätzel solar cell is fabricated from cheap, low purity materials by simple and low cost procedures. There is therefore considerable excitement at the possibility that development of these novel devices will result in cheap and environmentally friendly energy production.
Preparation of these cells depends critically on the type of semiconductor used. The ideal material must have a high surface area for light absorption and charge separation. In the Grätzel cell, a high surface area is readily achieved by using nanometric particles of TiO2 (diameters 10-20 nm). For fabrication of a photoelectrical cell, these nano-dispersed TiO2 particles are sintered together to give a high surface area, nanoporous thin film supported upon a glass substrate. In keeping with the simple fabrication procedures involved with these films, this procedure is based upon silk screen printing techniques from a colloidal suspension of the TiO2 particles, followed by heating the film using a hot air blower. The resulting films combine high surface area with optical transparency, excellent stability and good electrical conductivity.

The remarkable range of properties of these films have practical applications, not only for solar energy conversion but also for photocatalytic water treatment, photochromic windows and molecular electronic devices and encapsulate the essence of the opportunities offered by nanotechnology.

12. Materials

The world market for materials is estimated at $10 billion p.a. and growing. Since the 1920's scientists have known that the properties of materials such as strength and the ability to conduct electricity were governed by the structure of their atoms and molecules. This insight led to the identification of semiconducting materials that laid the foundations of today's electronics industry.

More recently, with the advent of the tools of nanotechnology, materials science has been transformed to a point that the relationship between the structure of a material and its properties may be controlled. Scientists and engineers are becoming increasingly able to understand, intervene and rearrange the atomic and molecular structure of matter, and control its form in order to achieve specific aims. Materials are closer to being designed to fit the needs of a specific end use, and simulate the properties of specific materials even before they are made.

This ability is not the result of a continuous evolution of knowledge, but a step-change resulting from increased computer power (itself a result of progress in materials science) and advanced instrumentation, which allows complex mathematical modelling of materials from the micro-structural to the quantum mechanics level. This modelling relates the properties of a material to its internal structure, and even its behaviour when processed. The properties and performance of a material can now be tailor-made, and even information on the behaviour of a material that has been modified by advanced surface treatment, coating, joining and adhesive technologies can be designed into the manufacturing process itself. Computer modelling and simulation at the atomic level is already being used to improve the performance of currently available materials. As discussed in Chapter 9, industry will eventually be able to design entirely new materials, and build them atom-by-atom and molecule by molecule. The arrival of such nanophase materials at the commercial scale will be accompanied by new processing and fabrication technologies. From this, nano net shape devices such as sensors, robots, electronics systems, computers, engines and surgical devices can be produced with applications in medicine, pharmacology, agriculture, mining, genetic engineering, energy and the environment. These developments will also dramatically cut the R&D and fabrication cycle times.

The consequences of these revolutionary developments in science and engineering need to be addressed from a long-term perspective both by firms and nationally. There are cumulative gains to be had from the capability to design, produce and use new materials in advanced nanotechnology-based products. Time is short - it may soon be impossible for new companies not already involved to enter into the field of advanced materials.

Nanostructured Materials and their Applications

As described previously, materials often behave very differently when nanostructured. Finer grain sizes can produce denser materials with greatly improved mechanical properties. The aerospace and defence industries will also benefit from new lightweight, high strength nano-composite materials, as will biomedicine, for example in stronger hip prostheses with extended life expectancy. The smaller the particle, the larger active surfaces per unit mass and greater chemical activity, for example, greater solubility in water. Nanoparticle technology will provide more durable and uniform surfaces on porcelain, and better inks for inkjet printing. The recently identified buckminsterfullerene, in the form of carbon C60 'buckyballs' has many potential applications, such as a very effective nanoparticle dry lubricant for engineering applications. The nanotube version can be used as a mould for making nanowires in metals such as gold for electronic connectors, and may even act as a conductor itself. Nanotubes can also be fabricated to form molecular sieves for faster and more selective filtration. (See below).

Unprecedented opportunities are arising for re-engineering existing products and engineering new ones at the nano metre scale for a wide range of commercial applications. For example, clusters of atoms (quantum dots, nanodots, inorganic macromolecules), grains less than 100 nanometers in size (nanocrystalline, nanophase, nanostructured materials), fibres less than 100 nanometers in diameter (nanorods, nanotubes, nanofibrils, quantum wires), films less than 100 nanometers in thickness, and composites that are a combination of any or all of these. The more important materials with nanoscale applications include carbides, nitrides, oxides, borides, selenides, tellurides, sulphides, halides, alloys, intermetallics, metals, organic polymers, and composites.

Thin films

Thin films or monolayers usually range from 1nm to 5nm thickness but may be only one molecule or even one atom thick in some cases. They can be organic or inorganic, and have a wide range of properties, from being chemically active to being wear resistant. Monolayers deposited on semiconducting substrates that emit electrons when sunlight falls on them form the basis of solar energy cells that can be expected to improve the efficiency of energy generation in the future (See Chapter 11). Thin layers can be deposited successively in different materials creating multi-layers with for example specific magnetic properties useful in magnetic recording with high packing densities; other properties include high erosion resistance in hostile environments (See Chapter 6), the ability to focus x-rays and the prevention of the transmission of laser light.

13. Health and Life Sciences - A Story of Convergent Technologies

The combination of many new techniques is opening the door to the resolution of biological questions (such as the functioning of the immune system) that would have been intractable even a few years ago. This new knowledge, together with the deciphering of the human and other animal and plant genomes is plunging us into the thick of a biomedical revolution. The result is an explosion of entirely new industries across the healthcare, medicine, food and nutrition, environmental management, chemical synthesis, agriculture and non-food agricultural sectors. Nanotechnology allied with biotechnology are the underpinning technologies pushing the rapid advances in genomics, combinatorial chemistry, high throughput robotic screening, drug discovery, gene sequencing and bioinformatics and their applications, some of which are as described in more detail below:

Lab-on-a-Chip: the Analytical Revolution

Lab-on-a-chip techniques directly build on knowledge gained from the semiconductor industry. Micro-scale channels are microfabricated on silicon, glass or polymer substrates and used to direct picolitres of sample fluid into active sensing sites that can be from 10-200 micrometres in diameter (and shrinking - already the first disposable analytical device manufactured to nanoscale tolerances is being produced in commercial quantities by Jenoptik, at a facility opened in Germany in September 1999).

Miniaturising the analytical process has the benefit of both reducing the costs of analysis, as well as dramatically speeding it up, making it possible to identify a disease or pollutant within minutes, and will quickly displace conventional techniques where samples are sent to a laboratory and put through labour-intensive processes that may take several hours to achieve a result.

This new technology has many applications, including fast throughput DNA analysis, cell separation and new drug discovery techniques which depend on measuring the reaction of single cells to various therapeutic compounds. It is leading to the creation of miniature, portable diagnostic laboratories for uses in the food, pharmaceutical and chemical industries, in disease prevention and control and in environmental monitoring.

In the food industry in particular, there are many applications. For example this kind of sensing could be used to determine whether or not GM ingredients were present in foodstuffs, and provide rapid indications of the presence of pesticides, hormones and antibiotics.

Chip technology also offers the potential for creating new biosensors that can detect minute chemical or bacteriological changes, working in a similar way as the nose detects smells. Preventive medicine could be made cheaper by using such systems, while applications are being pursued in the defence sector as premature warning systems for gas attacks, and in environmental monitoring situations, to raise an early alarm to increases in the levels of pollutants or toxic gases.

It is suggested that a device will be available within a few years that will map an individual's entire genetic code from a drop of blood, almost instantaneously. This can be used to screen for mutations that cause hereditary disease. Their capabilities can also help tailor medicine to the specific genetic character of any one individual, and variations can be crucial in determining a person's susceptibility to disease or response to drugs. Although several individuals may be diagnosed with the same disease, they may vary considerably in their reaction to treatment. Using DNA chips, this response can be gauged 100 to 1000 times faster than before, allowing treatment to be tailored to the individual. These chips also have applications in agriculture, and may enable scientists to understand why some strains of plants are hardier and more disease resistant than others.

Although chips currently cost over £1250 each to make, within three years the costs should fall dramatically, making these revolutionary tools widely available. To quote one writer, 'What silicon chips did for computing, DNA chips may do for biomedical research.'

A future development in chip technology is in the timed release of measured doses of chemicals from inside a microchip, triggered by a microprocessor, remote control, or an inbuilt sensor. This so-called 'pharmacy-on-a-chip' can monitor conditions such as diabetes, causing an automatic 'shot' of insulin to be administered, and act as an artificial means of regulating and maintaining the body's own hormonal balance.

Nanoparticles and Drug Delivery and Targeting

There is increasing investment in new and more effective drug delivery systems because the acceptance of new drug formulations is expensive and slow, taking up to 15 years to obtain full accreditation for some drugs, with no guarantee of success. Pharmaceutical companies in the main are keen to investigate new techniques that can more effectively deliver or target existing drugs, as this offers a new and less costly route to increasing their product portfolio.

Apart from using silicon chip technology, other delivery and targeting techniques are being investigated in order to maximise drug action and minimise side effects.

For example, light-activated coatings are applied to particulate drugs for the treatment of bone conditions such as arthritis of the fingers and feet. The drugs remain insoluble due to the coating, becoming preferentially concentrated at the joints. The coatings are dissolved by exposure to light, allowing the drugs to be released exactly where needed.
The selective delivery of drugs has always been a challenge, particularly in the case in cancer treatment. One approach is to use nanospheres to direct the drugs to the target tissues. However, the problem has been that such particles are similar in size to viruses and bacteria, which the body has developed very efficient mechanisms to deal with. It was discovered that bacteria that have very hydrophilic surfaces could avoid being destroyed by macrophages and remain circulating in the body for longer periods. To emulate this effect nano-sized drug particles are coated with a polymer such as polyethylene glycol (PEG). It was discovered that certain PEG surface characteristics could also cause particles to be specifically directed not only to organs such as the spleen and liver but also to tissues such as bone marrow. This avenue of research will shortly result in therapeutic procedures.
Studies are also focussing on using magnetic particles to guide and position drugs at target sites. Magnetic particles are also being considered for hyperthermic therapy in cancer treatment. When these particulate delivery systems are brought into cancer cells, they can be used as heating material stimulated in the body by an external magnetic field.

Nanoparticles and Gene Therapy
Nanoparticles are now also being used as delivery mechanisms in gene therapy - a means of rectifying genetic disorders, such as cystic fibrosis, where 'good' DNA is inserted into specific sites in target cells to replace the faulty gene. Effective particle design requires a multidisciplinary approach and depends on understanding aspects of colloidal science, biophysics and molecular biology, and the ability to create the necessary dimensions and surface properties.

Textured Surfaces for Tissue Regeneration, Growth and Repair
It has been known for a long time that the morphology and topography of surface dramatically affects the behaviour of cells on that surface. Recently, considerable work has been taking place to create nano and micro textured surfaces that are cell-friendly, and promote cell growth that can be controlled. Applications are wide ranging, and include the creation of substrates for cell culturing, textures that encourage neural regeneration and the acceptance of prostheses, microsubstrates for bioartificial organs and as a medium for the regeneration of tissues such as bone, tendon and nerves.
'Cell-friendly' surfaces are also vital for the implantable sensors or drug delivery devices described above to work effectively within the body. They are also important for the success of one of the largest areas of therapy, namely plastic bypasses and catheters
Specific examples of substrate effects include

- an observed increase in biosynthetic activity and mobility of bone cells on polymer films cast in micromachined moulds, with applications for bone regeneration and bioengineering of prosthetics
- the observation of the regeneration of severed tendons on textured surfaces leading to the use of textured bandages to accelerate healing for tissues where previously damage was almost irreparable
- the directed growth of nerve cells on micromachined structures with the suggestion of eventual artificial neural implants or even structures that may be adapted towards achieving the holy grail of biocomputers

NanoMachines - Some Breakthroughs
Popular folklore has it that vanishingly small machines could someday serve as tiny mechanical doctors. The vision of machines small enough to be injected into the human blood stream to search for viruses, attack cancerous growth, destroy fat cells or even undertake repair has been a theme of science fiction. The working parts of these machines would be built around gears no bigger than a protein molecule.

14. Nanotechnology and Optical Fibre Communication Systems

The Present
Nanotechnology has played a vital role in dramatically advancing optical fibre communications systems from the crude prototypes of 20 years ago based on bulk gallium arsenide lasers and multimode fibre with transmission distances of a few kilometres and bit rates of a few megabits per second. We now have systems that are the backbone of the UK network based on single mode fibre with bit rates a thousand times greater and distance is no object. This has been made possible by two key developments in nanotechnology:

- The development of the multiquantum well laser based on indium phosphide technology which operates in single longitudinal mode and has good thermal characteristics
- The discovery of the erbium doped fibre amplifier and the use of nanoscale fibre gratings to provide uniform amplification over a substantial fraction of the low loss fibre window

The underlying technology that has made this possible are novel crystal growth techniques which permit single crystals of metals, insulators and semiconductors to be grown with interfaces smooth to the atomic layer limit. When coupled with an in-built ability to grow extremely thin layers (< 10nm). The thickness regime, which is well within the nanoscale, is approached where the electronic structure of the materials is modified to produce new materials with properties not found in nature but influenced by quantum size effects.

The Future
For the UK to enjoy the full economic benefits of the information technology revolution, communications networks that can deal with the vast increase in data transmission, especially via the Internet, will be essential. Such networks will have to exploit the ultimate information carrying capacity of silicon fibre using bit rates of 100 gigabits per second and transmission over all the wavelengths in the low loss and minimum dispersion windows. All optical switches and signal processing will also be required to reduce the software burden. Nanotechnology will play an essential role in bringing about such networks via the development of:

- high speed multiquantum well electroabsorption modulators for external modulation of the laser sources since direct modulation is not feasible at such high bit rates.
- multiquantum well semiconductor amplifiers and quantum dot structures to act as ultrafast all optical switches.
- fibre microenvironments for amplifiers that can operate at wavelengths inaccessible to the erbium doped fibre amplifier.
- filters based on fibre grating technology and photonic nanostructures, and
- microscopic 'optical benches' based on silicon micromachining to hold the optical devices in a precise relationship to each other.

As a result of government and EU funding over the past 15 years or so (JOERS, LINK etc) the UK is in a strong position to exploit the opportunities for nanotechnology in optical fibre communications systems. More possibilities also exist in this area for further R&D related to future needs.

15. Precision Engineering, Optics and Analytics

This area is only referred to in passing, as the precision, optics and surface engineering communities are well established with good information and communication channels.

In optics and precision engineering in particular, there is a need for developing treatment processes for ultrasmooth, aspherical surfaces with high form tolerances, correction processes for polishing faults, deposition methods for thin films on optics and the production of suitable machines for the controlled structuring of sub100 nm features. The application of ultrasmooth optical elements in photolithography steppers and the elongation of the optical possibilities to other wavelength areas (e.g. X-ray, infrared) is of likewise industrial importance (e.g. for X-ray projection lithography). Based on thin layer results there is a long-term market goal in the preparation of low cost nanoparticle layers for new solar cells, photo detectors or field emission displays.

Analytics is a central element in the nanoworld. The measurement and characterisation methods have to be adapted to higher needs in production and product quality. Main points can be done today by scanning probe methods. This big application potential comes out of the possibility to use nearly every interaction principle in the nanoscopic range which is already well known in the macroscopic world.

From an industrial point of view this field has high development potential.

16. Financial Services

The financial services sector is an end user rather than developer of nanotechnology, but is profoundly affected by its application. Other industries within the services sector which are fundamentally underpinned by IT include leisure, and education and training, though these are not discussed in depth here. IT includes all aspects of communications, rapid data transmission, information storage and access, multi-media, displays technology and virtual reality. There are important training issues here, and the need for organisations working in the area to know what the leading edge technology is, and its implications for their own future competitiveness.

The applications of nanotechnology will impinge heavily on the future of financial services, and the City as a global centre of international finance and banking services. It will affect activities as diverse as retail banking, electronic trading and exchanges, mathematical modelling, simulation and econometric techniques. Nanotechnology is also having an increasing impact on telecommunications technologies, and this is transforming the competitive environment and the very nature of the financial institutions and the services they provide. Serious implications also exist in the training and support infrastructure needed to maintain the competitiveness, innovative performance and locational advantage of the UK as a major player.

New technologies deriving from nanotechnology that are increasingly affecting education and training requirements (and the means of delivering them!) are in the use of advanced mathematical techniques and in the design of financial products such as the analysis of market trends, forecasting, risk analysis and management and investment portfolio analysis. Advancing hardware and software technologies also impose increasingly demanding requirements in terms of the sophistication of the knowledge base of employees.

At the same time, the need for local presence in the provision of such services is being undermined through the use of 'virtual' meetings, global and personal communications. Advances in displays, virtual environments, augmented reality and telepresence techniques will all increasingly impact on the location of the financial services 'centre'. Due to these advances, most, if not all, aspects of financial services such as obtaining and acting on real time data, trader and client interactions and most of the other financial services, will be location independent. There is a major issue here that the City and all players in the financial services sector need to urgently consider.

17. Nanotechnology and Society

Benefits to the Ageing and Disabled

Highly sophisticated and increasingly miniaturised technology is being successfully applied both to improve the quality of life for the disabled and extend the expectation of active and fulfilling lives of the aged population. Much of the technology owes its existence to military research, and its cheapness and accessibility to mass production techniques. Some of these advances are described below.

External Aids

People who can't use their hands to type are benefiting from modified eye-tracking technology developed for astronauts. An infrared beam is used to illuminate a user's face while a small video camera records the position of the eyes. Eye movements direct a small dot on a screen 'keyboard', causing it to type a specific letter by letting a gaze rest on it for half a second. Commands, such as saving or printing a file, can be executed by looking at particular places on the screen. In addition, the system can be used to control household appliances, heaters, and switch on and off the radio and television.

Another system relies on headbands that contain sensors that measure electrical signals from the brain and from slight muscle movements in the forehead, originally evolved for fighter pilots. Those signals are converted into digital signals that are fed into a computer and split into about a dozen readings that are displayed on a computer screen. Users learn how to channel their brain waves and make subtle muscle movements to control the readings on the screen.

The blind are also getting help from sensors that are increasingly small and reliable. One research project is incorporating sensors that measure the distance to the object closest to a person in a prototype 'super cane'. The cane has a motorized, steerable foot with ultrasonic sensors on all sides. Users can push a small joystick near the handle to tell the cane where they want to go. The cane complies, steering the user around obstacles.

An algorithm developed for air traffic controllers is the basis of a navigation system for developing a wheelchair that can automatically steer through crowds. The chair uses sonar sensors and a laser to calculate the position and velocity of the objects around it. A map of the environment is constructed every second, which is used to direct the chair. The person in the chair selects the direction and speed, and the wheelchair does the rest.

Implants

Some specific applications for nanotechnology is in a multidisciplinary approach to improving implants for the alleviation of degenerative disease. Nanotechnology can be said to be taking the potential for rehabilitation of the sick and elderly into totally a new domain - the domain of intelligent, learning prosthetic devices. Some of the devices presently being researched include

Retinal implants: Many people suffer from degeneration of the retina with old age. Research is examining one solution, through the creation of a photosensor array connected to a signal processor that will detect incoming light. It is envisaged that this 'module' will be external to the eye, possibly in the form of a pair of spectacles. It will transmit the signal to an implanted receiver at the retinal interface, and which is connected via microcontacts to the retinal nerves (ganglions). There are still many problems such as biocompatibility, the optimisation of signal transmission and the form of the microcontacts to be solved.

Other implants: The work on other kinds of implants is at a much earlier stage, and no concerted effort has yet been made to coordinate research or apply the multi-disciplinary team concept to the problem.

- *Auditory implants.* Implants in use today can be considered as fairly crude, low technology devices in comparison with what is possible. In cochlear implants currently, the electrode system consist of no more that 22 electrodes (as opposed to a thousand or more in the retinal implants), which do not even make direct contact with the ganglions in the ear. The vital question is how to improve the electrode-ganglion contact.
- *Spinal implants.* Considerable resources of time and money are being invested in improving grip in paraplegic patients, both in Europe and the US.
- *Cranial implants.* These are designed to improve the condition of patients suffering from brain-related diseases, mainly by supplying biochemicals to the brain and monitoring the effects, for example, in the alleviation of the effects of Parkinson's disease.

Sustainability

Nanotechnology is viewed as a key technology in the development of a sustainable society (Smalley 1995). For example, the development of ultralight materials will result in energy, fuel and materials savings; improvements in solar cells will result in better deployment of renewable energy; new battery and fuel cell technology will provide more efficient energy storage, and improved insulating materials will result in increased energy savings.

18. Time to Market

How far we are from realizing practical benefits from nanotechnology really depends on which aspect of nanotechnology is being considered. It may be tiny gears, camshafts and motors engineered on the nanometre (billionth of a meter) scale; or integrated circuits whose smallest features are on the scale of tens of nanometres, or the product of chemical 'self-assembly'. The common goal shared by all these researchers is to make devices that are smaller than anything now available.

Applications using techniques at the nanoscale, close to, or already in the marketplace:

- New sensors for applications in medicine, environmental pollution assessments and in the preparation of pure chemicals and pharmaceuticals
- Better photovoltaic techniques for renewable energy sources
- New lighter and stronger materials for defence, aerospace, automotive and medical applications
- 'Smart' wrappings for the food industry that indicate freshness or otherwise
- Display technologies for better, lighter, slimmer and flexible screens
- 'Lab-on-a-chip' - diagnostic techniques
- Sunburn creams with u-v light absorbing nanoparticles

- Glasses with scratch-resistant coatings

Applications that may come onstream in the medium term:

Anti-corrosion coatings: 5-15 years
Tougher and harder cutting tools: 5-15 years
Plastic electronics - flat panel displays: 5-10 yrs
Longer lasting medical implants: 5-15 years
Chip available commercially with 100nm features: c 7 yrs

Those still at the stage of prediction:

Nanostructured materials for nanoelectronic components: 10-20 yrs
High-density memories, ultra fast processors: 10-20 yrs
Nanomachines or medical applications in which tiny machines circulate in the bloodstream cleaning out fat deposits from our arteries: 25 years at least.

19. Some General and Specific Issues

Nanotechnology both offers almost limitless potential to industry particularly in the creation of new high added value niche products or in the export of know-how. There will be many social benefits also, such as the reduction of environmental pollution, better healthcare, improvement of quality of life for the aged, better transport and easier production of renewable energy. Developments in nanotechnology need to go hand-in-hand with ethical considerations. Dangers exist that must be carefully assessed, for example in the area of genetic manipulation, whether in the quest for better crops, or to reduce congenital defects or in the production of transgenic animals for food or medicine or even in the screening of unwanted characteristics in human offspring.

The speed of advancement of scientific knowledge is related to the ultimate rate determining factors.

In the first instance the rate controlling factors for nanotechnology are likely to be:

- Identifying desirable applications that win commercial and public acceptance
- Creating process routes to the products that meet the needs of these applications

Specific risk issues

- The risks associated with genetics whether these are related to plants or animals (including human beings wherever products based on nanotechnology incorporate genetic material or have genetic modification or repair as an objective.
- The controlled distribution of biological and nerve agents in warfare.
- Methods of assessing risk, particularly those relating to toxicity, may themselves be inadequate to the new situations posed by applications of nanotechnology in many different fields
- Promoting the public debate and understanding of the benefits and risks associated with nanotechnology. Many issues that are perceived to have widespread risks are first drawn to the attention of the polity by the media, often television. These exposés can be very powerful and can set the public agenda long before any formal policy process begins (an example is in the use of genetically modified foods). Further risks can arise from early litigation with courts setting precedents, through their judgements, in the worst case in the absence of significant scientific argument or evidence.

And finally...
There is already one highly successful nanotechnological system: we call it life. All the goals of nanotechnology are already fulfilled in living systems, and most of our attempts at nanotechnological applications can be called biomimetic, either applying the structural principles of living systems to different compounds or using the compounds of living systems for different purposes. **Nadrian C. Seeman**

Appendix 1: Nanotechnologies vs Key UK Industrial Sectors Appendix 2:

Spending on Nanotechnology Research USA
America is a world-leader in nanoscale science research. From 1985 to 1997 the total support for projects related to nanotechnology was estimated at $ 452 million, coming in roughly equal parts from the NSF, various industrial sponsorship, and other government funding (RAND). Their combined level of support for nanotechnology research is estimated at about $ 115 million/year for 1997/98. Most of the reported research is in the pre-competitive phase. Approximately 25% of the total funding is spent for applied research as part of development projects. The largest single agency research expenditure is at NSF, about $ 65 million/year. The Americans have established several research networks, including the NSF-funded National Nanofabrication Users Network, started in 1996.One prominent new dedicated academic lab is being built at Rice University. The Center for Nanoscale Science and Technology (CNST) will be a 90,000 sq.ft. lab with 12 faculties. A degree program in nanotechnology is planned. The lab has launched a$ 32.3 million funding campaign. The US, in particular California, is also home to virtually all the work in molecular nanotechnology. Dedicated centres include the Institute for Molecular Manufacturing and the Foresight Institute.

Japan
It is universally agreed that Japan has the only fully-coordinated and funded national policy of nanotechnology research. The most prominent product of this national policy has been the ongoing Ministry for International Trade and Industry (MITI) program on atom manipulation, 1991 - 2001, entitled 'Research and Development of Ultimate Manipulation of Molecules'. The program was funded at the 25 billion Yen level. Of the total, $ 167 million are allocated for the development of 'microrobots'. Both academic and industrial groups participate, private companies are expected to contribute nearly 100 billion Yen in the R&D effort. Member firms include Fuji, Hewlett-Packard Japan, Hitachi, Mitsubishi, NEC and Sony, together with a small number of foreign firms such as Texas Instruments. RAND has estimated the total spending from MITI and STA ERATO projects, combined with funding from Japan's Science and Technology Agency and attached industry money, to be $ 538 million from 1985 to 1997.

United Kingdom No up to date information exists.

Europe
Around ECU (Euro now) 69 million of European money was spent on nanoscale research from 1988 to 1998, compared with about ECU 200 million by the Japanese MITI in a similar period. The Swiss are investing over 150 million SFrs in nano related programmes, mostly over the next 3 years, and 13 billion SFrs in the 'Exploitation of Knowledge' in the period 2000-2003. In Germany, in the autumn of 1998, the German ministry of Education and Research installed 6 nanotechnology

networks. These were chosen from 14 bids. The total budget is 150 million DM for 5 years. The areas covered are:

- Ultrathin functional layers
- Applications of nanostructures in opto-electronics
- Developments of lateral nanostructures
- Chemical functionalisation of nanostructures
- Ultraprecise surface measurements
- Nanostructure analysis methods

The estimate for nanoscience research spending is currently around 70 - 100 million DM per annum.

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Appendix 4: Sectors