NanoDialogue

How to design a participatory process for a consortium of science centres and science museums on an emerging issue at the European level.

Section A: General introduction
No. 2: NanoDialogue Working Material

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NanoDialogue

I. Context

This case study deals with nanotechnologies and nanosciences (N&N), and the overall objective of the case is to develop a participatory process within the context of museums and science centres.

What are nanotechnologies and nanosciences?
Nanotechnologies and the nanosciences are umbrella terms that encompass science and technologies of the very small scale. One nanometre is one millionth of a millimetre.

What are the uses of N&N?
Nanotechnologies and nanosciences are interdisciplinary subjects; therefore the fields of applications – and the possibilities - of N&N are numerous as they are diverse. It should be noted that by no means all of the applications areas listed below have already been realised, although many are in the development stages.

Fields of applications	Possible uses
Medical applications	- new and improved diagnostic equipment - faster detection and diagnosis of illnesses - targeted delivery of drugs - new medicines - better prosthetics and transplantations
Information technologies	- higher recording densities - improved electrical circuitry - artificial intelligence
Energy production and storage	- solar and fuel cells - cheaper, more efficient energy - new resources - more effective storage of energy
Materials	- new and improved materials - stronger, lighter, cleaner materials
Manufacturing	- miniaturised micro-systems (top-down) - miniaturised structures at the molecular level (bottom-up)
Food	- detection and neutralisation of micro-organisms or pesticides
Environment	- innovations to clean-up the environment
Security	- enhanced security systems e.g. electronic tagging of banknotes - new defence capabilities - enhanced personal security
Common use objects	- LCD television screens - sports equipment e.g. stronger tennis racquets that incorporate nano-tubes - stain-repellent clothing or with UV protection - improved surfaces of materials e.g. self-cleaning windows/glass

Citizens and awareness
Some nanotechnology products have reached the marketplace, others are in the development stages and discussed more speculatively. The public profile of such products is increasing, however, public awareness of N&N and the potential ethical, social, legal and economic issues it may raise is low.[1] This is viewed by some as cause for concern, as the possible benefits and risks of N&N may have a profound impact upon citizens' lives. Comparisons may be drawn with other technological developments, such as genetically modified crops and the ensuing GM controversy, which raised widespread public debate regarding the ethical, legal, social and economic implications. Some policy-makers are concerned that N&N may follow a similarly controversial public trajectory; therefore upstream engagement, along with a more transparent approach to public policy, is desirable.

The need for societal debate: ethical, legal, social and economic aspects
Nanotechnologies and nanosciences may present both benefits and risks, however, it is unknown how these dual possibilities will develop. In 2003, the UK government commissioned The Royal Society and The Royal Academy of Engineering to carry out an independent study into the current and future developments in nanoscience and nanotechnologies and their impacts.[2] The study was carried out a Working Group (expert panel) that comprised of experts from the fields of science, engineering, social science and ethics, and two interest groups (one consumer association, and one from the science and technology industry).

In 2004, the report *Nanoscience and Nanotechnologies: opportunities and uncertainties* was published. The report made recommendations that addressed the industrial application of nanotechnologies, the possible adverse health, safety and environmental impacts, along with a broad range regulatory issues. The recommendations also focussed upon social and ethical issues, stakeholder and public dialogue, and methods to ensure the responsible development of nanotechnologies.[3] The societal impacts were described thus:

> The future applications of nanotechnologies are difficult to predict, especially as they converge with other technologies such as information technology. The use of small sensors and powerful computers could lead to

[1] European Commission Directorate General Research, 'Europeans and Biotechnology in 2002', *Special Eurobarometer 58.0*, 2nd Edition (Brussels: March 2003). Available: http://ec.europa.eu/public_opinion/archives/ebs/ebs_177_en.pdf; European Commission Directorate General Research, 'Social Values, Science and Technology', *Special Eurobarometer 225* (Brussels: June 2005). Available: http://ec.europa.eu/public_opinion/archives/ebs/ebs_225_report_en.pdf.

[2] The Royal Society & The Royal Academy of Engineering (2004) Nanoscience and Nanotechnologies: opportunities and uncertainties. pp. vii. The remit of the study was outlines as follows: define what is meant by nanoscience and nanotechnologies; summarise the current state of scientific knowledge about nanotechnologies; identify the specific applications of the new technologies, in particular where nanotechnologies are already in use; carry out a forward look to see how the technologies might be used in the future, where possible estimating the likely timescales in which the most far-reaching applications of the technologies might become reality; identify what health and safety, environmental, ethical and social implications or uncertainties may arise from the use of the technologies, both current and future; and identify areas where additional regulation needs to be considered.

[3] Ibid. pp. 85-87

greater personal security and safety, but the same technologies could also be used to spy on people and raise concerns about civil liberties.

Military applications could include nano-sized sensors to speed the detection of chemical and biological weapons. But conversely nanotechnologies could create new threats that are hard to detect and counter.

There are other concerns too, namely: Who decides which areas to develop? Who should control the use of nanotechnologies? Who should benefit from related developments?[4]

[4] http://www.royalsoc.ac.uk/page.asp?id=2472

II. The Initiative

The NanoDialogue project: enhancing dialogue on nanotechnologies and nanosciences in society at European level

The NanoDialogue project began as a proposal to address the call from the European Commission's Sixth Framework Programme (FP6), which aimed to create a European Research Area (ERA) to foster scientific excellence, competitiveness and innovation. The budget of FP6 was 17.5 billion Euros, and the allocation to *Nanotechnologies, multifunctional materials and new production processes* was 1.3 million Euros.

NanoDialogue attempted to establish an integrated process of communication and social debate concerning nanotechnologies and nanosciences (N&N) within a European context, by providing information on N&N to raise awareness among publics regarding the latest developments in this field of research. The project engaged researchers, civil society and citizens in a social dialogue on nanotechnologies and their related sciences.

The distinctive features of NanoDialogue were that it was a multi-centre project with bases in eight European countries; and these were: Belgium, Estonia, France, Germany, Italy, Portugal, Spain and Sweden. The partner consortium included museums and science centres, along with an academic research institution, and a not-for-profit organisation that represents science and technology centres and museums throughout Europe. The participatory method and process to be developed by the partner consortium were to be analogous so as to ensure replicability in their usage by the partners, and importantly, to ensure the comparability of the results from the project. In addition, a series of educational activities were to be held to coincide with, and complement, the project.

Coordinators

IDIS Citta della Scienza is a science centre that is based in Naples, Italy.

Length of the project

NanoDialogue is a two-year project that began 1st March 2004 and ended 28th February 2007.

NanoDialogue funding

850, 000 Euros.

The contracted aims and objectives as stated by the coordinators

The core aims of NanoDialogue were:

(i) To provide information and raise awareness among the general public on the latest research in nanotechnologies and nanosciences

(ii) To implement social dialogue between the research community, civil society and citizens, testing high quality communication tools and participatory methodologies

(iii) To identify the main issues and preoccupations of these groups concerning nanotechnologies and nanosciences

The partner consortium

The realisation of these aims and objectives was facilitated by the NanoDialogue partner consortium, composed of 11 European institutions from the fields of participatory research, social participation and science communication:

- Fondazione IDIS - Città della Scienza, Italy
  Science centre
- Association MQC2, Italy
  Scientific exchange association
- Centre for the Study of Democracy, University of Westminster - United Kingdom
  Academic research institution
- ECSITE - The European Network of Science Centres and Museums, Belgium
  European organisation representing science centres, museums and institutes
- Centre de Culture Scientifique, Technique et Industriel de Grenoble, France
  Science centre
- Flanders Technology International Foundation, Belgium
  Science museum
- Deutsches Museum, Germany
  Science museum
- Universeum AB, Sweden
  Science centre
- Ciência Viva-Agência Nacional para a Cultura Científica e Tecnológica, Portugal
  Science centre
- Parc Cientific de Barcelona, Spain

Science centre

- Ahhaa, Estonia
  Science centre

III. Appendices

Appendix 1: Participatory Methods Toolkit. A Practitioner's Manual.

Steyaert, S., Lisoir, H. (Eds.): Participatory Methods Toolkit. A Practitioner's Manual. King Baudouin Foundation, Flemish Institute for Science and Technology Assessment, Brussels. 2005. (www.kbs-frb.be; www.viwta.be)

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Appendix 2: The Royal Society & The Royal Academy of Engineering report

Nanoscience and nanotechnologies: opportunities and uncertainties[5]

Summary

Overview

Nanoscience and nanotechnologies are widely seen as having huge potential to bring benefits to many areas of research and application, and are attracting rapidly increasing investments from Governments and from businesses in many parts of the world. At the same time, it is recognised that their application may raise new challenges in the safety, regulatory or ethical domains that will require societal debate. In June 2003 the UK Government therefore commissioned the Royal Society and the Royal Academy of Engineering to carry out this independent study into current and future developments in nanoscience and nanotechnologies and their impacts.

The remit of the study was to:

- define what is meant by nanoscience and nanotechnologies;
- summarise the current state of scientific knowledge about nanotechnologies;
- identify the specific applications of the new technologies, in particular where nanotechnologies are already in use; carry out a forward look to see how the technologies might be used in future, where possible estimating the likely

[5] The full report of which this is a summary is *Nanoscience and nanotechnologies: opportunities and uncertainties*. London: The Royal Society & The Royal Academy of Engineering, 2004. Available from the Royal Society Publications Sales Department, price £25; also free of charge on the Society's website www.royalsoc.ac.uk/policy and The Royal Academy of Engineering's website www.raeng.org.uk

timescales in which the most far-reaching applications of the technologies might become reality;
- identify what health and safety, environmental, ethical and societal implications or uncertainties may arise from the use of the technologies, both current and future; and
- identify areas where additional regulation needs to be considered.

In order to carry out the study, the two Academies set up a Working Group of experts from the relevant disciplines in science, engineering, social science and ethics and from two major public interest groups. The group consulted widely, through a call for written evidence and a series of oral evidence sessions and workshops with a range of stakeholders from both the UK and overseas. It also reviewed published literature and commissioned new research into public attitudes. Throughout the study, the Working Group has conducted its work as openly as possible and has published the evidence received on a dedicated website as it became available (www.nanotec.org.uk).

Significance of the nano scale

A nanometre (nm) is one thousand millionth of a metre. For comparison, a single human hair is about 80,000 nm wide, a red blood cell is approximately 7,000 nm wide and a water molecule is almost 0.3nm across. People are interested in the nano scale (which we define to be from 100nm down to the size of atoms (approximately 0.2nm)) because it is at this scale that the properties of materials can be very different from those at a larger scale. We define nanoscience as the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale; and nanotechnologies as the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the nanometre scale. In some senses, nanoscience and nanotechnologies are not new. Chemists have been making polymers, which are large molecules made up of nano scale subunits, for many decades and nanotechnologies have been used to create the tiny features on computer chips for the past 20 years. However, advances in the tools that now allow atoms and molecules to be examined and probed with great precision have enabled the expansion and development of nanoscience and nanotechnologies.

The properties of materials can be different at the nano scale for two main reasons. First, nano materials have a relatively larger surface area when compared to the same mass of material produced in a larger form. This can make materials more chemically reactive (in some cases materials that are inert in their larger form are reactive when produced in their nano scale form), and affect their strength or electrical properties. Second, quantum effects can begin to dominate the behaviour of matter at the nano scale - particularly at the lower end - affecting the optical, electrical and magnetic behaviour of materials. Materials can be produced that are nano scale in one dimension (for example, very thin surface coatings), in two dimensions (for example, nano wires and nanotubes) or in all three dimensions (for example, nano particles). Our wide-ranging definitions cut across many traditional scientific disciplines. The only feature common to the diverse activities characterised as ‘nanotechnology’ is the tiny dimensions on which they operate. We have therefore found it more appropriate to refer to ‘nanotechnologies’.

Current and potential uses of nanoscience and nanotechnologies

Our aim has been to provide an overview of current and potential future developments in nanoscience and nanotechnologies against which the health, safety, environmental, social and ethical implications can be considered. We did not set out to identify areas of nanoscience and nanotechnologies that should be prioritised for funding.

(i) Nano materials

Much of nanoscience and many nanotechnologies are concerned with producing new or enhanced materials. Nano materials can be constructed by 'top down' techniques, producing very small structures from larger pieces of material, for example by etching to create circuits on the surface of a silicon microchip. They may also be constructed by 'bottom up' techniques, atom by atom or molecule by molecule. One way of doing this is self-assembly, in which the atoms or molecules arrange themselves into a structure due to their natural properties. Crystals grown for the semiconductor industry provide an example of self assembly, as does chemical synthesis of large molecules. A second way is to use tools to move each atom or molecule individually. Although this ‘positional assembly’ offers greater control over construction, it is currently very laborious and not suitable for industrial applications.

Current applications of nano scale materials include very thin coatings used, for example, in electronics and active surfaces (for example, self-cleaning windows). In most applications the nano scale components will be fixed or embedded but in some, such as those used in cosmetics and in some pilot environmental remediation applications, free nano particles are used. The ability to machine materials to very high precision and accuracy (better than 100nm) is leading to considerable benefits in a wide range of industrial sectors, for example in the production of components for the information and communication technology (ICT), automotive and aerospace industries.

It is rarely possible to predict accurately the timescale of developments, but we expect that in the next few years nano materials will provide ways of improving performance in a range of products including silicon based electronics, displays, paints, batteries, micro machined silicon sensors and catalysts. Further into the future we may see composites that exploit the properties of carbon nanotubes – rolls of carbon with one or more walls, measuring a few nanometres in diameter and up to a few centimetres in length – which are extremely strong and flexible and can conduct electricity. At the moment the applications of these tubes are limited by the difficulty of producing them in a uniform manner and separating them into individual nanotubes. We may also see lubricants based on inorganic nano spheres; magnetic materials using nano crystalline grains; nano ceramics used for more durable and better medical prosthetics; automotive components or high-temperature furnaces; and nano-engineered membranes for more energy-efficient water purification.

(ii) Metrology

Metrology, the science of measurement, underpins all other nanoscience and nanotechnologies because it allows the characterisation of materials in terms of dimensions and also in terms of attributes such as electrical properties and mass. Greater precision in metrology will assist the development of nanoscience and nanotechnologies. However, this will require increased standardisation to allow calibration of equipment and we recommend that the Department of Trade and Industry ensure that this area is properly funded.

(iii) Electronics, optoelectronics and ICT

The role of nanoscience and nanotechnologies in the development of information technology is anticipated in the International Technology Roadmap for Semiconductors, a worldwide consensus document that predicts the main trends in the semiconductor industry up to 2018. This roadmap defines a manufacturing standard for silicon chips in terms of the length of a particular feature in a memory cell. For 2004 the standard is 90nm, but it is predicted that by 2016 this will be just 22nm. Much of the miniaturisation of computer chips to date has involved nanoscience and nanotechnologies, and this is expected to continue in the short and medium term. The storage of data, using optical or magnetic properties to create memory, will also depend on advances in nanoscience and nanotechnologies.

Alternatives to silicon-based electronics are already being explored through nanoscience and nanotechnologies, for example plastic electronics for flexible display screens. Other nano scale electronic devices currently being developed are sensors to detect chemicals in the environment, to check the edibility of foodstuffs, or to monitor the state of mechanical stresses within buildings. Much interest is also focused on quantum dots, semiconductor nano particles that can be 'tuned' to emit or absorb particular light colours for use in solar energy cells or fluorescent biological labels.

(iv) Bio-nanotechnology and nano medicine

Applications of nanotechnologies in medicine are especially promising, and areas such as disease diagnosis, drug delivery targeted at specific sites in the body and molecular imaging are being intensively investigated and some products are undergoing clinical trials. Nano crystalline silver, which is known to have antimicrobial properties, is being used in wound dressings in the USA. Applications of nanoscience and nanotechnologies are also leading to the production of materials and devices such as scaffolds for cell and tissue engineering, and sensors that can be used for monitoring aspects of human health. Many of the applications may not be realised for ten years or more (owing partly to the rigorous testing and validation regimes that will be required). In the much longer term, the development of nano electronic systems that can detect and process information could lead to the development of an artificial retina or cochlea. Progress in the area of bio-nanotechnology will build on our understanding of natural biological structures on the molecular scale, such as proteins.

(v) Industrial applications

So far, the relatively small number of applications of nanotechnologies that have made it through to industrial application represent evolutionary rather than revolutionary advances. Current applications are mainly in the areas of determining the properties of materials, the production of chemicals, precision manufacturing and computing. In mobile phones for instance, materials involving nanotechnologies are being developed for use in advanced batteries, electronic packaging and in displays. The total weight of these materials will constitute a very small fraction of the whole product but be responsible for most of the functions that the devices offer.

In the longer term, many more areas may be influenced by nanotechnologies but there will be significant challenges in scaling up production from the research laboratory to mass manufacturing. In the longer term it is hoped that nanotechnologies will enable more efficient approaches to manufacturing which will produce a host of multi-functional materials in a cost-effective manner, with reduced resource use and waste. However, it is important that claims of likely environmental benefits are assessed for the entire lifecycle of a material or product, from its manufacture through its use to its eventual disposal. We recommend that lifecycle assessments be undertaken for applications of nanotechnologies.

Hopes have been expressed for the development and use of mechanical nano-machines which would be capable of producing materials (and themselves) atom-by-atom (however this issue was not raised by the industrial representatives to whom we spoke). Alongside such hopes for self-replicating machines, fears have been raised about the potential for these (as yet unrealised) machines to go out of control, produce unlimited copies of themselves, and consume all available material on the planet in the process (the so called 'grey goo' scenario). We have concluded that there is no evidence to suggest that mechanical self-replicating nano machines will be developed in the foreseeable future.

Health and environmental impacts

Concerns have been expressed that the very properties of nano scale particles being exploited in certain applications (such as high surface reactivity and the ability to cross cell membranes) might also have negative health and environmental impacts. Many nanotechnologies pose no new risks to health and almost all the concerns relate to the potential impacts of deliberately manufactured nano particles and nanotubes that are free rather than fixed to or within a material. Only a few chemicals are being manufactured in nano particulate form on an industrial scale and exposure to free manufactured nano particles and nanotubes is currently limited to some workplaces (including academic research laboratories) and a small number of cosmetic uses. We expect the likelihood of nanoparticles or nanotubes being released from products in which they have been fixed or embedded (such as composites) to be low but have recommended that manufacturers assess this potential exposure risk for the lifecycle of the product and make their findings available to the relevant regulatory bodies.

Few studies have been published on the effects of inhaling free manufactured nano particles and we have had to rely mainly on analogies with results from studies on exposure to other small particles – such as the pollutant nano particles known to be present in large numbers in urban air, and the mineral dusts in some workplaces. The evidence suggests that at least some manufactured nano particles will be more toxic per unit of mass than larger particles of the same chemical. This toxicity is related to the surface area of nano particles (which is greater for a given mass than that of larger particles) and the chemical reactivity of the surface (which could be increased or decreased by the use of surface coatings). It also seems likely that nano particles will penetrate cells more readily than larger particles.

It is very unlikely that new manufactured nano particles could be introduced into humans in doses sufficient to cause the health effects that have been associated with the nano particles in polluted air. However, some may be inhaled in certain workplaces in significant amounts and steps should be taken to minimise exposure. Toxicological studies have investigated nano particles of low solubility and low surface activity. Newer nano particles with characteristics that differ substantially from these should be treated with particular caution. The physical characteristics of carbon and other nanotubes mean that they may have toxic properties similar to those of asbestos fibres, although preliminary studies suggest that they may not readily escape into the air as individual fibres. Until further toxicological studies have been undertaken, human exposure to airborne nanotubes in laboratories and workplaces should be restricted.

If nano particles penetrate the skin they might facilitate the production of reactive molecules that could lead to cell damage. There is some evidence to show that nano particles of titanium dioxide (used in some sun protection products) do not penetrate the skin but it is not clear whether the same conclusion holds for individuals whose skin has been damaged by sun or by common diseases such as eczema. There is insufficient information about whether other nano particles used in cosmetics (such as zinc oxide) penetrate the skin and there is a need for more research into this. Much of the information relating to the safety of these ingredients has been carried out by industry and is not published in the open scientific literature. We therefore recommend that the terms of reference of safety advisory committees that consider information on the toxicology of ingredients such as nano particles include a requirement for relevant data, and the methodologies used to obtain them, to be placed in the public domain.

Important information about the fate and behaviour of nano particles that penetrate the body’s defences can be gained from researchers developing nano particles for targeted drug delivery. We recommend collaboration between these researchers and those investigating the toxicity of other nano particles and nanotubes. In addition, the safety testing of these novel drug delivery methods must consider the toxic properties specific to such particles, including their ability to affect cells and organs distant from the intended target of the drug.

There is virtually no information available about the effect of nano particles on species other than humans or about how they behave in the air, water or soil, or about their ability to accumulate in food chains. Until more is known about their environmental impact we are keen that the release of nano particles and nanotubes to the environment is avoided as far as possible. Specifically, we recommend as a precautionary measure that factories and research laboratories treat manufactured nano particles and nanotubes as if they were hazardous and reduce them from waste streams and that the use of free nano particles in environmental applications such as remediation of groundwater be prohibited.

There is some evidence to suggest that combustible nano particles might cause an increased risk of explosion because of their increased surface area and potential for enhanced reaction. Until this hazard has been properly evaluated this risk should be managed by taking steps to avoid large quantities of these nano particles becoming airborne.

Research into the hazards and exposure pathways of nano particles and nanotubes is required to reduce the many uncertainties related to their potential impacts on health, safety and the environment. This research must keep pace with the future development of nano materials. We recommend that the UK Research Councils assemble an interdisciplinary centre (perhaps from existing research institutions) to undertake research into the toxicity, epidemiology, persistence and bioaccumulation of manufactured nano particles and nanotubes, to work on exposure pathways and to develop measurement methods. The centre should liaise closely with regulators and with other researchers in the UK, Europe and internationally. We estimate that funding of £5-6M pa for 10 years will be required. Core funding should come from the Government but the centre would also take part in European and internationally funded projects.

Social and ethical impacts

If it is difficult to predict the future direction of nanoscience and nanotechnologies and the timescale over which particular developments will occur, it is even harder to predict what will trigger social and ethical concerns. In the short to medium term concerns are expected to focus on two basic questions: 'Who controls uses of nanotechnologies?' and 'Who benefits from uses of nanotechnologies?' These questions are not unique to nanotechnologies but past experience with other technologies demonstrates that they will need to be addressed.

The perceived opportunities and threats of nanotechnologies often stem from the same characteristics. For example, the convergence of nanotechnologies with information technology, linking complex networks of remote sensing devices with significant computational power, could be used to achieve greater personal safety, security and individualised healthcare and to allow businesses to track and monitor their products. It could equally be used for covert surveillance, or for the collection and distribution of information without adequate consent. As new forms of surveillance and sensing are developed, further research and expert legal analysis might be necessary to establish whether current regulatory frameworks and institutions provide appropriate safeguards to individuals and groups in society. In the military context, too, nanotechnologies hold potential for both defence and offence and will therefore raise a number of social and ethical issues.

There is speculation that a possible future convergence of nanotechnologies with biotechnology, information and cognitive sciences could be used for radical human enhancement. If these possibilities were ever realised they would raise profound ethical questions.

A number of the social and ethical issues that might be generated by developments in nanoscience and nanotechnologies should be investigated further and we recommend that the research councils and the Arts and Humanities Research Board fund a multidisciplinary research programme to do this. We also recommend that the ethical and social implications of advanced technologies form part of the formal training of all research students and staff working in these areas.

Stakeholder and public dialogue

Public attitudes can play a crucial role in realising the potential of technological advances. Public awareness of nanotechnologies is low in Great Britain. In the survey of public opinion that we commissioned, only 29% said they had heard of 'nanotechnology' and only 19% could offer any form of definition. Of those who could offer a definition, 68% felt that it would improve life in the future, compared to only 4% who thought it would make life worse.

In two in-depth workshops involving small groups of the general public, participants identified both positive and negative potentials in nanotechnologies. Positive views were expressed about new advances in an exciting field; potential applications particularly in medicine; the creation of new materials; a sense that the developments were part of natural progress and the hope that they would improve the quality of life. Concerns were about financial implications; impacts on society; the reliability of new applications; long-term side-effects and whether the technologies could be controlled. The issue of the governance of nanotechnologies was also raised. Which institutions could be trusted to ensure that the trajectories of development of nanotechnologies are socially beneficial? Comparisons were made with genetically modified organisms and nuclear power.

We recommend that the research councils build upon our preliminary research into public attitudes by funding a more sustained and extensive programme involving members of the general public and members of interested sections of society.

We believe that a constructive and proactive debate about the future of nanotechnologies should be undertaken now – at a stage when it can inform key decisions about their development and before deeply entrenched or polarised positions appear. We recommend that the Government initiate adequately funded public dialogue around the development of nanotechnologies. The precise method of dialogue and choice of sponsors should be designed around the agreed objectives of the dialogue. Our public attitudes work suggests that governance would be an appropriate subject for initial dialogue and given that the Research Councils are currently funding research into nanotechnologies they should consider taking this forward.

Regulation

A key issue arising from our discussions with the various stakeholders was how society can control the development and deployment of nanotechnologies to maximise desirable outcomes and keep undesirable outcomes to an acceptable minimum – in other words, how nanotechnologies should be regulated. The evidence suggests that at present regulatory frameworks at EU and UK level are sufficiently broad and flexible to handle nanotechnologies at their current stage of development. However some regulations will need to be modified on a precautionary basis to reflect the fact that the toxicity of chemicals in the form of free nano particles and nanotubes cannot be predicted from their toxicity in a larger form and that in some cases they will be more toxic than the same mass of the same chemical in larger form. We looked at a small number of areas of regulation that cover situations where exposure to nano particles or nanotubes is likely currently or in the near future.

Currently the main source of inhalation exposure to manufactured nano particles and nanotubes is in laboratories and a few other workplaces. We recommend that the Health and Safety Executive carry out a review of the adequacy of existing regulation to assess and control workplace exposure to nano particles and nanotubes including those relating to accidental release. In the meantime they should consider setting lower occupational exposure levels for chemicals when produced in this size range.

Under current UK chemical regulation (Notification of New Substances) and its proposed replacement being negotiated at European level (Registration, Evaluation and Authorisation of Chemicals) the production of an existing substance in nano particulate form does not trigger additional testing. We recommend that chemicals produced in the form of nano particles and nanotubes be treated as new chemicals under these regulatory frameworks. The annual production thresholds that trigger testing and the testing methodologies relating to substances in these sizes, should be reviewed as more toxicological evidence becomes available.

Under cosmetics regulations in the European Union, ingredients (including those in the form of nano particles) can be used for most purposes without prior approval, provided they are not on the list of banned or restricted use chemicals and that manufacturers declare the final product to be safe. Given our concerns about the toxicity of any nano particles penetrating the skin we recommend that their use in products be dependent on a favourable opinion by the relevant European Commission scientific safety advisory committee. A favourable opinion has been given for the nano particulate form of titanium dioxide (because chemicals used as UV filters must undergo an assessment by the advisory committee before they can be used) but insufficient information has been provided to allow an assessment of zinc oxide. In the meantime we recommend that manufacturers publish details of the methodologies they have used in assessing the safety of their products containing nano particles that demonstrate how they have taken into account that properties of nano particles may be different from larger forms. We do not expect this to apply to many manufacturers since our understanding is that nano particles of zinc oxide are not used extensively in cosmetics in Europe. Based on our recommendation that chemicals produced in the form of nano particles should be treated as new chemicals, we believe that the ingredients lists for consumer products should identify the fact that manufactured nano particles have been added. Nano particles may be included in more consumer products in the future, and we recommend that the European Commission, with the support of the UK, review the adequacy of the current regulatory regime with respect to the introduction of nano particles into any consumer products.

Although we think it unlikely that nano particles or nanotubes will be released from most materials in which they have been fixed, we see any risk of such release being greatest during disposal, destruction or recycling. We therefore recommend that manufacturers of products that fall under extended producer responsibility regimes such as end-of-life regulations publish procedures outlining how these materials will be managed to minimise possible human and environmental exposure.

Our review of regulation has not been exhaustive and we recommend that all relevant regulatory bodies consider whether existing regulations are appropriate to protect humans and the environment from the hazards we have identified, publish their reviews and explain how they will address any regulatory gaps. Future applications of nanotechnologies may have an impact on other areas of regulation as, for example, developments in sensor technology may have implications for legislation relating to privacy. It is therefore important that regulatory bodies include future applications of nanotechnologies in their horizon-scanning programmes to ensure that any regulatory gaps are identified at an appropriate stage.

Overall, given appropriate regulation and research along the lines just indicated, we see no case for the moratorium which some have advocated on the laboratory or commercial production of manufactured nano materials.

Ensuring the responsible development of new and emerging technologies

Nanoscience and nanotechnologies are evolving rapidly, and the pressures of international competition will ensure that this will continue. The UK Government's Chief Scientific Adviser should therefore commission an independent group in two years time, and again in five years time, to review what action has been taken as a result of our recommendations, to assess how nanoscience and nanotechnologies have developed in the interim, and to consider the ethical, social, health, environmental, safety and regulatory implications of these developments. This group should include representatives of, and consult with, the relevant stakeholder groups.

More generally, this study has highlighted again the value of identifying as early as possible new areas of science and technology that have the potential to impact strongly on society. The Chief Scientific Adviser should therefore establish a group that brings together representatives of a wide range of stakeholders to meet bi-annually to review new and emerging technologies, to identify at the earliest possible stage areas where issues needing Government attention may arise, and to advise on how these might be addressed. The work of this group should be made public and all stakeholders should be encouraged to engage with the emerging issues. We expect this group to draw upon the work of the other bodies across Government with horizon-scanning roles rather than to duplicate their work.

We look forward to the response to this report from the UK Government and from the other parties at whom the recommendations are targeted. This study has generated a great deal of interest among a wide range of stakeholders, both within the UK and internationally. As far as we are aware it is the first study of its kind, and we expect its findings to contribute to the responsible development of nanoscience and nanotechnology globally.

Recommendations

The industrial application of nanotechnologies

R1 We recommend that a series of lifecycle assessments be undertaken for the applications and product groups arising from existing and expected developments in nanotechnologies, to ensure that that savings in resource consumption during the use of the product are not offset by increased consumption during manufacture and disposal. To have public credibility these studies need to be carried out or reviewed by an independent body.

R2 Where there is a requirement for research to establish methodologies for lifecycle assessments in this area, we recommend that this should be funded by the research councils through the normal responsive mode.

Possible adverse health, safety and environmental impacts

The lack of evidence about the risk posed by manufactured nano particles and nanotubes is resulting in considerable uncertainty.

R3 We recommend that Research Councils UK establish an interdisciplinary centre (probably comprising several existing research institutions) to research the toxicity, epidemiology, persistence and bioaccumulation of manufactured nano particles and nanotubes as well as their exposure pathways, and to develop methodologies and instrumentation for monitoring them in the built and natural environment. A key role would be to liaise with regulators. We recommend that the research centre maintain a database of its results and that it interact with those collecting similar information in Europe and internationally. Because it will not be possible for the research centre to encompass all aspects of research relevant to nano particles and nanotubes, we recommend that a proportion of its funding be allocated to research groups outside the centre to address areas identified by the advisory board as of importance and not covered within the centre

R4 Until more is known about environmental impacts of nano particles and nanotubes, we recommend that the release of manufactured nano particles and nanotubes into the environment be avoided as far as possible.

R5 Specifically, in relation to two main sources of current and potential releases of free nano particles and nanotubes to the environment, we recommend:

(i) that factories and research laboratories treat manufactured nano particles and nanotubes as if they were hazardous, and seek to reduce or remove them from waste streams;

(ii) that the use of free (that is, not fixed in a matrix) manufactured nano particles in environmental applications such as remediation be prohibited until appropriate research has been undertaken and it can be demonstrated that the potential benefits outweigh the potential risks.

R6 We recommend that, as an integral part of the innovation and design process of products and materials containing nano particles or nanotubes, industry should assess the risk of release of these components throughout the lifecycle of the product and make this information available to the relevant regulatory authorities.

R7 We recommend that the terms of reference of scientific advisory committees (including the European Commission's Scientific Committee on Cosmetic and Non-Food Products or its replacement) that consider the safety of ingredients that exploit new and emerging technologies like nanotechnologies, for which there is incomplete toxicological information in the peer-reviewed literature, should include the requirement for all relevant data related to safety assessments, and the methodologies used to obtain them, to be placed in the public domain.

Regulatory issues

R8 We recommend that all relevant regulatory bodies consider whether existing regulations are appropriate to protect humans and the environment from the hazards outlined in this report and publish their review and details of how they will address any regulatory gaps.

R9 We recommend that regulatory bodies and their respective advisory committees include future applications of nanotechnologies in their horizon scanning programmes to ensure any regulatory gaps are identified at an appropriate stage.

Recommendations R10 to R14 are based on applying our conclusions - that some chemicals are more toxic when in the form of nanoparticles or nanotubes and that safety assessments based on the testing of a larger form of a chemical cannot be used to infer the safety of chemicals in the form of nano particles - to a series of regulatory case studies:

R10 We recommend that chemicals in the form of nano particles or nanotubes be treated as new substances under the existing Notification of New Substances (NONS) regulations and in the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (which is currently under negotiation at EU level and will eventually supersede NONS). As more information regarding the toxicity of nano particles and nanotubes becomes available, we recommend that the relevant regulatory bodies consider whether the annual production thresholds that trigger testing and the testing methodologies relating to substances in these forms should be revised under NONS and REACH.

R11 Workplace:

(i) We recommend that the Health & Safety Executive (HSE) review the adequacy of its regulation of exposure to nano particles, and in particular considers the relative advantages of measurement on the basis of mass and number. In the meantime, we recommend that it considers setting lower occupational exposure levels for manufactured nano particles.

(ii) We recommend that the HSE, Department for Environment Food and Rural Affairs and the Environment Agency review their current procedures relating to the management of accidental releases both within and outside the workplace.

(ii) We recommend that the HSE consider whether current methods are adequate to assess and control the exposures of individuals in laboratories and workplaces where nano tubes and other nano fibres may become airborne and whether regulation based on electron microscopy rather than phase-contrast optical microscopy is necessary.

R12 Consumer products:

(i) We recommend that ingredients in the form of nano particles undergo a full safety assessment by the relevant scientific advisory body before they are permitted for use in products. Specifically: we recommend that industry submit the additional information on microfine zinc oxide that is required by the SCCNFP as soon as reasonably practicable so that it can deliver an Opinion on its safety.

(ii) We recommend that manufacturers publish details of the methodologies they have used in assessing the safety of their products containing nano particles that demonstrate how they have taken account that properties of nano particles may be different from larger forms.

(iii) We recommend that the ingredients lists of consumer products should identify the fact that manufactured nano particulate material has been added.

(iv) We recommend that the EC's new Scientific Committee on Emerging and Newly Identified Health risks gives a high priority to the consideration of the safety of nano particles in consumer products.

(v) In the light of the regulatory gaps that we identify we recommend that the EC (supported by the UK) review the adequacy of the current regulatory regime with respect to the introduction of nano particles into consumer products. In undertaking this review they should be informed by the relevant scientific safety advisory committees.

R13 We recommend that the Department of Health review its regulations for new medical devices and medicines to ensure that particle size and chemistry are taken into account in investigating possible adverse side effects of medicines.

R14 We recommend that manufacturers of products that incorporate nano particles and nanotubes and which fall under extended producer responsibility regimes such as end-of-life regulations be required to publish procedures outlining how these materials will be managed to minimise human and environmental exposure.

R15 Measurement:

(i) We recommend that researchers and regulators looking to develop methods to measure and monitor airborne manufactured nano particulates liaise with those who are working on the measurement of pollutant nano particles from sources such as vehicle emissions.

(ii) We recommend that the Department of Trade and Industry supports the standardisation of measurement at the nanometre scale required by regulators and for quality control in industry through the adequate funding of initiatives under its National Measurement System Programme and that it ensures that the UK is in the forefront of any international initiatives for the standardisation of measurement.

Stakeholder and public dialogue

R18 We recommend that the research councils build on the research into public attitudes undertaken as part of our study by funding a more sustained and extensive programme of research into public attitudes to nanotechnologies. This should involve more comprehensive qualitative work involving members of the general public as well as members of interested sections of society, such as the disabled, and might repeat the awareness survey to track any changes as public knowledge about nanotechnologies develops.

R19 We recommend that the Government initiates adequately funded public dialogue around the development of nanotechnologies. We recognise that a number of bodies could be appropriate in taking this dialogue forward.

Ensuring the responsible development of nanotechnologies

R20 We recommend that the Office of Science and Technology commission an independent group in two and five years' time to review what action has been taken on our recommendations, and to assess how science and engineering has developed in the interim and what ethical, social, health, environmental, safety and regulatory implications these developments may have. This group should comprise representatives of, and consult with, the relevant stakeholder groups. Its reports should be publicly available.

R21 We recommend that the Chief Scientific Advisor should establish a group that brings together representatives of a wide range of stakeholders to look at new and emerging technologies and identify at the earliest possible stage areas where potential health, safety, environmental, social, ethical and regulatory issues may arise and advise on how these might be addressed.

Working Group, Review Group and Secretariat members

Working Group

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The two academies gratefully acknowledge the contribution of the reviewers. With the exception of Sir John Enderby and Mr Philip Ruffles, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release.

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Secretariat

The core secretariat was: Sara Al-Bader, Dr Jofey Craig (June 2003 - September 2003), Dr Andrew Dunn (October 2003 – August 2004) and Dr Rachel Quinn at the Royal Society and Richard Ploszek at the Royal Academy of Engineering. Valuable administrative and web support was provided by Karen Scott-Jupp (Royal Society). The secretariat is grateful to the many other staff at the two Academies who contributed to the successful completion of this study.

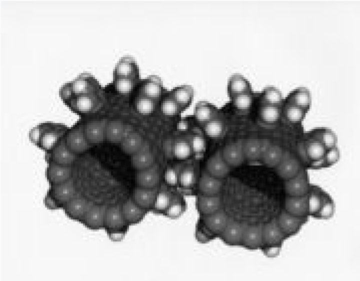
Appendix 3: Wikipedia

http://en.wikipedia.org/wiki/Nanotechnology

Nanotechnology

From Wikipedia, the free encyclopedia

"Nanotech" redirects here. For other uses, see Nanotech (disambiguation).



Molecular gears from a NASA computer simulation. Note this has nothing to do with reality. Gears, teeth and shafts do not work on the nano-scale.

Nanotechnology is a field of applied science and technology covering a broad range of topics. The main unifying theme is the control of matter on a scale smaller than one micrometre, as well as the fabrication of devices on this same length scale. It is a highly multidisciplinary field, drawing from fields such as colloidal science, device physics, and supramolecular chemistry. Much speculation exists as to what new science and technology might result from these lines of research. Some view nanotechnology as a marketing term that describes pre-existing lines of research applied to the sub-micron size scale.

Despite the apparent simplicity of this definition, nanotechnology actually encompasses diverse lines of inquiry. Nanotechnology cuts across many disciplines, including colloidal science, chemistry, applied physics, biology. It could variously be seen as an extension of existing sciences into the nanoscale, or as a recasting of existing sciences using a newer, more modern term. Two main approaches are used in nanotechnology: one is a "bottom-up" approach where materials and devices are built from molecular components which assemble themselves chemically using principles of molecular recognition; the other being a "top-down" approach where nano-objects are constructed from larger entities without atomic-level control.

The impetus for nanotechnology has stemmed from a renewed interest in colloidal science, coupled with a new generation of analytical tools such as the atomic force microscope (AFM) and the scanning tunneling microscope (STM). Combined with refined processes such as electron beam lithography, these instruments allow the deliberate manipulation of nanostructures, and in turn led to the observation of novel phenomena. Nanotechnology is also an umbrella description of emerging technological developments associated with sub-microscopic dimensions. Despite the great promise of numerous nanotechnologies such as quantum dots and nanotubes, real applications that have moved out of the lab and into the marketplace have mainly utilized the advantages of colloidal nanoparticles in bulk form, such as suntan lotion, cosmetics, protective coatings, and stain resistant clothing.

Contents

Fundamental concepts

Usage of the term

For information about the origins of nanotechnology, see History of nanotechnology.

Wikibooks has more about this subject:
The Opensource Handbook of Nanoscience and Nanotechnology

Nanotechnology is an umbrella term that is used to describe a variety of techniques to fabricate materials and devices on the nanoscale. The genesis for nanotechnology has its roots in the colloidal science of the late 19th century. These early innovations have been combined with more recent developments in device manufacture. The term has served in some regards as a means to generate new lines of funding from government agencies. One nanometer (nm) is one billionth, or 10^{-9} of a meter. For comparison, typical carbon-carbon bond lengths, or the spacing between these atoms in a molecule, are in the range .12-.15 nm, and a DNA double-helix has a diameter around 2 nm. On the other hand, the smallest cellular lifeforms, the bacteria of the genus Mycoplasma, are around 200 nm in length.

Nanotechnological techniques include those used for fabrication of nanowires, those used in semiconductor fabrication such as deep ultraviolet lithography, electron beam lithography, focused ion beam machining, nanoimprint lithography, atomic layer deposition, and molecular vapor deposition, and further including molecular self-assembly techniques such as those employing di-block copolymers. However, all of these techniques preceded the nanotech era, and are extensions in the development of scientific advancements rather than techniques which were devised with the sole purpose of creating nanotechnology or which were results of nanotechnology research.nano technology is also in an i-pod

General fields involved with proper characterization of these systems include physics, chemistry, and biology, as well as mechanical and electrical engineering. However, due to the inter- and multidisciplinary nature of nanotechnology, subdisciplines such as physical chemistry, materials science, or biomedical engineering are considered significant or essential components of nanotechnology. The design, synthesis, characterization, and application of materials are dominant concerns of nanotechnologists. The manufacture of polymers based on molecular structure, or the design of computer chip layouts based on surface science are examples of nanotechnology in modern use. Colloidal suspensions also play an essential role in nanotechnology.

Technologies currently branded with the term 'nano' are little related to and fall far short of the most ambitious and transformative technological goals of the sort in molecular manufacturing proposals, but the term still connotes such ideas. Thus there may be a danger that a "nano bubble" will form (or is forming already) from the use of the term by scientists and entrepreneurs to garner funding, regardless of (and perhaps despite a lack of) interest in the transformative possibilities of more ambitious and far-sighted work. The above prediction has come to pass, as by 2006 over $400 million has been invested in Nanotechnology, mostly by venture capital, with very meager results. From this perspective, Nanotechnology may be viewed as a collection of wishful predictions, aimed at generating unwarranted excitement among venture capitalists.

The National Science Foundation (a major source of funding for nanotechnology in the United States) funded researcher David Berube to study the field of nanotechnology. His findings are published in the monograph “Nano-Hype: The Truth Behind the Nanotechnology Buzz". This published study (with a foreword by Mihail Roco, head of the NNI) concludes that much of what is sold as “nanotechnology” is in fact a recasting of straightforward materials science, which is leading to a “nanotech industry built solely on selling nanotubes, nanowires, and the like” which will “end up with a few suppliers selling low margin products in huge volumes."

Larger to smaller: a materials perspective

A unique aspect of nanotechnology is the vastly increased ratio of surface area to volume present in many nanoscale materials which opens new possibilities in surface-based science, such as catalysis. A number of physical phenomena become noticeably pronounced as the size of the system decreases. These include statistical mechanical effects, as well as quantum mechanical effects, for example the “quantum size effect” where the electronic properties of solids are altered with great reductions in particle size. This effect does not come into play by going from macro to micro dimensions. However, it becomes dominant when the nanometer size range is reached. Additionally, a number of physical properties change when compared to macroscopic systems. One example is the increase in surface area to volume of materials. This catalytic activity also opens potential risks in their interaction with biomaterials.

Nanotechnology can be thought of as extensions of traditional disciplines towards the explicit consideration of these properties. Additionally, traditional disciplines can be re-interpreted as specific applications of nanotechnology. This dynamic reciprocation of ideas and concepts contributes to the modern understanding of the field. Broadly speaking, nanotechnology is the synthesis and application of ideas from science and engineering towards the understanding and production of novel materials and devices. These products generally make copious use of physical properties associated with small scales.

Materials reduced to the nanoscale can suddenly show very different properties compared to what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances become transparent (copper); inert materials become catalysts (platinum); stable materials turn combustible (aluminum); solids turn into liquids at room temperature (gold); insulators become conductors (silicon). Materials such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nanotechnology stems from these unique quantum and surface phenomena that matter exhibits at the nanoscale.

Nanosize powder particles (a few nanometres in diameter, also called nanoparticles) are potentially important in ceramics, powder metallurgy, the achievement of uniform nanoporosity and similar applications. The strong tendency of small particles to form clumps ("agglomerates") is a serious technological problem that impedes such applications. However, a few dispersants such as ammonium citrate (aqueous) and imidazoline or oleyl alcohol (nonaqueous) are promising additives for deagglomeration. (Dispersants are discussed in "Organic Additives And Ceramic Processing," by Daniel J. Shanefield, Kluwer Academic Publ., Boston.)

Another concern is that the volume of an object decreases as the third power of its linear dimensions, but the surface area only decreases as its second power. This somewhat subtle and unavoidable principle has huge ramifications. For example the power of a drill (or any other machine) is proportional to the volume, while the friction of the drill's bearings and gears is proportional to their surface area. For a normal-sized drill, the power of the device is enough to handily overcome any friction. However, scaling its length down by a factor of 1000, for example, decreases its power by 1000^3 (a factor of a billion) while reducing the friction by only 1000^2 (a factor of "only" a million). Proportionally it has 1000 times less power per unit friction than the original drill. If the original friction-to-power ratio was, say, 1%, that implies the smaller drill will have 10 times as much friction as power. The drill is useless.

This is why, while super-miniature electronic integrated circuits can be made to function, the same technology cannot be used to make functional mechanical devices in miniature: the friction overtakes the available power at such small scales. So while you may see microphotographs of delicately etched silicon gears, such devices are curiosities with limited real world applications, for example in moving mirrors and shutters. Surface tension increases in the same way, causing very small objects tend to stick together. This could possibly make any kind of "micro factory" impractical: even if robotic arms and hands could be scaled down, anything they pick up will tend to be impossible to put down. The above being said, molecular evolution has resulted in working cilia, flagella, muscle fibers, and rotary motors in aqueous environments, all on the nanoscale, so we are faced with existence proofs which technological design has not been able to duplicate and for which no design approach has been articulated.

All these scaling issues have to be kept in mind while evaluating any kind of nanotechnology.

Simple to complex: a molecular perspective

Modern synthetic chemistry has reached the point where it is possible to prepare small molecules to almost any structure. These methods are used today to produce a wide variety of useful chemicals such as pharmaceuticals or commercial polymers. The ability of this is to extend the control to the next, seeking methods to assemble these single molecules into supramolecular assemblies consisting of many molecules arranged in a well defined manner.

These approaches utilize the concepts of molecular self-assembly and/or supramolecular chemistry to automatically arrange themselves into some useful conformation through a bottom-up approach. The concept of molecular recognition is especially important: molecules can be designed so that a specific conformation or arrangement is favored due to non-covalent intermolecular forces. The Watson-Crick basepairing rules are a direct result of this, as is the specificity of an enzyme being targeted to a single substrate, or the specific folding of the protein itself. Thus, two or more components can be designed to be complementary and mutually attractive so that they make a more complex and useful whole.

Such bottom-up approaches should, broadly speaking, be able to produce devices in parallel and much cheaper than top-down methods, but could potentially be overwhelmed as the size and complexity of the desired assembly increases. However, the bottom-up approach is viewed by many thoughtful scientists as being mostly wishful thinking. Most useful structures require complex and thermodynamically unlikely arrangements of atoms. The basic laws of probability and entropy make it very unlikely that atoms will "self-assemble" in useful configurations, or can be easily and economically nudged to do so. About the only example of this is crystal-growing, which, having been around for millenia, clearly owes no credit to Nanotechnology.

Molecular Nanotechnology: a long-term view

Advanced nanotechnology, sometimes called molecular manufacturing, is a term given to the concept of engineered nanosystems (nanoscale machines) operating on the molecular scale. By the countless examples found in biology it is currently known that billions of years of evolutionary feedback can produce sophisticated, stochastically optimized biological machines, and it is hoped that developments in nanotechnology will make possible their construction by some shorter means, perhaps using biomimetic principles. However, K Eric Drexler and other researchers have proposed that advanced nanotechnology, although perhaps initially implemented by biomimetic means, ultimately could be based on mechanical engineering principles (see also mechanosynthesis)

When the term "nanotechnology" was independently coined and popularized by Eric Drexler, who at the time was unaware of an earlier usage by Norio Taniguchi, it referred to a future manufacturing technology based on molecular machine systems. The premise was that molecular-scale biological analogies of traditional machine components demonstrated that molecular machines were possible, and that a manufacturing technology based on the mechanical functionality of these components (such as gears, bearings, motors, and structural members) would enable programmable, positional assembly to atomic specification (see the original reference PNAS-1981). The physics and engineering performance of exemplar designs were analyzed in the textbook Nanosystems.

Another view, put forth by Carlo Montemagno, is that future nanosystems will be hybrids of silicon technology and biological molecular machines, and his group's research is directed toward this end.

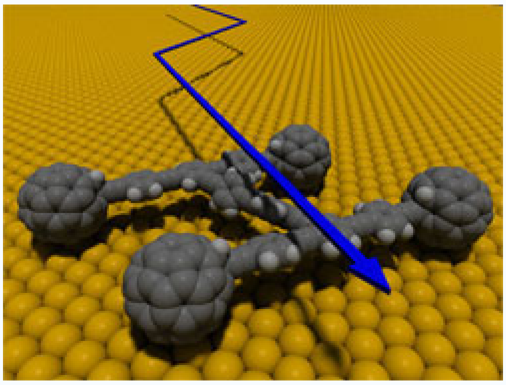
The seminal experiment proving that positional molecular assembly is possible was performed by Ho and Lee at Cornell University in 1999. They used a scanning tunneling microscope to move an individual carbon monoxide molecule (CO) to an individual iron atom (Fe) sitting on a flat silver crystal, and chemically bound the CO to the Fe by applying a voltage.

Though biology clearly demonstrates that molecular machine systems are possible, non-biological molecular machines are today only in their infancy. Leaders in research on non-biological molecular machines are Dr. Alex Zettl and his colleagues at Lawrence Berkeley Laboratories and UC Berkeley. They have constructed at least three distinct molecular devices whose motion is controlled from the desktop with changing voltage: a nanotube nanomotor, a molecular actuator, and a nanoelectromechanical relaxation oscillator.

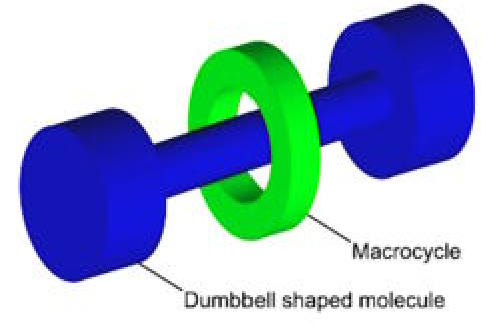
Manufacturing in the context of productive nanosystems is not related to, and should be clearly distinguished from, the conventional technologies used to manufacture nanomaterials such as carbon nanotubes and nanoparticles.

There exists the potential to design and fabricate artificial structures analogous to natural cells and even organisms. Note that these are just blue-sky "potentials", and fall closer to the disciplines of Applied Biology and gene-splicing than to Nanotechnology.

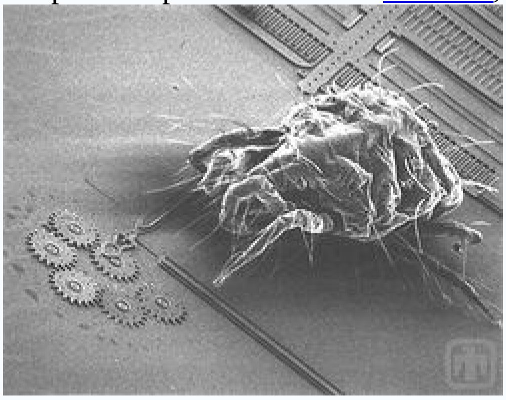
Current research



Space-filling model of the nanocar on a surface, using fullerenes as wheels.



Graphical representation of a rotaxane, useful as a molecular switch.



A mite next to a gear set produced using MEMS. Courtesy Sandia National Laboratories, SUMMiTTM Technologies, www.mems.sandia.gov.

As nanotechnology is a very broad term, there are many disparate but sometimes overlapping subfields that could fall under its umbrella. The following avenues of research could be considered subfields of nanotechnology. Note that these categories are fairly nebulous and a single subfield may overlap many of them, especially as the field of nanotechnology continues to mature.

See also List of nanotechnology applications.

Nanomaterials

This includes subfields which develop or study materials having unique properties arising from their nanoscale dimensions.

- **Colloid science** has given rise to many materials which may be useful in nanotechnology, such as carbon nanotubes and other fullerenes, and various nanoparticles and nanorods.
- Nanoscale materials can also be used for **bulk applications**; most present commercial applications of nanotechnology are of this flavor.
- Headway has been made in using these materials for medical applications; see **Nanomedicine**.

Bottom-up approaches

These seek to arrange smaller components into more complex assemblies.

- **DNA Nanotechnology** utilizes the specificity of Watson-Crick basepairing to construct well-defined structures out of DNA and other nucleic acids.
- More generally, **molecular self-assembly** seeks to use concepts of supramolecular chemistry, and molecular recognition in particular, to cause single-molecule components to automatically arrange themselves into some useful conformation.

Top-down approaches

These seek to create smaller devices by using larger ones to direct their assembly.

- Many technologies descended from conventional **solid-state silicon methods** for fabricating microprocessors are now capable of creating features smaller than 100 nm, falling under the definition of nanotechnology. Giant magnetoresistance-based hard drives already on the market fit this description, [1] as do atomic layer deposition (ALD) techniques.
- Solid-state techniques can also be used to create devices known as **nanoelectromechanical systems** or NEMS, which are related to microelectromechanical systems or MEMS.
- Atomic force microscope tips can be used as a nanoscale "write head" to deposit a chemical on a surface in a desired pattern in a process called **dip pen nanolithography**. This fits into the larger subfield of nanolithography.

Functional approaches

These seek to develop components of a desired functionality without regard to how they might be assembled.

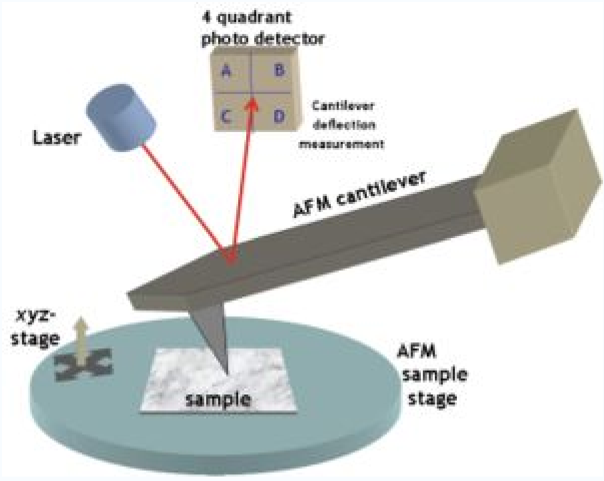
- **Molecular electronics** seeks to develop molecules with useful electronic properties. These could then be used as single-molecule components in a nanoelectronic device. For an example see rotaxane.
- Synthetic chemical methods can also be used to create **synthetic molecular motors**, such as in a so-called nanocar.

Speculative

These subfields seek to anticipate what inventions nanotechnology might yield, or attempt to propose an agenda along which inquiry might progress. These often take a big-picture view of nanotechnology, with more emphasis on its societal implications than the details of how such inventions could actually be created.

- **Molecular nanotechnology** is a proposed approach which involves manipulating single molecules in finely controlled, deterministic ways. This is more theoretical (some would say merely hypothetical) than the other subfields and is beyond current capabilities.
- **Nanorobotics** centers on self-sufficient machines of some functionality operating at the nanoscale.
- **Programmable matter** based on artificial atoms seeks to design materials whose properties can be easily and reversibly externally controlled.

Tools and techniques



Typical AFM setup. A microfabricated cantilever with a sharp tip is deflected by features on a sample surface, much like in a phonograph but on a much smaller scale. A laser beam reflects off the backside of the cantilever into a set of photodetectors, allowing the deflection to be measured and assembled into an image of the surface.

Nanoscience and nanotechnology only became possible in the 1910's with the development of the first tools to measure and make nanostructures. But the actual development started with the discovery of electrons and neutrons which showed scientists that matter can really exist on a much smaller scale than what we normally think of as small, and/or what they thought was possible at the time. It was at this time when curiosity for nanostructures had originated.

The atomic force microscope (AFM) and the Scanning Tunneling Microscope (STM) are two early versions of scanning probes that launched nanotechnology. There are other types of scanning probe microscopy, all flowing from the ideas of the scanning confocal microscope developed by Marvin Minsky in 1961 and the scanning acoustic microscope (SAM) developed by Calvin Quate and coworkers in the 1970's, that make it possible to see structures at the nanoscale. The tip of a scanning probe can also be used to manipulate nanostructures (a process called positional assembly). However, this is a very slow process. This led to the development of various techniques of nanolithography such as dip pen nanolithography, electron beam lithography or nanoimprint lithography. Lithography is a top-down fabrication technique where a bulk material is reduced in size to nanoscale pattern.

The top-down approach anticipates nanodevices that must be built piece by piece in stages, much as manufactured items are currently made. Scanning probe microscopy is an important technique both for characterization and synthesis of nanomaterials. Atomic force microscopes and scanning tunneling microscopes can be used to look at surfaces and to move atoms around. By designing different tips for these microscopes, they can be used for carving out structures on surfaces and to help guide self-assembling structures. Atoms can be moved around on a surface with scanning probe microscopy techniques, but it is cumbersome, expensive and very time-consuming. For these reasons, it is not feasible to construct nanoscaled devices atom by atom. Assembling a billion transistor microchip at the rate of about one transistor an hour is inefficient.

One hope is that these techniques may eventually be used to make primitive nanomachines, which in turn can be used to make more sophisticated nanomachines. But the whole nanomachine concept is wild speculation, as we are unable to even conceptually design human scale machines that can independently make other machines. If we can't make them on a convenient scale, what are the chances they can be made on a nano scale? Also nanomachines have the very substantial hurdles of friction and surface-tension.

In contrast, bottom-up techniques build or grow larger structures atom by atom or molecule by molecule. These techniques include chemical synthesis, self-assembly and positional assembly. Another variation of the bottom-up approach is molecular beam epitaxy or MBE. Researchers at Bell Telephone Laboratories like John R. Arthur. Alfred Y. Cho, and Art C. Gossard developed and implemented MBE as a research tool in the late 1960s and 1970s. Samples made by MBE were key to to the discovery of the fractional quantum Hall effect for which the 1998 Nobel Prize in Physics was awarded. MBE allows scientists to lay down atomically-precise layers of atoms and, in the process, build up complex structures. Important for research on semiconductors, MBE is also widely used to make samples and devices for the newly emerging field of spintronics.

Newer techniques such as Dual Polarisation Interferometry are enabling scientists to measure quantitatively the molecular interactions that take place at the nano-scale.

Societal implications

Potential risks of nanotechnology can broadly be grouped into three areas:

- the risk to health and environment from nanoparticles and nanomaterials;
- the risk posed by molecular manufacturing (or advanced nanotechnology);
- societal risks.

Nanoethics concerns the ethical and social issues associated with developments in nanotechnology, a science which encompass several fields of science and engineering, including biology, chemistry, computing, and materials science. Nanotechnology refers to the manipulation of very small-scale matter – a nanometer is one billionth of a meter, and nanotechnology is generally used to mean work on matter at 100 nanometers and smaller.

Social risks related to nanotechnology development include the possibility of military applications of nanotechnology (such as implants and other means for soldier enhancement) as well as enhanced surveillance capabilities through nano-sensors. However those applications still belong to science-fiction and will not be possible in the next decades. Significant environmental, health, and safety issues might arise with development in nanotechnology since some negative effects of nanoparticles in our environment might be overlooked. However nature itself creates all kinds of nanoobjects, so probable dangers are not due to the nanoscale alone, but due to the fact that toxic materials become more harmful when ingested or inhaled as nanoparticles (see nanotoxicology).

See also

- List of nanotechnology topics
- Femtotechnology
- Mesotechnology
- Nanoengineering
- NanoSafe
- Nanotechnology in fiction
- Nanotitanate
- Nanotoxicology
- Picotechnology
- Top-down and bottom-up design

Further reading

- Geoffrey Hunt and Michael Mehta (2006), Nanotechnology: Risk, Ethics and Law. London: Earthscan Books.
- Hari Singh Nalwa (2004), Encyclopedia of Nanoscience and Nanotechnology (10-Volume Set), American Scientific Publishers. ISBN 1-58883-001-2
- Michael Rieth and Wolfram Schommers (2006), Handbook of Theoretical and Computational Nanotechnology (10-Volume Set), American Scientific Publishers. ISBN 1-58883-042-X

- David M. Berube 2006. *Nano-hype: The Truth Behind the Nanotechnology Buzz*. Prometheus Books. ISBN 1-59102-351-3
- Jones, Richard A. L. (2004). *Soft Machines*. Oxford University Press, Oxford, United Kingdom. ISBN 0198528558.
- Akhlesh Lakhtakia (ed) (2004). *The Handbook of Nanotechnology. Nanometer Structures: Theory, Modeling, and Simulation*. SPIE Press, Bellingham, WA, USA. ISBN 0-8194-5186-X.
- Daniel J. Shanefield (1996). *Organic Additives And Ceramic Processing*. Kluwer Academic Publishers. ISBN 0-7923-9765-7.
- Fei Wang & Akhlesh Lakhtakia (eds) (2006). *Selected Papers on Nanotechnology -- Theory & Modeling (Milestone Volume 182)*. SPIE Press, Bellingham, WA, USA. ISBN 0-8194-6354-X.

- Roger Smith, *Nanotechnology: A Brief Technology Analysis*, CTOnet.org, 2004. [2]
- Arius Tolstoshev, *Nanotechnology: Assessing the Environmental Risks for Australia*, Earth Policy Centre, September 2006. [3]

External links

Publishers and Prospectus

- American Association for Cancer Research: Nanotechnology
- Center for Responsible Nanotechnology
- NIH Nanomedicine Roadmap Initiative
- Institute of Physics Journal of Nanotechnology

- Journal of Nanoscience and Nanotechnology
- European Nanoforum
- Nanoscience and Applications

Nanotechnology materials and projects

- NanoHive@Home (Distributed Computing Project)
- The making of Buckypaper - Nanotubes on Steroids

Higher Education Nanotechnology Centers

- CeNTech - Center for Nanotechnology
- Birck Nanotechnology Center
- University at Albany College of Nanoscale Science and Engineering
- KTH - Royal Institute of Technology Nanostructure Physics Department
- Center for Nanotechnology in Society at UCSB
- Cenamps, a national centre for small-scale technologies
- Manufacturing Engineering Centre (MEC), Cardiff University, UK
- Institute for NanoBioTechnology at Johns Hopkins University
- MESA+ institute for nanotechnology

Nanotechnology & Ethics

- The Nanoethics Group

Other

- Capitalizing on Nanotechnolgy's Enormous Promise
- Nanotechnology Now News and information source on everything nano
- Product and technology overview of nanotechnology companies and institutes for nanotechnology
- Nanotechnology Product Directory
- Nanotechnology News & Resources
- Nanotechnology Consumer Products Inventory From the Project On
- Nanotechnology in Victoria

Emerging Nanotechnologies

- nanolinks.eu - The global inventory of nanotech communities Meetings, News, Risk-Discussion, Organisations and Initiatives
- Foresight Nanotech Institute Think tank and public interest institute
- RARE Corporation Nanotechnology professional development short courses

Appendix 4: Websites

European technology gateway (N&N events and news):

http://www.nanoforum.org/

FP6 FAQs:

http://ec.europa.eu/research/fp6/pdf/faq_en.pdf