Nanotechnology: views of Scientists and Engineers

Report of a workshop held as part of the Nanotechnology study
(http://www.nanotec.org.uk/)

Comments on this document are requested by 5 December 2003

NB The views summarised within this document do not represent a consensus of the views of the attendees and do not necessarily reflect the views of the Nanotechnology working group.

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1) Introduction

In June 2003 the UK Government commissioned the Royal Society (http://www.royalsoc.ac.uk) and the Royal Academy of Engineering (http://www.raeng.org.uk) to carry out an independent study of likely developments in nanotechnology and to examine whether nanotechnology raises or is likely to raise new health and safety, environmental, social or ethical issues which are not covered by current regulation. The terms of reference for the study are as follows:

- define what is meant by nanoscience and nanotechnology;
- summarise the current scientific knowledge on nanotechnology;
- identify applications of nanotechnology, both currently and potentially, with indications of when they might be developed;
- consider environmental, health and safety, ethical and social implications of the technology, both now and in the future; and
- suggest areas where additional regulation should be considered.

Details of the study can be found on the dedicated web site http://www.nanotec.org.uk/.

As part of the study the working group held a workshop for 42 scientists and engineers at the Royal Society on 30 September 2003. Approximately 80% of attendees were from the academic community, 15% from industry and the remaining 5% were from government and non-government organisations. Of the total, 20% of attendees were engaged in biological, medical or pharmaceutical research, 65% in physics, chemistry or engineering, and the remainder comprised of health and safety, policy, and business information professionals. This is the report of that workshop. Sections 3-6 are summaries of the breakout groups that looked at developments in four specific areas of nanotechnology. Section 7 contains a summary of three, multi-disciplinary, breakout groups that considered the health, safety, environmental and social issues that nanotechnology might present. The programme for the workshop, including the questions that attendees were asked to address can be found in Appendix A. The list of attendees can be found in Appendix B.

Please note that the views summarised within this document do not represent a consensus of the views of the attendees and do not necessarily reflect the views of the Nanotechnology working group.

2) How to respond to this document

The working group welcomes comments on this report, which it will use in the preparation of the final report, to be completed next year. In particular, we would welcome comments on whether this report is an accurate representation of:

- The current state and expected applications of nanoscience and nanotechnology
- The health, safety and environmental benefits and risks of nanotechnology

Please send your comments (preferably by e-mail) to Dr Andrew Dunn, The Royal Society, 6-9 Carlton House Terrace, London SW1Y 5AG (email - nano@royalsoc.ac.uk) by 5 December 2003.

3) Nanoengineering and Measurement

a) Definitions

The group considered the working definitions used by the main Working Group for the study. It was decided that the separation of "nanotechnology" and "nanoscience" in the definition was important. However, it was felt that the "nanotechnology" definition was too narrow in that it incorporated "top down" nanoengineering well but did not cover surface treatments and structures so well and did not capture the aspects of ultraprecision engineering, whereby objects are defined in shape to sub-100nm precision.

There was some discussion about the length scale used in the definition. It was felt that the definition should include reference to the special behaviours of materials at these length scales. It was suggested that the length scale might be smaller, maybe 10nm and below, where quantum effects are observed, but this was countered on the basis that novel effects are observed in machining materials at the 100nm scale as well. The final compromise was that the length scale, although important to be included in the definition, was arbitrary and should be used in conjunction with "novel bulk or quantum (physico-chemical) effects". It was pointed out that dimensionality was also important from a purely economic aspect – the shrinkage of semiconductor circuits being a particular case in point. Here there is no particular advantage in terms of novel physical properties in shrinking the dimensionality, but there are very important economic consequences. It was also suggested that the effects of dimensionality on health and safety issues could be included, as well as the physical properties.

b) Current State of Knowledge

One key issue identified by the group was metrology. While Atomic Force Microscopy and Scanning Probe Microscopy (collectively SPM) were led from ouside the UK, they were in a good state in the UK and Europe. However, there was a problem with repeatability of results and standards. Round robin tests conducted by NPL had shown huge amounts of variability. While a relative measurement often sufficed within a lab or organisation, there was little repeatability of results outside due to variation in the cantilever beams and equipment. The repeatable measurement of forces (for example in the study of bonding between biomolecules, such as DNA, and surfaces) was a particular case in point. It was agreed that the UK had a leading position in the establishment of traceable standards for the SPM and that NIST (USA) and PBT (Germany) were also entering this field. Such standards will be essential in moving these tools out of the science arena and into the technology arena. It was noted that SPM tools were already being used for manipulation as well as observation and would be key tools in the further development of nanoengineering.

The use of SPM as a process tool to manipulate materials and "add value through size" in the chemical industry was discussed. The essential nature of MEMS (MicroElectroMechanical Systems) as a route create massively parallel SPM's (e.g. "Millipede") for such applications was noted. The group saw SPM becoming an important process tool by around 2020 with this possibly heralding the real commercial revolution in nanotechnology.

Particle beam and X-ray spectroscopy were mentioned as key technologies with two out of three of the main companies supplying equipment being based in the UK.

The area of ultra-precision engineering, whereby material can be removed at sub-100nm precision, was noted as an important area. For example, the whole of the semiconductor process industry is based upon the ability to manipulate device wafers to this level of precision and this was based upon the ability to machine and measure components at this level. The ability to remove material to this level of precision was also cited as being important in minimising sub-surface damage and improving system reliability in a wide range of components. The UK has a very strong position in this field.

The Group discussed what was required to make the potential process tools of the future become economic for the production. This discussion looked at the use of nanoengineering in production rather than the production of nano products per se. The consensus was that the use of MEMS as a production technology was inevitable, but scaling up of production was the key, for instance, scaling up from one device to 100 or 1,000. With this technology there was the potential to create truly green manufacturing with no waste, no solvents and very efficient use of materials.

c) Applications

It was noted during the discussions of the group that the topic area they were considering was already rich in applications (the SPM, particle beam and ultra-precision engineering industrial sectors noted above are currently generating many billions of dollars in revenue world-wide). The Group also felt that MEMS/NEMS would be among the first new applications of nanoscale engineering in the market place. This led to some discussion around market drivers for such devices. It was agreed that applications for the young would be most important, with China and India becoming very important as demographic differences between them and the West kicked in in the 2020 timeframe discussed. It was noted that in the microelectronic industry, a key market driver had similarly been the youth market for mobile phones and games. An example that was discussed in the field of MEMS was shape memory allows which were finding applications within toys, specifically to make a doll that could react to sound by moving its eyes.

Again with applications, the group considered that market forces would be important. A combination of technology push and market pull would be required. Another example discussed was mobile communications in the Far East, and China in particular, where 3G and eventually 4G would expand rapidly. For microelectronics, it was noted that the defence market had been a key driver in the 1980's, but it was not felt that this would be a significant driver for nanotechnology. However, it was noted that the US DoD was currently a major investor in the field.

The application of MEMS to nanomanufacturing in the chemical industry was discussed, where there was a requirement to produce materials with "6 " or even "9 " reliability. Here, the ability of MEMS to be scaled-up with the high reproducibility inherent in the electronics industry was seen as being very important.

Another area where nanotechnology in general might be capable of providing important applications in the future was in the provision of clean potable water from sea-water through the use of nanoscale filtration.

This moved discussion on to strategy. The group felt that the UK did not have a strategic view on the development of nanotechnology, in contrast with its major international competitors. It was noted that the UK did organise a number of technology missions around the world and that much information was being brought back and disseminated, but the strategic vision called for had still not developed. The importance of networks was stressed with the group feeling that the nanotechnology community is not yet good at this. A significant lack of networking in the commercial area was noted. It was felt that the lack of a research centre was a disadvantage when compared with e.g. France where Grenoble is currently a large and growing centre of excellence.

The group discussed the possibility that manufacturing in the field would inevitably move to the Far East. It was felt that although this may happen, most of the companies involved were already truly global in their outlook and were probably not thinking in terms of moving manufacture to the cheapest areas in the same way as has been seen in the past. A related issue of moving manufacture abroad was discussed briefly; that of exporting health and safety issues to countries less able to deal with them.

d) Science Fiction

There was nothing in the topic area specifically assigned to the group that could be said to be "science fiction". The group picked-up on Drexler's ideas as having been a source for the current hype about the field; however, Gene Rodenberry and Star Trek were also identified as other sources. The key to science fiction scare stories becoming significant was felt to be their sublimation into pop culture.

Questions as to what was physically possible were discussed. It was decided that the only way to categorically rule out any of the scare stories would be to address the issue of their possibility based on the laws of physics alone. The group did not feel it was possible to do that within the context of the time available. It was felt that it should be possible to put likely timescales on many possible developments. The idea that some sort of self-replicating "nanobots" could wreak havoc was explored, but it was felt that the complexity of such systems would mean that, even if their construction was to be physically possible, which was doubtful, their realisation was a very long way in the future. The prospect of "Jules Verne" injectable devices was felt to be very unlikely, but single nano devices with a single simple function could be envisaged. The issues of the hazards of artificially-created self-replicating systems were discussed. It was suggested that prions had already indicated that a self-replicating particle without any intelligence could cause problems, but that this was a biological particle and it could only replicate when in very specific environments. This was a far-cry from the "grey goo" hazard that seemed to be exercising the popular mind. Some aspects of bionanotechnology could generate concern, especially when combined with the prospect of self-replication. It was felt that public unease at least in part depended on the use of language in the description of technological developments. For example, some of the group felt that the term "smart" could cause public concern, being confused with artificially intelligent devices.

In summary, the group felt that the "gray goo" scenario could only be conclusively ruled out through careful analysis based upon the rigorous use of known physical laws (it is probably not sufficient to simply say "this is impossible"), but even if the technology to create self-replicating nanobots were to be physically possible, which many doubted, it would not be available until the distant future, perhaps 2080 at least.

e) Other Areas

Nanomaterials were felt to be an area with fuzzy limits. It seemed probable that most of the health and safety issues would manifest themselves here. Problems such as those with PM10s, which could be considered to be similar to nanoparticles, were recognised and understood and there seem to be potential problems with the hazards of production, use and disposal of new materials. Health and safety issues were discussed. Some attendees wondered whether carbon nanotubes and nanoparticles may have the potential to be hazardous in unpredictable ways, but it was felt that companies had learned the lessons associated with these hazards and that regulations existed to prevent the uncontrolled release of hazardous materials. A possible consideration for the working group might be whether new regulations relating specifically to nanoparticles were either necessary or desirable. Again, this could only be determined through the acquisition and application of knowledge about the systems concerned.

The group decided that the lack of a strategy for nanotechnology discussed earlier could hold up development across the board was also felt that there was a real need to look at what could be possible in what timescales. In order to facilitate both of these, the generation of a road map was proposed. Road maps have been used for a number years in the semi-conductor industry where they have specific goals, identifying areas where new research and development needs to be carried out to attain them. For nanotechnology, the specific goals and technologies could not at first be identified, but a general road map would give the framework onto which specific technologies and goals could be mapped.

The generality of the proposed nanotechnology road map meant that it would be helpful to consider aspects of technology push, consumer pull, control and regulation, and health and safety issues. It was suggested that such a road map could be of use to the main working group in the present study as it would help to put some of the prospective developments into a temporal context and show important potential technology linkages and potential markets. The development of a general road map for specific targets and technologies could be a recommendation of the study. The creation of such a road map would need a significant amount of resource to be allocated to it. It would also require the cooperation of the industrial concerns in the field.

4) Nanomaterials

a) What would you add to/change about the working group's definition of nanotechnology?
The group were generally happy with both definitions. The following points were made:

Nanoscience:

- It was noted that colloid science covers a very similar dimension range. Care is needed to distinguish what is new about nanoscience compared to much of chemistry
- The upper and lower size limits should be fuzzy: for example photonic crystals go up to 300nm; atom manipulation is sub 1 nm nanoscience.
- The definition does not directly acknowledge sub-atomic or quantum phenomena.

Nanotechnology:

- This should be expanded to include the word 'systems', eg a functional set of components – a combination of nano (possibly more than one aspect) and meso technology will be essential in practice.
- This definition implies that nanotechnology will always follow on from nanoscience ('*the application of this knowledge*') whilst in practise both nanoscience and nanotechnology will take place simultaneously, and perhaps technology before the 'science'. This is not unique to nanotechnology: there are many examples of complicated & well-developed technologies where the underpinning science is not well understood.

b) What is the current state of knowledge in the field of your breakout group, and where is research going?

i) Definitions by dimensionality

It is convenient to classify nanomaterials in terms of the dimensionality of the nanostructures involved. Thus
3-D: (confined in 3 dimensions) e.g. quantum dots, particles, precipitates, colloids, catalysts, etc.
2-D: (confined in 2-D, extended in 1-D) e.g. nanotubes, fibres, interconnects/wires, fibrils, etc.
1-D: (confined in 1-D, extended in 2-D) e.g. surface coatings, thin films, device junctions (diodes etc.), interfaces etc.
1-D nanosystems are generally well understood and technologically advanced. Atom scale control is already possible for devices and coatings by various deposition techniques.
2-D systems are moderately understood in terms of properties, but manufacture is much less advanced.
3-D nanosystems provide the greatest challenges in terms of both properties and controlled manufacture. This is also where the dramatic increase in surface area, and hence chemical activity, is most evident.
A general remark – the electrical transport properties across interfaces remain poorly understood in terms of science/predictive capability. This affects all nanomaterials.

ii) Biology related

Considerable synergy exists between biostructures and nanomaterials. This is an active area of opportunity. For example much research has been undertaken on using cells as scaffolding on which to build clusters – bio- to inorganic templating. Similarly, templated inorganic surfaces affect cellular function.

c) What applications of this technology currently exist, and what can be envisaged in the short and long term?

i) Sunscreens

These typically contain both physical and chemical components. There is currently a limited understanding of which the most important wavelengths are that need to be protected against. Once this understanding increases it is hoped to develop tuned systems.

Little is known about the fate of sunscreens, including their metabolism, adsorption through skin, and where they end up in the environment.
Enhanced DNA repair enzymes are currently being incorporated into cosmetic formulations.

The driver for the use of nanoparticles in sunscreens was actually cosmetic: viscous, white pastes were not popular so the particle size needed to be lowered in order to overcome this. One obvious side effect was the dramatic increase in surface area. Free radicals are thought to damage skin, and are generated by the surface of the nanoparticle components. Two methods have been devised to overcome this problem of particle activity. One involves coating the particles – however, it is difficult to achieve an even coverage. More efficient is the use of p-type (rather than n-type) semiconductor materials. These can be produced by doping the original materials prior to mixing them with the other components of the sunscreens.
Free radical damage has been shown with *in vitro* models, but it is considerably harder to demonstrate *in vivo.*

ii) Self-cleaning windows

These involved the use of highly activated titanium dioxide, engineered to be highly hydrophobic, very anti-bacterial, utilising n-type doped materials.

iii) Nanocrystalline alloys

One example of how properties can significantly change on the nanoscale is the strength of materials. For example, nanocrystalline materials become considerably stronger as the particle size decreases. Nanocrystalline nickel is as strong as hardened steel, and nanocrystalline aluminium alloys can be up to twice as strong as their conventional equivalents. The nanostructuring can be made in two main ways: electroplating and consolidation from powder. Electroplating is preferable to consolidation as it does not involve the use of any ultrafine particles. The latter involve processing difficulties and possible hazards.

iv) Micromachined silicon sensors

There are a number of mass produced, cheap, efficient micromachined sensors (such as accelerometers) used in cars, cameras etc. Whilst these do not necessarily do anything completely new, they are smaller allowing either more sensors or freeing up space to allow miniaturisation. They are also easily intergrated with electronics.

v) Field-emission array displays

It was thought that a large electronics company intends to launch a 28”x70” screen on the market in 2004 or 2005 that is based on field-emission arrays rather than quantum dots. They are based on a ‘bucky paste’ that contains a volatile solvent, and nanotubes/particles. During annealing the solvent is evaporated and the nanocomponents self-assemble. The result is a screen with lower power consumption and heat generation.

vi) Films and coatings

There are a large number of coatings and films that are 1-d nanomaterials. Examples include:

- Multiwell quantum well lasers
- Smart materials such as self-cleaning surfaces
- Super hard coatings (some are carbide based)
- GMR read heads on PC hard drives. Magnetic nanostructures
- Coatings on fibre optic cables and other devices

vi) Environmental drivers

New alternative sources of energy are one potential driver for nanomaterials. Applications include fuel cells, nanomaterials with better electrical and mechanical properties, low cost photovoltaics and (perhaps) utilising carbon nanotubes to store hydrogen. Fraser Armstrong (Oxford) has been working on bio-fuel cells.

vii) Biomaterials

Bristol based company Nanomagnetics are currently manufacturing magnetic nanoparticles via a biological route. Research has also been undertaken on using yeast to produce similar materials.

viii) Bioremediation

Another possible application for nanomaterials is bioremediation. The driver would be to design systems capable of fixing heavy metals, PCBs, cyanide and other environmentally damaging materials.

ix) Improving understanding existing technologies

Nanoscience and nanotechnology have provided improved analytical tools that can be used to increase our understanding of existing technologies. For example, it is now possible to study biomolecules by trapping them in nanostructures making x-ray crystallography possible. The probe microscopies (esp. AFM) provide rapid, easy surface characterisation for thin film manufacture.

d) What are the potential hold-ups in turning research into products? What is needed (time, money etc) to enable this process to happen?

i) Hazards

There are three stages during which the hazards of any material need to be assessed:

- In production
- In use
- In disposal

There are a number of hazard-related issues associated with the production of nanomaterials:

- Very fine powders can be pyrophoric, so good housekeeping is required. Electrodeposition or melt spinning can be used to avoid these problems.
- Fluid based systems have many advantages, not least that they avoid free fine-scale particles. However, they generate the problem of how to deal with the disposal of the manufacturing process feedstocks. This problem is not unique to nanomaterials, but is still a serious issue.

- Lessons might be learnt from microbiological aerosol production where there are many well-established practices to deal with fine particles.

ii) Quantum dots

There is currently no reliable method of producing quantum dots of the same size reproducibly, either by lithography or the colloidal route. This is a significant limitation for their wider application. In contrast q*uantum lasers* are a possibility as they require fewer dots to function.

iii) Electron transport across material junctions

The long standing problem of the Schottky barrier / Ohmmic barrier, and understanding exactly how electrons transfer at material junctions, causes difficulties for nano- as for conventional materials. Alloy-based nanomaterials will often be made in a trial and error approach to obtain the required electrical properties. A related issue is a lack of understanding of how charges get into and out of cells, which has huge importance to bio-nanomaterials.

iv) Protein misfolding

It is not known how nanoparticles will interact with proteins. There is the possibility of causing protein misfolding, which is known to sometimes have damaging effects.

v) Empirical understanding of complex many particle systems

Much of our current understanding of multiphase systems is empirical at best. This knowledge has been built up over many years of chemical engineering and physical chemistry studying 'real' systems such as food. Surfactant and colloid science has only started to fully utilise DLVO theory on the attractive and repulsive forces between particles in the past 10-15 years although the theory's key papers were published by Derjaguin and Landau in 1941 and Vervey and Overbeek in 1948.

It was noted that 'real' systems are significantly more complicated than model ones, where our understanding is better. Impurities will influence surface properties, even at very low levels. There is clearly a need for nanoscience study of particle surfaces and interfaces.

vi) Toxicity issues

Experience from other materials (e.g. asbestos) shows that it is not necessary to have a complete understanding of precisely how a new material might affect people in order to determine regulation. Rather, it is essential to know what the dose response is. It is not sufficient to assess the properties of the individual chemical components that make up nanomaterials, as the toxicity will depend on the particle size, particle concentration and surface area.

A huge number of fine particles are produced from a wide range of other existing processes (car exhausts, masonry etc) that will/may have an impact on human health. Nanoparticles are not new! The bio-interactions of fine particles are not well-known, for example whether the particles can pass through skin or go into cells. It is also not known how the toxicity will vary from either the bulk or molecularly dispersed material. It can be postulated that nanoparticles might have a greater toxicity than a molecularly dispersed form of the same material due to either the combination of particle shape and size (cf silicosis).

Peter Dobson, University of Oxford, is involved in organising an EU workshop during summer 2004 on the direct absorption of fine particles through the skin.

It is also important to find out where nanoparticles go once they enter the body via different routes, and ultimately where they go inside cells. This might be achieved by studying luminescent tagged systems.

vii) Lessons from asbestos

Whilst there is not a full understanding of the mechanisms that make asbestos toxic, there is sufficient understanding to prevent significant harm to people. It is known that the size and shape of the particles is important, although the influence of exact shape, durability, solubility and surface chemistry, are not well understood.

e) What are the science 'fictions' in this field?

i) Public perceptions

There is a perception that things that are too small to be seen are somehow in the realm of science fiction. It is important for scientists to engage with the public about nanoscience and nanotechnology to inform them about the opportunities and risks

For example, the use of clean rooms in the fabrication of nanomaterials can be a cause of disquiet amongst the public. Clean rooms are often associated (e.g. in movies) with highly infectious diseases and radiation, and not the life improving technologies such as integrated circuit manufacture, where they are mostly actually used.

Smart materials and self-replicating materials are often confused. This distinction is important and needs to be made clear. ‘Self-replicating’ may cause alarm, with erroneous visions of intelligent nano-machines.

ii) Exaggerated proposals from scientists

Scientists making exaggerated claims about their research and in research proposals can do considerable damage. These claims fuel public perceptions that nanotechnology is either ‘science fiction,’ or dramatic and radical, and therefore risky.

5) Electronics and optoelectronics

a) What would you add to/change about the working group's definition of nanotechnology?

Nanoscience is the study of matter at atomic and molecular scales (typically 0.1nm to 100nm), where properties differ significantly from those at larger scale.

- Generally the group was happy with this definition.
- The group noted that even though this definition of nanoscience is broad, it is not intended to replace existing disciplines (e.g. chemistry).
- It was agreed that a length scale needs to be included and that the scale given was appropriate, as it is below 100nm that properties change becoming dependent upon size and shape.

Nanotechnology is the application of this knowledge to make useful materials, structures and devices.

- It was agreed that "…by controlling shape and size at the nanometer scale" be added to the end of the definition, so that the control/manipulation element to nanotechnology was captured.

It was agreed that debate over definitions of nanoscience and nanotechnology could be very time-consuming, and that the working group's definition was broadly accepted and workable.

b) What is the current state of knowledge in the field of your breakout group, and where is research going?

Current research

i) Electronics

- Current research mainly involves silicon-based semiconductors. The International Technology Roadmap for Semiconductors (ITRS) (http://public.itrs.net/) sets out the progress of semiconductor technology and is well-defined until 2016.
- Chip dimensions have been shrinking for 4 decades (100nm transistor in production in 1988, 15nm transistor today). Nanotechnology has featured for many years in characterization and fabrication, as well as devices.
- Semiconductors is a highly focused area where the science and technology are closely coupled. Around 10% of all world trade and 1% of all R&D is in IT and electronics.
- Data storage technology (e.g. magnetic hard disk, optical (CD and DVD) and flash memory) is strongly linked to Si roadmap and already uses nanotechnology, though its roadmap does not extend as far as that of the ITRS.
- Modeling: Issues in describing short gate-length transistors are basically understood. Work is continuing to simulate highly confined devices either by modifying a Monte Carlo treatment or by incorporating a full quantum mechanical approach. How modeling develops once the end of roadmap is reached is less clear.

ii) Optoelectronics

- Currently, elements for circuits are of the order of several microns in size, and circuits of the order of cms.

- There are examples of nanotechnology in optoelectronics - eg quantum well lasers and liquid crystal displays have nanometre precision in 2-D - but in general no commercial device needs 1nm precision to work.
- There is now an optoelectonics roadmap, which builds substantially on the silicon roadmap but is 10-20 years behind it in terms of dimensional tolerances.
- Almost all tools in optoelectronics come from electronics. As metrology becomes more demanding the nanotechnology tools in electronics will be the first choice for optics.
- Unlike semiconductors, there is no single fabrication technology in optoelectronics.
- Optical components are beginning to be integrated into silicon e.g. vertical lasers.

Where is research going?

- It was agreed that the distinction should be made between research that is on the silicon roadmap, and that that is beyond or alternative to it. (For example Semitech have developed an alternative roadmap for alternative materials).

On roadmap

- New, improved architectures.
- High-K dielectrics, new light sources, new interconnects

Beyond roadmap

- New materials. Although also part of the roadmap, research into development and characterization of fundamentally new nanostructured materials with tailored physical properties will be important. Allied to this will be new processes for incorporating these materials. The importance of being aware of but not driven by industry needs was highlighted.
- Nanotube transistors
- Plastic electronics. Here key enabling processes are needed, in which Kodak are likely to lead. Devices such as plastic transistors have many potential applications (e.g. environmental monitoring, customs, as alternative to bar codes) if prices can be kept down.
- Molecular electronics. Here the difference between plastic and molecular electronics was highlighted – plastic electronics is based on condensed phase properties of polymers, whereas molecular is based on properties of individual or a small number of molecules. The group were not convinced that single-molecule electronics existed yet.

The need for realism about new device structures, especially as a replacement for silicon, was noted. Bio or plastic electronics may offer a key niche market but there is such investment in silicon that it will continue to be the dominant technology for the foreseeable future. The III-V's industry was also noted as an important one.

c) What applications of this technology currently exist, and what can be envisaged in the short and long term?

i) Near-term (< 10 years)
–Quantum dots for broadband amplifiers
–Integrating sensors on silicon, and with communications
–Nanostructured materials for roadmap
–Solid-state lighting
–Single photons on demand for quantum cryptography

–All-plastic circuits (smartcards etc)
–Advanced characterization
–Biocompatibility
–Solid-state memory

ii) Long-term (> 10 years)
–Smart dust
–Nanoscale molecular logic
–Process convergence
–Point-of-care health screening
–Quantum computing

d) What are the potential hold-ups in turning research into products? What is needed (time, money etc) to enable this process to happen?

The need for research to link into technology drivers at an early stage was highlighted.

The following potential hold-ups were identified

- Processability – there are intrinsic difficulties in manufacturing such small devices.
- Scale-up – need to integrate nano-phenomena to the macro world in order for people to view or use it.
- Cost of demonstrator stage (accessing a FAB facility)
- Public perception and engagement – if the public perceive these technologies negatively or do not engage with them this will adversely affect their development.
- Regulatory issues (for healthcare applications)
- Skills base (especially in the UK). The need for government promotion of interdisciplinary research was discussed. Funding agencies play a critical role in encouraging collaboration and should coordinate to produce common calls in a common language. However, the idea of developing 'nanotechnology' degrees was considered premature; what is needed are good multidisciplinary teams, not interdisciplinary people. Training at a Masters level was considered ideal - the example was given of the joint Cambridge-MIT Institute which is developing an interdisciplinary Masters programme which will be awarded jointly by engineering, mathematics, medicine and biology departments. In order to facilitate cooperation, good networking and technical help is needed.
  H. Fuchs, of Physikalisches Institut, Munster, and H. Craighead at Cornell University in USA were also highlighted as two examples of people who have established a strong interdisciplinary environment although there are many other examples.
- Nationally and internationally networked facilities.

e) What are the science 'fictions' in this field?

The group took a broad view of science 'fictions' and included not only those ideas that are physically impossible but those that are very unlikely due to economic, social or technological constraints.

- Practical single-molecule electronics
- Practical single-atom data storage
- Virtual life systems – the digitization of all matter
- 3D totally self-assembled functional architectures
- Controlling physical properties beyond isolated nanostructures. It has been suggested that nanotechnology could potentially convert one element or compound into another at will. It was agreed that neither the technological nor the economic arguments supported this assertion. There is an enormous difference between controlling the physical properties of a single nanostructure in isolation and manufacturing a material whose properties are those of the individual nanostructures.

f) Consider the same questions with respect to a related or interfacing technology

The group chose bionanotechnology because they considered the interface between biology and electronics to promise the biggest breakthroughs. Nanotechnology is providing the tools for the structure-function relationship of molecules to be probed and understood. Potential applications of such knowledge included sensing (single-cell, single-molecule), monitoring, treatment, targeted drug delivery. In order to maximize potential of this area there needs to be promotion of interdisciplinary activities (e.g. Masters programmes), cohesion between funding agencies, and a networking of resources.

However, such developments also have important ethical and regulatory implications, and must proceed carefully.

6) Bionanotechnology and nanomedicine

a) Comments on the definition

- *There was support for the NNI and DTI definitions.*
- *However there was a need to recognise that the definition might evolve over time*
- *It was suggested that it might be possible to use the dictionary definition of technology and add 'nano'.*
- *It was felt that there was a need to mention manipulation in the definition*
- *One simple definition of nanotechnology is:* 'Nanotechnology is the application of nanoscience'
- *There was a lot of discussion about whether 'useful' is an appropriate word. People's definition of whether an application is useful will vary. The response to the suggestion of replacing with 'of benefit to mankind' was that it was too anthropogenic and might exclude applications of benefit to the environment.*
- *Nanoscience is not a new discipline but a new agenda that different disciplines can contribute to.*

Specific comments in brackets:
Nanoscience is the study of matter *(suggestion that 'matter' implied a physics bias to nanotechnology, suggest finding another term)* at atomic and molecular scales (typically 0.1nm to 100nm), where properties differ significantly from those at larger scale.
Nanotechnology is the application of this knowledge to make useful (remove useful) *materials, structures and devices* (not obvious that this could relate to bionanotechnology so add: ', including biological and medical applications').

Suggestions:
"Nanoscience is the study of novel phenomena and properties of materials that occur at extremely small length scales – on the scale of atoms and molecules."

"Nanotechnology is the application of nanoscale science, engineering and technology to produce novel materials and devices, including biological and medical applications."

b) Current state of knowledge and where is research going

i) General
- Research is strong in building up systems rather than breaking them down

ii) Targeting drug delivery
- Lots of research is being undertaken into in vivo cellular uptake targets for drugs. This includes developing DNA delivery vehicles for gene therapy and the delivery of therapeutic proteins to their site of action.
- We need to understand the barriers that control drug release and to be able to internally monitor the system.
- Avoiding flocculation of such small particles in the body is a challenge
- If we can target drugs using nanomaterials then we may be able to use drugs that failed previously as they were too toxic when delivered via conventional routes. This is highly relevant to cancer drugs.

iii) Tissue engineering

- There will be a big demand for nanotechnology in tissue engineering, especially in areas such as cell therapy and organ regeneration.
- Nano scaffolding for cells, response of cells to textured surfaces. Has relevance to implants (e.g. hips). The ability to suggest a pattern to cells is the key; embossing methods could be important.
- As with drug delivery, biodegradability is the key and being able to tune this over time.

iv) Drug discovery
- Focus is on designer drugs that are targeted to an individual's medical profile.
- Nanoarrays are used for screening. If there was an improved knowledge of cellular markers and systems biology, then we could use nano for ultra high throughput analysis.
- The industry does not necessarily badge its work as nanotechnology but is active in the field.
- These developments are reflected in miniaturization and lab-on-a-chip devices that allow rapid sample movement, reagent mixing and analysis.

v) Non-invasive imaging/monitoring
- Research in non-invasive imaging/monitoring utilizing hollow spheres, including fullerenes and buckyballs. Quantum dots may be used in the future to look at a single cell providing we can get them in without destroying the cell. Non-invasive imaging could reduce number of animals used in testing.

vi) Hybrid biological/physical entities
- Research is starting to produce hybrid biological/physical entities e.g. molecular motors. This is at the basic research level with little prospect of commercial applications in the near future. Current research programmes should provide a better understanding of the underlying biology – which is essential for future applications. Robustness and stability are a major challenge; in the future this area may impact on nanofluidics and lab-on-a-chip devices.

vi) Other
- The development of nanocrystals as simple detection systems for bacteria.
- Research into the effect of nanoscale particles on protein folding and structure, and in particular the possibility that proteins may be unfolded by nanometre scale particles.
- Getting nanosytems/materials that match particular drugs is a challenge. Use of nanoparticle-based materials is not well developed
- Nanotechnology has a role in sensors for environmental monitoring

c) Applications (current or next 2 years)
- Polymer macromolecular complexes for the delivery of therapeutic proteins to their site of action
- Microdroplets of the antibiotic Cyclosporin in micelle based systems
- Oral vaccines based on nanoparticles are close to market, advantageously this avoids the need for injection
- Super-paramagnetic crystals for diagnostics in healthcare
- Nanocrystaline silver in wound dressings – on market
- Hip joints with nanostructured covering containing anti-inflammatory drugs
- Matrices for cell growth
- Monolayers as biosensors
- Biocompatible phospholipid monolayers
- Use of quantum dots as analysis tools for drug screening
- Self cleaning surfaces (e.g. glass)

- Antifouling paints without bio-accumulating chemicals
- Widespread use of nanoparticles in cosmetics
- Microneedles for injection of vaccines & artificial tan at right level of skin;
- Smart soap powders that remove only the stain and not the dye in the material.
- Arrays of AFM cantilevers for multiple sensing and analysis applications, including environmental monitoring and health screening.

d) Long-term applications

- Creating novel tissue engineering scaffolds for organ regeneration.
- Gene therapy delivery, targeted delivery of DNA to the cell nucleus.
- High throughput gene sequencing. Great value in being able to sequence a genome in half a day. But bioinformatics and data storage will need to develop at an equivalent rate for these benefits to be realised.
- Connecting nanoelectronics with neurons. Utilization of body parameters for the control of devices, from the automated control of artificial limbs to mobile phones that detect willingness to accept a call and planes that can be controlled via brain impulses.
- Big Pharma next 10-15 years. Designer drugs based on a person's genotype. Also increased efficiency of screening techniques and less waste/use of solvents etc.
- Great potential to increase energy efficiency (Smalley's work).
- Prospect for imaging systems based on moving microtubules over a surface.
- The nanoscale research will also lead to a greater understanding of biology rather than have general applications. This highlights importance of not being governed by applications when setting research priorities.
- Cochlea and retinal implants; integration of biology and Silicon devices.

e) Barriers to progress in nanotechnology

- A lack of understanding of biological systems will slow many developments
- Hype/oversimplification by biotech companies including university spin-offs. Pressure for universities to generate income through tech transfer means there are fewer people to take an independent view of some of the claims about progress.
- Nanotechnology suffers from the problems that other interdisciplinary research areas face. UK funding is based on individual disciplines and also separates pure and applied fields – Research Councils need to have overlapping remits. It is difficult to attract people to a new field like nanotechnology as there is a perception of poor job security in the field. The Research Assessment Exercise is also hindering collaboration. Industry want graduates from specific disciplines and postdocs trained in interdisciplinary areas. There is concern that the UK will be unable to provide workforce that industry will need. In Asia they have identified the type of skills and number of people required and established appropriate university courses. Existing UK nanotech strategies don't explain how the skills base will be provided.
- Links with industry: It was felt that science needs to have close links with industry to turn nanoscience into nanotechnology. These close links tend to worry the public. There was the question of whether UK industry was aware of the potential of nanotechnology? Noted that pharmaceutical companies (that do recognise the potential) are unusual in investing 20% sales in R&D – for other companies it was 2-3%.
- Funding – researchers could always use more quicker funding decisions needed to keep up with advances in field. It was thought that total EU funding for nanotech was equivalent to funding in the US.

- Other concerns about funding include: whether funding for nanotechnology is new money or ‘recycled’ money; the fact that the full economic costs of research can’t be recovered and that there isn’t enough money for consumables on training studentships.
- Infrastructure. Nanosci/tech is becoming ‘big science’ with large infrastructure requirements. This requires large amounts of money to sustain the infrastructure and enable continuity in staffing; platform grants will help.
- Public perception/concerns. Community claims that nanotech will be very big. With any technology there will be the fear that possession of the technology gives power to a small number of people.

f) Science Fictions

- Nanorobots – the biocomplexity of putting a nanorobot in the body to enter and repair cells has been massively overestimated. ‘We’ll never know enough to go in and cure a cell’. This scenario also fails to recognise that the emphasis in health care is on developing non-invasive techniques and essentially persuading the body to heal itself. Much of the discussions around the artificial life/nanotech interface are highly speculative.
- Immortality – that nanotech will lead to immortality to allow death to become optional.
- Drug targeting with high specificity is likely to be much more difficult than many predict: diagnostic applications may be achieved more readily, but drug delivery with integrated controlled release is a major challenge

7) Health, safety, environmental and social issues

a) Overview

Following on from the technical sessions of the morning, the afternoon sessions comprised of three interdisciplinary groups which were asked to consider the following terms of reference of the study:

- What health, safety and environmental issues arise from developments in nanotechnology, and what will be the benefits and risks?
- Is there a need for new regulation?
- What are the social and ethical issues of nanotechnology?
- What other factors may influence the development of nanotechnology?

Although a clear minority of attendees had direct health, safety and environmental expertise, the majority of participants felt that it was important to consider and discuss these issues. This document represents a summary of the discussions in all three breakout groups. The issues raised will be followed up in subsequent meetings and workshops that the working group is holding.

b) Health, safety and environmental issues

The majority of participants raised nanoparticles as a topic of discussion due to their potential (and in some cases current) uses in the medical, cosmetic and electronics industries. A key point was made that although air breathing animals including humans have been exposed to nanoparticles generated by combustion throughout evolution, nanotechnology is now enabling new families of small particles, such as carbon nanotubes, which have potential applications across a wide spectrum of industries. Possible benefits of nanoparticles highlighted by the workshop included better targeted drugs and delivery, highly sensitive nanosensors for the detection of diseases, flat panel displays, sun creams, and ultra-strong, ultra-light composite materials.

Numerous positive environmental aspects of nanotechnology were discussed including applications under development in solar energy, desalination, water purification and bioremediation. The general point was also made that nanotechnology has the potential to create minimal waste, no solvent chemical processes with a much enhanced and efficient use of materials.

It was noted that new nanoparticles might impact on the environment during manufacture, use or disposal. It was suggested that one reasonably close to market application was the use of carbon nanotubes in displays and the environmental impacts of this were discussed. As discussed below, while some participants were keen to discover if nanotubes may have similar properties to asbestos, once they are fixed in materials and unable to become airborne, it was thought they would not present a risk. However, depending on the results of toxicity studies, disposal or recycling of products containing nanotubes may need to be carefully controlled to ensure containment.

Although the majority of attendees were not toxicologists, they were keen to discuss the issue of toxicity . They were aware that there are important adverse health effects of inhalation of asbestos fibres, and the similarity at least in shape was noted with carbon nanotubes. It was noted that in general, any long thin durable fibre is likely to cause similar effects to asbestos, unless it has an intrinsic property such as solubility in lung fluid making it less inherently toxic. The participants would like to see further study into the potential durability and toxicity of nanotubes.

There was less discussion on non-fibrous nanoparticles, although it was noted that such particles (generated by combustion and photochemistry) may be responsible for the adverse effects of air pollution. Such effects are likely to be dose-dependant, and this gave rise to discussion on the problems of measurement of nanoparticles against the background concentration of many tens of thousands in urban air. These problems will arise both with monitoring of control measures and with assessment of dose for toxicological studies. It was suggested that a trans-national effort was required to study the toxicology of nanoparticles.

The use of nanoparticles in skin preparations such as sunscreens was noted. It was thought that there was little knowledge at present on issues such as transport through the skin and toxic effects on dermal cells, and that appropriate toxicological studies were necessary.

Thin films of nanomaterials were generally considered to be of much less concern to health, safety and the environment due to the fact that they are attached to a surface and hence are much less likely to relocate to unwanted areas. Expected and current applications of nano-thin films included self-cleaning windows, computer disk drives, and smart coatings.

c) Regulation

Currently, dosage of particles for regulation purposes is defined by mass per unit volume, however this does not take into account particle size, which when approaching the nanometre scale can significantly affect properties such as absorption or reactivity. Hence it is clear that agglomeration, particle size and surface reactivity will now have to be taken into account when deciding the regulation of nanoparticles.

The issue of whether entirely new regulations or merely a modification of existing ones would be sufficient for nanoparticles remained unresolved among the participants. The point was made however that there are many types of nanoparticles and that they should not be treated as a general case when deciding regulation. To resolve this issue, further toxicological studies must be performed in order to effectively inform regulators.

The point was also made that regulations may differ between locales e.g. in the USA sun creams are categorised as drugs for regulation, while in the UK they are regulated as cosmetics.

d) Social and ethical issues

A general point was made relating to the publics' perception and media reporting of nanotechnology. It was felt that in order to conduct a rational debate, a realistic projection of the potential impacts (positive and negative) of nanotechnology must be communicated to the public. It was felt that hyped up reports from some scientists or writers have only served to confuse the publics perception of nanotechnology. This has caused confusion between what is fact and what is fiction, and may create unjustified fears. Key messages that the group felt should be put in the public domain were that nanoparticles are not new-very small particles have always been around, and that nanotechnology is multidisciplinary and an enabling technology rather than a new discipline in its own right. The best solution to these public fears was seen as better public understanding at a scientific level through the provision of better science information in school and university undergraduate curricula. The participants believed that initial progress in nanotechnology would likely be by small incremental steps in existing technology and products rather than by a series of dramatic breakthroughs. Similarly, the publics' perception that nanotechnology is different from other technologies is incorrect. Nanotechnology has however prompted the collaboration of scientists from differing fields of existing technology on a scale that probably has not been seen before.

d) Other factors

A point was raised relating to the publics awareness of commercial research and development into nanotechnology. It was felt that in general, major corporations were becoming less open to engaging the public, and indeed their own peers, in discussion about their nanotechnology research programs. A national strategy which included engaging the public, and encouraging more open discussion between peers in industry was seen as a worthwhile recommendation for the main study.

Appendix A

Nanotechnology workshop agenda
30 September 2003
The Royal Society

9.30 – 10.00 **Registration and coffee**
10.00 – 10.15 **Welcome and overview of nanotechnology study by Chair**
10.15 – 12.30 **Breakout groups**

Groups will be self-selected and led by a member of the working group.

Nanoengineering & measurement (led by Roger Whatmore)
Nanofabrication, nanometrology, nanoelectromechanical systems (NEMS), quantum well growth

Nanomaterials (led by John Pethica)
Quantum dots, nanomagnetics, nanocomposites, carbon nanotubes, nanoparticles, nanoclusters, new forms of carbon, molecular self-assembly

Electronics & optoelectronics (led by Mark Welland)
Photonics, semiconductor optoelectronics, memory and data storage, new methods for data input/output, plastic electronics, molecular electronics, quantum computing

Bionanotechnology & nanomedicine (led by John Ryan)
Drug delivery, tissue engineering, biosensors, biomaterials/implants, lab-on-a-chip technology

For the first part of the discussion groups will be asked to consider the following questions:

- What is the current state of knowledge in this field, and where is research going?
- What applications of this technology currently exist, and what can be envisaged in the short and long term?
- What are the potential hold-ups in turning research into products? What is needed (time, money etc) to enable this process to happen?
- What are the science 'fictions' in this field?

The groups will then consider the same questions with respect to a related or interfacing technology, particularly where they can identify potentially significant research or applications.

12.30 – 13.30 **Lunch**

13.30 - 14.15 **Feedback from breakout groups**

14.15 – 16.00 **2nd breakout groups**

These will be assigned and cross-disciplinary, and will be asked to consider the following questions

- What health, safety and environmental issues arise from developments in nanotechnology? What are the benefits and risks?
- Is there a need for new regulation?
- What are the major obstacles to progress in the UK?
- What are the social/ethical implications of nanotechnology?

16.00 – 16.15 **Wrap-up and thanks by Chair**

Appendix B – List of Attendees

Dr Michael Adams	Unilever
Sara Al-Bader	Royal Society Secretariat
Sir Geoffrey Allen	University of East Anglia
Professor Ray Allen	University of Sheffield
Dr Rachel Brazil	Royal Society of Chemistry
Professor Brian Briscoe	Imperial College
Professor Tony Cass	Imperial College
Professor Derek Chetwynd	University of Warwick
Dr Andrew Clarke	Kodak
Professor Roland Clift*	University of Surrey
Dr Jofey Craig	Royal Society Secretariat
Dr Peter Cumpson	National Physical Laboratory
Professor Graham J Davies	University of Birmingham
Mr Julian Delic	Health and Safety Executive
Professor Peter Dobson	University of Oxford
Dr Peter Dowding	Infinaeum
Professor Ann Dowling*	University of Cambridge
Dr John Ellis	X-FAB UK Ltd
Professor Andrew Fisher	University College London
Professor Donald Fitzmaurice	University College Dublin
Professor Sandy Florence	The London School of Pharmacy
Dr John Gallop	National Physical Laboratory
Dr Nick Green	Royal Society Secretariat
Mr Paul Holister	Cientifica
Mr Fintan Hurley	Institute of Occupational Medicine
Professor Mike Kelly	University of Cambridge
Professor Thomas Krauss	University of St Andrews
Beatrice Leigh	GlaxoSmithKline
Dr Lynne Macaskie	University of Birmingham
Patrick Mesquida	University College London
Professor Mervyn Miles	University of Bristol
Dr Julia Moore	National Science Foundation
Dr Vic Morris	Institute of Food Research
Professor Ray Oliver*	ICI
Professor Richard Palmer	University of Birmingham
Professor John Pethica*	Trinity College Dublin

Professor Nick Pidgeon*	University of East Anglia
Richard Ploszek	Royal Academy of Engineering Secretariat
Professor Julia Polak	Imperial College
Dr Rachel Quinn	Royal Society Secretariat
Professor John Ryan*	University of Oxford
Dr Matthew Schneemilch	Imperial College
Professor Anthony Seaton*	University of Aberdeen
Dr Hayaatun Sillem	Royal Academy of Engineering Secretariat
Dr Jeremy Sloan	University of Oxford
Professor George Smith	University of Oxford
Professor Ken Snowdon	Newcastle University
Professor Richard Syms	Imperial College
Professor Saul Tendler*	University of Nottingham
Dr Lang Tran	Institute of Occupational Medicine, Edinburgh
Dr Alexander Tsavalos	Health and Safety Executive
Professor Mark Welland*	University of Cambridge
Professor Roger Whatmore*	Cranfield University
Professor Chris Wilkinson	Glasgow University
Mr Neil Wilson	University of Warwick
Professor Anthony R Young	St Johns Institute of Dermatology, Kings College London

* member of nanotechnology working group