Current and potential commercial nanotechnology applications

The market for nanotechnology products is already huge and is predicted to grow rapidly in the coming years. This topic guide examines some of the key commercial applications and uses case studies to show how the market needs are met. Particular emphasis will be placed on the application of nanotechnology to computing and semiconductor applications. The miniaturisation of computing devices follows a pattern described as Moore’s law and this topic guide looks at the implications of that for nanotechnology.

Finally, the career prospects in the nanotechnology sector are considered, along with the challenges faced by the sector.

On successful completion of this topic you will:
- know current and potential future commercial nanotechnology applications (LO4).

To achieve a Pass in this unit you need to show that you can:
- describe commercial applications of nanomaterials (4.1)
- state Moore’s Law and materials requirements for its continuation in silicon to 2020 (4.2)
- outline current challenges to nanotechnology (4.3)
- describe future growth areas in nanotechnology, including career prospects (4.4).
1 Commercial applications

The market for nanotechnology

Studies of the global market for nanotechnology products suggest that it may exceed US$3 trillion by 2018 (source: Global Industry Analysts, 2012). This figure is dominated by the value of markets for nanoscale semiconductors as well as those for some nanoparticles, such as carbon black additives, which have been in high-volume use for many years, predating the introduction of nanotechnology.

A second report (BCC research, 2011), which excluded semiconductors and the high-volume additives, estimated the global market for nanotechnology at over US$20 billion in 2011, and predicted that it would rise to almost US$50 billion by 2017.

This second report covered nanomaterials (nanoparticles, nanotubes, nanostructured materials and nanocomposites), nanotools (nanolithography tools and scanning probe microscopes) and nanodevices (nansensors and nanoelectronics). It excluded the use of nanoscale semiconductors, as well as certain other applications of nanoparticles such as the use of carbon black additives, as these have been in high-volume use for many years, predating the introduction of the nanotechnology techniques covered in this unit.

Take it further


Individual reports on the market for different types of nanomaterial can also be accessed from the report website.


Nanoelectronics

Transistors

Transistors are the fundamental building blocks of electronic devices. They possess three (or sometimes four) separate terminals, each made from a different type of semiconductor material. When placed at a junction of an electronic circuit, the behaviour of the different semiconductor materials enables them to switch or amplify input signals.

The speed at which transistors operate is dependent on their size; using nanotechnology can clearly be used to reduce the size of transistors. This can, however, generate too much heat, reducing efficiency. However, whereas conventional transistors are based on silicon semiconductors, nanotechnology enables them to be built from materials such as carbon nanotubes or indium arsenide, which produce far less heat. These are discussed further in Section 2 of this topic guide.
Other advantages or potential advantages could include:
- reduced weight
- reduced power consumption
- making electronic circuits from flexible materials.

**Take it further**

Brief, non-technical reports into recent research developing new applications of nanoelectronics are available from [http://www.understandingnano.com/nanotechnology-electronics.html](http://www.understandingnano.com/nanotechnology-electronics.html).


**Activity**

Choose one example of a new application of nanotechnology in nanoelectronics (for example, the use of carbon nanotubes or graphene in electronic circuits) and explain why this might have been commercially desirable.

**Photonics and optoelectronics**

Nanomaterials can have unusual optical properties because of the way in which electrons in the material are constrained in one or more dimensions.

The ancient use of nanoparticles in pigments added to glass makes use of this optical effect; the colour of the pigment depends on the size of the nanoparticles.

**Quantum dots**

These have been discussed several times in previous topic guides. As explained elsewhere, they have a band gap somewhat greater than semiconductors, and the size of the band gap can easily be manipulated by altering the size of the quantum dot.

This has enabled them to be used in several ways in photonics applications. For example:
- They are becoming widely used in QDLEDs (quantum dot light-emitting diodes). When stimulated by the passage of an electric current or an ultraviolet light source, quantum dots emit precise wavelengths of light; by combining quantum dots of different sizes, a range of very pure coloured emissions can be produced. In computer or TV displays this could lead to very pure and vibrant colours being produced with low power consumption. Because quantum dots can be produced as colloids from solution, they can be deposited on polymer-based substrates, leading to the development of ultrathin, flexible displays.
- They may have exciting applications as chemical or biological sensors. Chemical bonding at the surface of a quantum dot affects the wavelength of the emitted light when the quantum dot is stimulated by ultraviolet light. Quantum dots can be made to specifically bind to a range of chemical or biochemical species and can thus be used to detect these species in solution or to produce images of cells containing these species.
They are also widely used in laser diodes, as well as having important applications in quantum computing (see page 5).

**Take it further**

Further information about quantum dots and their applications in photonics can be found at [http://www.rp-photonics.com/quantum_dots.html](http://www.rp-photonics.com/quantum_dots.html), with links to more technical information about photonics principles.

The use of QDLEDs is described in more detail at [http://www.qdvision.com/qled-technology](http://www.qdvision.com/qled-technology).

**Metallic nanoparticles**

The historic use of gold nanoparticles has been mentioned already. The unusual colours observed in substances containing these particles relies on an effect called plasmon resonance, which is only weakly seen for bulk metal surfaces in contact with **dielectrics**, but is much more intense for metallic nanoparticles.

The optical properties of these nanoparticles depend not only on their size but also on the nature of the dielectric and any molecules bound to the surface of the nanoparticles.

Applications include:

- sensors – used in a similar way to the quantum dot sensors described above
- in photodynamic therapy for cancer: gold nanoparticles can be modified to bind specifically to tumour cells. When irradiated with radiation of specific wavelengths, they absorb it strongly and convert it into heat, which kills the cells to which they are attached.

**Take it further**


**Computing**

**Magnetic data storage**

Data can be stored in computer systems and other applications by magnetic storage media. In previous decades, storage on magnetic floppy discs was very common, but today such magnetic storage is restricted mostly to computer hard drives and magnetic strips on credit cards.

The principle of magnetic data storage is that small grains of magnetic materials, such as iron oxide, may become magnetised in two different directions by a recording process, and the data is stored as patterns of magnetisation.

The density of data achievable from magnetic storage has changed dramatically over the decades:

- **1956**: 2 kbit/in²
- **2005**: 100–250 Gbit/in² (an increase of approximately 10 000 000 fold).
To continue this trend, the magnetic grains could be formed from nanoparticles; recent research has used iron-based alloys with a grain size of 3 nm or less.

**Quantum computing**

A practical quantum computer is probably many years away. But the potential of the technology is incredible and will provide a massive market for the nanotechnology required to build such a device.

Essentially quantum computing makes use of the potential for individual particles (such as electrons and atoms) to simultaneously exist in two separate states, a phenomenon known as superposition.

Quantum dots can be engineered to contain electrons which simultaneously possess opposite spins, and much research is currently being carried out to develop quantum computers based on such quantum dots.

**Take it further**


A more recent and detailed (but still non-technical) article is [http://computer.howstuffworks.com/quantum-computer.htm](http://computer.howstuffworks.com/quantum-computer.htm).

**MEMS and NEMS**

As discussed in Topic guide 11.3, MEMS and NEMS are micro- or nanoscale devices containing moving mechanical components.

MEMS devices have rapidly found a market to replace the equivalent macroscale devices as microsensors or microactuators. The ability to use similar fabrication techniques to those used in integrated circuit technology has reduced costs and increased product quality and performance compared to macroscale devices.

Strictly, some of these MEMS devices fall outside the definition of nanotechnology but the developing field of NEMS devices will integrate conventional integrated circuit technology and nanotechnology.

**Take it further**

Good coverage of the current applications of MEMS devices is available on the MEMS-exchange website [https://www.mems-exchange.org/MEMS/what-is.html](https://www.mems-exchange.org/MEMS/what-is.html); other examples of applications of MEMS are discussed at [http://www.csa.com/discoveryguides/mems/overview.php](http://www.csa.com/discoveryguides/mems/overview.php).
Case study: MEMS as sensors

In an acceleration sensor (or accelerometer), a beam attached to a ‘spring’ (which can be a tethered cantilever) moves in response to an applied acceleration, as shown in Figure 11.4.1. The movement of the beam relative to fixed plates is converted into an electrical signal.

The various components of the accelerometer are fabricated from silicon or silica and can be seen in the electron micrograph of a MEMS accelerometer (see Figure 11.4.2).

Take it further

An excellent video clip is available on YouTube (at http://www.youtube.com/watch?v=KZVgKu6v808) that describes the principles and fabrication of an accelerometer used in a smartphone to detect the orientation of the phone.

Activity

MEMS accelerometers are used as orientation sensors in mobile phones, as described in the Take it further feature above. Research other possible uses of MEMS or NEMS accelerometers.
Nanotechnology applications

Nanobio applications

The interplay of nanotechnology with biology has created several areas with interesting applications, for example:

- using nanotechnology to study biological systems
- using nanotechnology to diagnose and treat medical problems (nanomedicine)
- using biological processes in nanofabrication techniques (biomimetics).

Studying biological systems

Quantum dots (see above) have been used to image biological processes occurring on a molecular level. The quantum dots are modified to allow them to bind to specific biological molecules. Irradiation with ultraviolet light causes them to emit light of a characteristic frequency and show the location of these biological molecules. Continuous monitoring of biological systems allows biologists to watch how the molecules behave during cell processes such as microtubule growth.

Nanomedicine

Examples of nanomedicine techniques already in use or under development include:

- drug delivery systems using nanoparticles
- phototherapy using gold nanoparticles (discussed above)
- the possibility of using scaffolds with nanoscale features in regenerative medicine, such as artificial retinas, bones or even complete organs
- nanoscale diagnostic biosensors to detect and assay traces of biological molecules (for example, using quantum dots, as discussed above)
- more speculatively, nanomachines (described as nanorobots) capable of performing repair work inside the body while being monitored and controlled from outside.
Drug delivery systems

Drugs are frequently delivered encapsulated in a macroscale polymer coating; this enables the drug to be released in the most appropriate part of the body, for example, the stomach or intestine.

If the encapsulation is on a nanoscale, then the drug can be targeted at particular cells and deliver a precisely calculated dose. The drug is frequently trapped within a lipid bilayer micelle (see Topic guide 11.2) or sometimes dissolved in the lipid bilayer itself. The key feature of nanoscale drug delivery systems is the ability to functionalise the surface of the nanoparticle to recognise specific tissue or cell types, to change the solubility of the particle or to prevent destruction by the immune system.

Biodegradable polymers can also be used to encapsulate the drug, allowing slow, controllable release of the drug.

Alternatives to encapsulation include attaching the drug to the surface of gold or fullerene nanoparticles.

MRI contrast agents

Magnetic nanoparticles, fabricated from substances such as gadolinium or iron, have been used to improve MRI scanning. An MRI scanner produces images of living tissues from the radio frequency (RF) radiation it emits when placed in a powerful magnetic field. A contrast agent is needed to increase the efficiency of this process; by using nanoparticles the contrast agent can be engineered to become concentrated in areas of particular interest such as tumours.

Take it further

A balanced article (from 2007) looking at the future prospects of drug delivery systems on the nano- and microscale is available at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1949907/.

A detailed paper evaluating the hazards of the medical use of nanoparticles is available at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2527668/.

Portfolio activity (4.1)

Prepare a report on current and future commercial applications of nanotechnology.

In your report you should:
- give an overview of the main areas in which nanotechnology is, or may become, important
- select two nanotechnology products that currently have commercial applications
- explain how the product meets the commercial need
- comment on the size of this market
- do the same analysis for two products that are in development.
2 Moore’s law

As described above, modern electronics and computing relies on the use of semiconductor based transistors. Over time, the size of transistors has been continuously reduced, leading to smaller and faster electronic components and hence increased processing power.

The story of Moore’s law

In 1965, a young engineer at Intel, then a small company manufacturing integrated circuits, wrote an article in the magazine *Electronics* predicting that the number of transistors on an integrated circuit (or ‘chip’) would double approximately every 2 years. Initially he suggested that this trend would continue for 10 years, but the prediction has proved remarkably accurate over a period which, at the time of writing, has now extended to almost 50 years.

Plotting transistor numbers per chip on a logarithmic scale against time, as shown in Figure 11.4.3, shows a linear pattern – which is exactly what Moore’s law predicts. Indeed, the observed increase in gradient suggests that the doubling time period may be decreasing, to nearer 18 months than 24 months.

Other implications of Moore’s law

Several other key performance indicators of integrated circuits have followed Moore’s law:

- In 1955, the annual production of transistors could be measured in the millions. In 2003, production came to around a quintillion, or a trillion million.
- In 1954, the average price of a transistor was US$5.52. In 2004, the average cost was 191 nanodollars, or 191 billionths of a dollar.
- The computational energy efficiency – measured as the number of computations per kWhr – has also doubled approximately every 1.6 years to reach $1 \times 10^{15}$ in 2010.

The future use of silicon

Conventional transistors are formed from three layers of silicon. The different layers of silicon contain impurities such as arsenic or boron to create ‘doped’ silicon crystals.

However, in the years leading up to 2020, the thickness of these layers will become reduced to as little as 5 nm, requiring nanotechnology fabrication techniques.
This produces a variety of problems for silicon-based transistors. Reducing the size of the layer to atomic levels means that, at some point, just a single doping impurity atom will be necessary, which means it will need to be fabricated with great care and control.

This could be done by:

- creating single atom transistors using scanning tunnelling microscopy techniques
- using new transistors based on combinations of group III and group V atoms (such as gallium-arsenide).

Other possibilities include the use of graphene or carbon nanotubes as semiconductor materials in place of silicon, but research on these is at an early stage.

**Take it further**


**The continuation of Moore's law – post 2020**

Although Moore's law has proved remarkably accurate over the past four decades or so, there are good reasons to suggest that transistor density will eventually reach a finite limit:

- at around 2020, components of integrated circuits will be close to atomic size and further size reduction will become impossible
- lithography will become more complex and costly as the size of components becomes similar to the wavelength of light
- the heat generated by the high density circuits will become a major problem
- quantum effects will become significant and will reduce the reliability of the devices (see below).

**Quantum effects**

Once components are reduced to an atomic scale, effects such as quantum tunnelling become significant. This was encountered in the context of the scanning tunnelling microscope in Topic guide 11.2 and describes the ability of electrons to pass through a barrier that would normally constrain them. This would allow leakage of current from the components of transistors and the reliability of these devices would start to reduce.

Of course quantum effects may have positive implications as well, such as the superposition phenomenon, which could theoretically be used in the development of quantum computers. But to overcome the undesirable quantum effects and to make use of the desirable ones will require the end of the use of conventional transistor technology based on silicon.
Nanofabrication techniques in semiconductors

Silicon-based integrated circuits are fabricated using lithography and micromachining techniques, as described in Topic guide 11.3.

As the size of the components in the system is reduced in accordance with Moore’s law, nanolithographic techniques will become more important. This will involve using X-rays or electron beams rather than light-based lithography as the dimensions of the components become close to the wavelength of visible light.

As discussed above, single atom transistors may be fabricated using scanning tunnelling or atomic force microscopy to place atoms precisely on a substrate.

Portfolio activity (4.2)
Write a report on the future of Moore’s law. In your answer you should:
• describe the prediction made by Moore
• explain the difficulties that will be encountered in the years up to 2020 if Moore’s law is to continue to be valid until 2020
• give some examples to illustrate how conventional silicon-based technology might be adapted to overcome these difficulties
• explain why many scientists believe that Moore’s law will reach a limit at some point beyond 2020.

Take it further
An article celebrating 40 years since the proposal of Moore’s law, including an interview with Gordon Moore, is available at http://news.bbc.co.uk/1/hi/technology/4446285.stm.

Take it further
3 Nanotechnology challenges and career prospects

If the market predictions for the growth of the nanotechnology sector are to be realised then a number of challenges will need to be overcome.

Skills and training

Skilled workforce

The nanotechnology sector will require skilled workers for a range of tasks:
- R & D
- manufacturing
- quality assurance
- preparation of documentation
- marketing
- distribution.

With the exception of semiconductor manufacture and the manufacture of some bulk nanoparticles such as carbon black, most products of the nanotechnology sector are low volume speciality products. Designing, fabricating and controlling the production of these products are high-skill operations and there will be high demand for workers with these skills.

Workers in the industry will require:
- safety and environmental awareness
- skills in operating specialised fabrication and characterisation equipment
- skills of process design and control
- professional skills such as problem solving, team management, report writing and presentation skills.

Skills shortages

The Institute of Nanotechnology reported in 2008 that 24% of nanotech companies regarded their most significant problem as the recruitment of nanotechnicians with suitable experience. The New Engineering Foundation in a 2009 report estimated that there was a shortfall of over 66 000 skilled workers in the nanotechnology sector – the largest of any engineering or scientific sector in the UK.

Many companies look to recruit graduates with suitable skills; however, at the time of writing (2013) only one university in the UK offered a specialist nanotechnology degree, while a small number of other institutions offer courses in nanotechnology combined with subjects such as physics, electronics or chemistry. Most nanotechnology courses in the UK are at postgraduate level.

Take it further


Take it further

A European report on the skills needed for the development of the nanotechnology industry was produced in 2006. It can be read at http://www.cedefop.europa.eu/EN/Files/5170_en.pdf.

Investment in nanotechnology

US and European investment

With a trillion dollar global market at stake, investment in nanotechnology in many parts of the world is at a very high level. Between 2003 and 2008, funding grew at 27% per annum, and in 2009, in the US alone, investment totalled US$5.7 billion, of which $1.9 billion came from federal and state funds.

In 2004, the European Union investment for nanotechnology was US$3 billion, similar to that of the US, with member states investing $1.4 billion and the EU itself $0.5 billion.

Investment in the UK

The UK has a leading place in nanotechnology research – it is placed fourth in the world in terms of patent applications and fifth in terms of published papers. There are concerns, however, over investment levels in the UK. As early as 2002, the Taylor report New Dimensions for Manufacturing: A UK Strategy for Nanotechnology concluded that ‘the UK is indeed behind its major international competitors in the industrial exploitation of nanotechnology, and in the level of UK industrial support for R&D on nanotechnology applications’. Despite this, government funding in 2008 was just US$0.12 billion – $1.96 per capita, compared to $5.06 in the US and $6.07 in Germany.

Take it further

The parliamentary report from 2004 provides much data about the investment issues affecting the UK nanotechnology industry: http://www.publications.parliament.uk/pa/cm200304/cmselect/cmsctech/56/56.pdf.

The view of the materials industry itself is represented by their 2009 report: http://www.matuk.co.uk/docs/Nano_report.pdf.

Risks of nanoparticles and public perception of nanotechnology

Several suggestions have been made about the lack of investment by UK industry and venture capitalists in nanotechnology, but one possible explanation is the concern over the health and safety aspects of the technology.

Grey goo – public perceptions

Nanotechnology has had a major public image problem since 2003, which saw the creation of headlines about the ‘grey goo problem’. This was an entirely hypothetical suggestion that the production of self-replicating nanomachines could result in a scenario in which the self-replication spiralled out of control, creating billions of machines consuming organic molecules as energy and converting the entire biosphere into a mass of grey, gooey nanostructures. Such a science fiction scenario proved attention grabbing to the public and has left a residual unease about the technology, which is unresolved to this day.

Risks of nanoparticles

However fantastical the grey goo scenario, there are genuine concerns over the potential risks of exposure to some types of nanoparticle. There is a particular health risk for nanoparticles because their nanoscale dimensions allow them to be transported around the body in the bloodstream and to penetrate many tissue types. Nanoparticles may enter the body by being breathed in, but also by absorption through the skin.

Many nanoparticles are able to pass through cell membranes, potentially causing dangerous interactions with cell processes.

Assessing the toxicity of nanochemicals

Nanoparticle toxicity cannot be assessed in the same way as that of ingestion of chemicals in a bulk form. Usually, the toxic effect of a chemical increases predictably with the mass of chemical ingested. In the case of nanochemicals, many other factors need to be taken into account, most notably the particle size of the nanochemical.

This data may not be widely available in all situations where nanochemicals are being used, making it difficult to predict the potential hazard of the substances.

The most likely risk from using nanochemicals is exposure to dust containing nanoparticles, which may consequently be breathed in or absorbed through the skin.

Take it further

A report from the National Building Specification on assessing the health risks of working with nanoparticles provides a helpful introduction to health and safety issues: www.thenbs.com/topics/constructionproducts/articles/nanoparticleRiskManagement.asp.

A very detailed, comprehensive survey of health and safety issues relating to the fabrication of nanoparticles is available in the 2004 HSE report: http://www.hse.gov.uk/research/rrhtm/rr274.htm.

Information about the toxicity of a range of nanoparticles can be found in the parallel 2004 HSE report: http://www.hse.gov.uk/aboutus/meetings/iacs/acts/watch/130105/p2annex1.pdf.
Other safety issues

The high surface/mass ratio of nanoparticles can also increase the risk of fire or explosions due to rapid oxidation of reactive metals or organic compounds.

I provide services to a number of clients, including DEFRA. The speed at which nanotechnology has developed means that there is often insufficient data about exposure levels to manufactured nanomaterials both in the environment and in occupational situations. I conduct field work to collect data about the exposure to a range of nanomaterials. The results of these studies and laboratory investigations under controlled conditions will enable my team to be able to create models of exposure levels that can be used to estimate risk levels for future scenarios in which nanomaterials are being used or fabricated.

Nanochemicals in the environment

Nanoparticles are now used in a range of consumer products on the market, such as cosmetics, foods, textiles and building materials. While there are already legally enforceable regulations about the safety of substances present in these products, there is concern that conventional risk assessment procedures may not be reliable when applied to nanoparticles, for the reasons discussed above.

Take it further

There is a useful forum, setting out some of the views about the safety of nanoparticles in consumer products in a reasonably objective manner, at http://www.nanoandme.org/home/.

Portfolio activity (4.3)

Write a report into the challenges that face the UK nanotechnology industry. In your answer you should comment on:
- to what extent the need for investment in the industry is being met by current sources of funding
- the scale of the skills shortage in nanotechnology
- the difficulty of assessing and controlling risk in the handling of nanoparticles.

Career prospects and future growth

Despite the challenges described above, the career prospects in the nanotechnology sector appear bright. Globally, it has been estimated by the National Science Foundation in the US that the nanotechnology industry will be employing 6 million workers by 2020 (of which 2 million are likely to be employed in the US).

While the UK’s nanotechnology sector is currently considerably smaller, a recent government report (UK Nanotechnologies Strategy, 2010) estimated the number of companies involved in nanotechnology at 220, with considerable potential for growth if the issues of skills shortages and investment are addressed successfully.

Future growth areas

In a fast-changing nanotechnology world, prediction of future growth areas is inevitably an uncertain science, but several of the applications already mentioned...
in this topic guide are likely to become commercially important over the next 5–10 years:

- quantum dots in LEDs
- drug delivery systems in medicine
- quantum computers based on quantum dots or graphene
- nanoparticles as diagnostic tools or biological sensors
- magnetic nanorods in data storage (nanomagnetics)
- using DNA to store information (bioinformatics).

**Take it further**


**Activity**

Most of the areas listed above have been discussed in detail in one of the topic guides for this unit, with the exception of the DNA storage aspect.

Research this aspect of nanoscience and write a short report on how DNA technology can be used in this way and the commercial potential of this.

**Portfolio activity (4.4)**

Select two nanotechnology products from those you have studied in this unit or found by research. Evaluate their potential as a future growth area. In your answer:

- describe the product and explain how it will meet a need
- explain why the market for this product is expected to grow
- comment on the type of jobs which might be created by the growth of this market.

**Checklist**

At the end of this topic guide you should be familiar with the following ideas:

- nanomaterials have very wide-ranging commercial applications in such areas as electronics, medicine and photonics
- the rapid doubling of transistor density in integrated circuits will continue until at least 2020, enabled by nanotechnology
- quantum effects and other issues will limit the capacity for density to continue increasing at the same rate indefinitely
- nanotechnology is predicted to grow rapidly worldwide over the next few years
- in the UK, this growth may be limited by the availability of investment, the shortage of suitably-skilled workers and by issues and regulations related to health and safety
- new applications of nanotechnology are continually being developed and will be areas of particular growth over the next few years.
Further reading
The pace of change in nanotechnology means that many texts looking at current developments and making predictions about future developments may become out of date very quickly. Websites, such as the ones scattered throughout the text in the appropriate places, may prove the most helpful source of current information.

The introductory presentations from the Nano4me website have been recommended as good starting points in previous topic guides (see http://nano4me.live.subhub.com/categories/modules). The two most helpful presentations in this section are Module 9: Nanotechnology, Biology, and Medicine, and Module 10: Nanotechnology: Impact on Microelectronics, which also covers Moore's law and the issues arising from it.

The end of the unit might be an appropriate point to read Engines of Creation (K. Eric Drexler, Fourth Estate Limited, 1996). A text that kick-started the nanotechnology revolution, it is now nearly 30 years old, but its thoughts and predictions on the importance and potential problems of nanotechnology are still regarded as relevant today.

The fascinating and potentially very important field of biomimetics, which has been touched on at several points throughout the whole unit, is introduced in Inorganic Chemistry (5th edition) (Shriver and Atkins, OUP, 2010), p681–686.

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David Goodfellow studied Natural Sciences at Cambridge and spent 20 years teaching A-level Chemistry in a sixth-form college. He was lead developer for the OCR AS Science in 2008 and for several years was chief examiner for the course. He now works as a freelance writer and examiner alongside part-time work as a teacher. Publications include a textbook for the AS Science course, teaching materials to accompany Chemistry GCSE courses and contributions to textbooks for BTEC First Applied Science.