NANOCAP

Nanotechnology Capacity Building NGOs

Nanotechnology:

A BRIEF INTRODUCTION

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About the Document

The present document is part of a series of papers written for the FP6 Project NANOCAP (acronym for “Nanotechnology Capacity Building NGOs”), which is a European Project that was set up to deepen the understanding of environmental, occupational health and safety risks, and ethical aspects of nanotechnology. More information about NANOCAP can be found on the project’s website www.nanocap.eu.

Nanotechnology is defined and described in an introductory paper, and its application in diverse field then described in separate papers:

- Nanotechnology- A Brief Introduction
- Applications of Nanotechnology: Energy (Part 1 and Part 2)
- Applications of nanotechnology: Environment
- Applications of Nanotechnology: Medicine (part 1 and Part 2)

The aim of these documents is to provide updated, concise yet accurate information about nanotechnology in fields of high societal impact like environment, energy and medicine based on scientific literature and authoritative reports. The documents also include some visions of potential applications of nanotechnology, whilst keeping the discussion at a realistic level. These documents have been written with the purpose of supporting environmental NGOs, trade unions, as well as other groups in learning about nanotechnology and its potentials in these diverse areas of applications. The authors’ intention is to help those groups forming a balanced view of nanotechnology, so to promote a constructive dialogue about this emerging technology. Other aspects of this discussion, such as potential environmental risks of nanomaterials, health and safety aspects, and ethical/societal concerns related to nanotechnology, are not covered in these papers but can be found in other sections of the NANOCAP website (www.nanocap.eu)

About the Authors

Luisa Filipponi is currently a Post Doctorate at the Interdisciplinary Nanoscience Center (iNANO) at the University of Aarhus (Denmark). She has a Bachelor degree in Chemistry (University of Bologna, Italy) and a PhD in Nano- and Microtechnology completed in 2006 at Swinburne University of Technology (Australia), through a project involving Nanotechnology Victoria (Nanovic) and the Cooperative Research Centre for Microtechnology. Her research focused on novel micro-and nanofabrication methods to develop nanoarrays for the selective detection of proteins and cells. Luisa is the author of a review for the Wiley Encyclopaedia of Biomedical Engineering (John Wiley & Sons, Inc., 2006), co-author of a chapter in the book ‘Microarray Technology and its Applications’ (Springer & Verlag, 2005), author and co-author of various scientific publications, as well as co-inventor of two patents. She currently focuses on science communication in particular related to nanoscience and nanotechnology.

Duncan Sutherland has worked in the area of nanotechnology for life science since 1995 publishing to date 45 scientific articles with a focus on nanostructured biomaterials and nanoscale biosensors. After completing his Ph.D in Physics at the University of Bristol he moved to Chalmers in Sweden where he became a project leader in the Chemical Physics Group of the Department of Applied Physics. During his time in Sweden he developed self-assembly based engineering approaches to nanofabrication utilising colloidal particles systems and applied them to the study of nanostructured interfaces in different life science applications. In March 2006 he moved to an Associate Professor position at the iNANO centre at the University of Aarhus, where he formed the Biointerfaces Group with research interests in biomaterials, biosensors, biofouling and nanotoxicology. In addition to his research activities, A/Prof. Sutherland is also involved in outreach activities, including communicating fundamental concepts, benefits and applications of nanotechnologies to NGOs, trade union representatives, industry members and the general public.

NANOTECHNOLOGY- A brief introduction

The aim of this paper is to provide some background information on nanoscience and nanotechnology, including definitions; to identify the key properties that make nanomaterials ‘special’; and to provide some common background information to the NANOCAP documents, where the application of nanotechnology to specific fields (Environment, Energy, Medicine, etc.) is discussed.

Definitions

NANOSCIENCE AND NANOTECHNOLOGY

A *nanometre* (nm) is 10^{-9} meter. To put this in context, the dot over this letter "i" is approximately one million nanometres in diameter; **Figure 1** shows examples of objects with length scales ranging from the macro to the nano world.

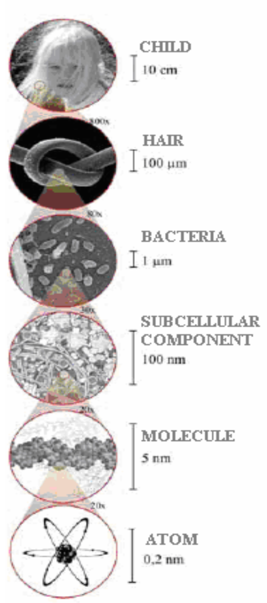


Figure 1 From the macro to nano world. Image courtesy of iNANO, University of Aarhus

Nanoscience is the study of phenomena on the *nanometre scale* (defined below). **Nanotechnology** manipulates matter at the atomic, molecular or macromolecular level to create and control objects on the nanometre scale, with the goal of fabricating novel materials, devices and systems that have new properties and functions because of their small size. The definition of nanotechnology[1] is rather broad and includes both nanotechnology-enabled materials (such as carbon nanotubes) and nanotechnology-enabled tools and processes.

The *nanometre scale* is commonly indicated as 1-100 nm, but nanoscience and nanotechnology often deal with objects larger then 100 nm. This variability arises from the interdisciplinary nature of nanotechnology, which arises from the convergence of chemistry, physics, material science, engineering, molecular biology, biology and medicine. In some fields objects studied are in the 1-100 nm length scale (e.g., quantum dots), but in other fields, such as biochips, objects have dimensions in the range of hundreds of nanometres.

Even though nanoscience is often perceived as a science of the future, it is actually the basis for all systems in our living and mineral world. We have

[1] There is not consensus among scientists on the definition of nanotechnology, so to date there is not an official definition of it. For other definitions of nanotechnology, see the Bibliography section (in particular “Nanoscience and nanotechnologies: opportunities and uncertainties”, report by The Royal Society and The Royal Academy of Engineering, 2004). It has also been suggested that reference should be made to *nanotechnologies* rather then nanotechnology, to take into account the broad spectra of materials, methods and applications involved in this field of science.

hundreds of examples of nanoscience under our eyes daily, from geckos that walk up side down on a ceiling, apparently against gravity, to butterflies with iridescent colours, to fireflies that glow at night. In Nature we encounter some outstanding solution to complex problems in the form of fine nanostructures to which precise functions are associated. In recent years, researchers have had access to new analytical tools to see and study those structures and related functions in depth. This has further stimulated the research in the nanoscience area, and has catalysed nanotechnology. So in a sense, natural nanoscience is the basis for nanotechnology.

WHAT IS A NANOMATERIAL

Nanotechnology manipulates matter for the deliberate fabrication of nano-sized materials. These are therefore '**intentionally made**' through a defined fabrication process. The definition of nanotechnology does not generally include 'non-intentionally made nanomaterials', that is, nano-sized particles or materials that belong naturally to the environment (e.g., proteins, viruses) or that are produced by human activity. In these NANOCAP documents, the term 'nanomaterial' will be used meaning 'intentionally-made nanomaterial'.

A nanomaterial is an object that has at least one dimension in the nanometre scale. Nanomaterials are categorized according to their dimensions as shown in **Table 1**:

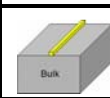
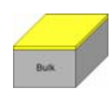
Nanomaterial Dimension	Nanomaterial Type	Example
All three dimensions < 100 nm	Nanoparticles, Quantum dots, nanoshells, nanorings, microcapsules	
Two dimensions < 100 nm	Nanotubes, fibres, nanowires	
One dimension < 100 nm	Thin films, layers and coatings	

Table 1. Nanomaterials categorized based on their dimensions.

What makes 'nano' special?

'Nano' means small, very small; but why is this special? There are various reasons why nanoscience and nanotechnology are so promising in material, engineering and related sciences. First, at the nanometre scale, the properties of matter, like energy, change. This is a direct consequence of the small size of nanomaterials, physically explained as **quantum effects**. The consequence is that a material (e.g., a metal) when in a nano-sized form can assumes properties which are very different from those when the same material is in a bulk form. For instance, bulk silver is non-toxic, whereas silver nanoparticles are capable of killing viruses upon contact. Properties like electric conductivity, colour, strength, weight, change when the nanoscale level is reached. The same metal can become a semiconductor or an insulator when the nanoscale is reached. The second exceptional property of nanomaterials is that they can be fabricated atom-by-atom, with a process called **bottom-up**. The information of this fabrication process is embedded in the material building blocks, so that these can **self-assemble** in the final product. Finally, nanomaterials have an **increased surface-to-volume** compared to bulk materials. This has important consequences for all those processes that occur at a material surface, such as catalysis and detection. The next sections will further discuss these properties highlighting their potential benefits in practical applications.

Nanoscience and nanotechnology depend on the exceptional properties of matter at the nanoscale level. In this context, *nano* doesn't only mean '1000 times smaller then *micro*', and nanotechnology is not just an extension of microtechnology to a smaller scale. It is an entire new paradigm that opens entirely new scientific opportunities.

QUANTUM EFFECT

Nanomaterials don't follow Newtonian physics, which applies to matter at bulk level. At the nanometre scale the properties of matter, like energy, momentum, mass, are not a *continuum*, like at the bulk level, but are made of specific units, or *quanta*. Energy, for example, in not absorbed or emitted constantly but only in multiples of specific, non-divisible energy units. **Quantum mechanics** is the field of physics that describes these quantum effects, which represent nothing but the discrete nature of matter at the smallest level (atomic, nuclear and particulate level). The exceptional properties of nanomaterials are a direct consequence of these **quantum effects**.

An example of quantum effect in nanosized particles is **colour**. The gold in a ring is notably yellow, but if gold is shrunk to a nanoparticle (10 nm to 100 nm in size) it becomes red if it is spherical, and colourless if it is shaped in a ring. Moreover, nanoparticles emit a specific colour depending on their nanometre-size. For instance, **quantum dots** (QD) are semiconducting nanocrystals, about 10 nm in size, that are able to 'trap' electrons in small spaces. A QD has a discrete, quantized energy spectrum, which results in the emission of a **monochromatic colour**. Depending on their size, QD emit different colours, as shown in **Figure 2**.

Figure 2. Ten distinguishable emission colours of ZnS-capped CdSe QDs excited with a near-UV lamp. From left to right (blue to red), the emission maxima are located at 443, 473, 481, 500, 518, 543, 565, 587, 610, and 655 nm. Reprinted by permission from Macmillan Publishers Ltd: Nature Biotech. 2001, 19, 631-635, Copyright 2001.

In addition to size, the **shape** of nanomaterials has an impact on their properties. For instance silver nanoprisms about 100 nm scatter red light while silver nanospheres scatter pale yellow light.

QD and metal nanoparticles hold great promise for nano-enhanced imaging which will bring progress to fields like environmental monitoring, medical diagnostic and treatment. QD are also investigated as novel light sources to improve LED technology.

SAME ATOMS, DIFFERENT MATERIAL

In Nature there are some pure materials that have striking different properties even though they are made of the same atoms. For instance, **graphite** and **diamond**: two very popular materials, one used conventionally in pencils and the other in jewellery. These two materials could not be more different: graphite is soft, light, flexible, and conducts electricity while diamond is extremely strong, hard and does not conduct electricity. Both materials are made of atoms of carbon linked through strong bindings (covalent), but in graphite each carbon uses three out of his four electrons to form single bonds with its neighbours, forming a linear sheet, whereas in diamonds each carbon uses all its four electrons to form four single bonds, resulting in a 3-D structure. The different properties of graphite and diamond are a consequence of the different way the carbon atoms in the materials are bonded together. Graphite and diamond are two pure forms of carbon called allotropes.

In 1985 a new allotrope of carbon was discovered formed of 60 atoms of carbons linked together though single covalent bonds arranged in a highly symmetrical, closed shell that resembles a soccer ball. This material was officially named Buckminster fullerene and is often referred to as buckyball, fullerene or simply C_{60}. Since its discovery, fullerenes with 70, 80 and even more carbons were discovered. In the early 1990s, an incredibly new carbon form was discovered, **carbon nanotubes**[2]. These appear like graphite sheets rolled up with fullerene-type end caps, but have totally different properties compared to graphite. **Figure 3** shows different forms of carbon allotropes (image **d** and **h** are structures of a C_{60} and a nanotube, respectively).

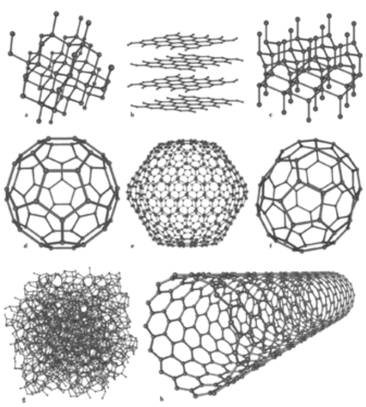


Figure 3. Eight allotropes of carbon: (a) diamond, (b) graphite, (c) lonsdaleite, (d) C60, (e) C540, (f) C70, (g) amorphous carbon and (h) a carbon nanotube. Image by Michael Ströc, (GNU Free Documentation License).

[2] It is now known that fullerenes and carbon nanotubes form naturally in common places like flames (produced by burning methane, ethylene and benzene) and in soot.

Since their discovery, scientists have developed methods to control the synthesis of carbon nanotubes to obtain regular structures with specific properties. Carbon nanotubes can be as single-wall nanotubes (SWNTs), with a diameter of approximately 1.4nm, or multi-wall nanotubes (MWNTs), consisting of 2 to 30 concentric tubes with an outer diameter of 30-50nm. Carbon nanotubes can range in length from a few tens of nanometers to several micrometers, and can have metallic properties (comparable to, or even better then copper) or can be semiconductors (like silicon in transistors), depending on their structure. Carbon nanotubes can also be modified to bind other molecules, making this material very useful in biological application. The remarkable material properties of carbon nanotubes, such as rigidity, durability, thermal conductivity and electrical conductivity, make these nanomaterials great candidates for wires, interconnectors, sensor elements and molecular electronic devices. Theoretical scientists have calculated that carbon nanotubes could make the strongest fibers ever made: about 100 time stronger then steel with only 1/6 of the weight. These fibers could be used for fabricating strong but lightweight materials, for instance for the aerospace industry.

Carbon nanotubes are an excellent example of **novel functional nanomaterials**, that is, materials that have exceptional properties due to their nanostructure and which synthesis can be tailored to produce nanotubes with specific properties and to perform specific functions.

SELF-ASSEMBLY

Fabrication of nanomaterials can be done in two ways (**Figure 4**): by self-assembly, that is, building the nanomaterial 'atom-by-atom' (**bottom-up approach**) or by 'carving' the nanomaterial out of a bulkier one (**top-down approach**). The concept of self-assembly derives from observing that, in natural biological processes, molecules self-assemble to create complex structures with nanoscale precision. Examples are the formation of the DNA double helix. In self-assembly, sub-units spontaneously organize and aggregate into stable, well defined structures through non covalent interaction. This process is guided by information that is coded into the characteristics of the sub-units and the final structure is reached by equilibrating to the form of lowest free energy.

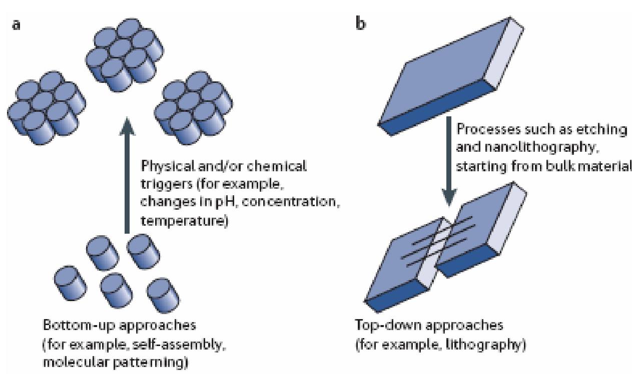


Figure 4 Schematic of (a) the bottom-up and (b) top-down approach. Reprinted by permission from Macmillan Publishers Ltd: Nature Reviews 2006, 7, 65-74, Copyright 2006.

Self-assembled nano and microstructures can be created with one or more components. For instance, **Figure 5** shows a self-assembled superlattice of magnetic and semiconductor nanoparticles. These multi-component nanocrystals assemblies have shown to have magnetic properties which differ from the properties of the individual components.

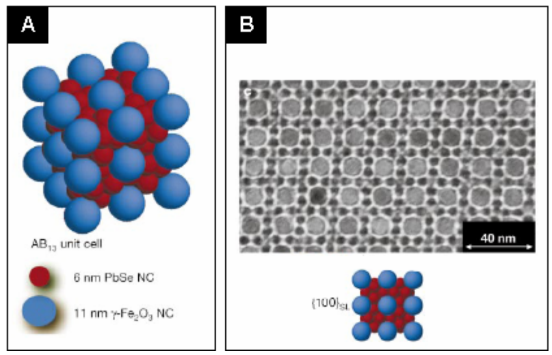


Figure 5. (A) Cartoon showing the cubic unit of a superlattice of magnetic (γ-Fe_2O_3) and semiconductor (PdSe) nanoparticles; (B) transmission electron microscope (TEM) image of the self-assembled superlattice with corresponding view. Reprinted by permission from Macmillan Publishers Ltd: Nature 2003, 423, 968-971, Copyright 2003.

By following a self-assembling method, scientist can create nanomaterials that have some very specific properties, controlled at the atomic level and designed to correspond to very specific functions. The aim is to use nano-sized building blocks that can self-assemble in functional 2D or 3D components that have dimensions devices can use. '**Biomimetic self-assembly**' employs the natural complementarity of some biomolecules, such DNA or proteins, to direct the assembly of attached nanoscale components.

SURFACE-TO-VOLUME

Nanomaterials have an increased surface-to-volume ratio compared to bulk materials. This means that for a given total volume of material, the external surface is greater if it is made of an ensemble of nanomaterial sub-units rather than of bulk material (**Figure 6**).

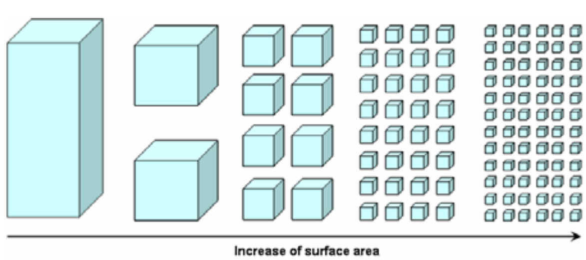


Figure 6. Schematic drawing showing how surface-to-volume increases when moving from a bulk material (far left) to nano-sized particles (far right).

The increased surface-to-volume of nanomaterials impacts the material **physical properties** such as its melting and boiling points, as well as its **chemical reactivity**. Reactions that occur at the material surface are particularly affected, such as **catalysis** reactions, **detection** reactions, and reactions that require the physical adsorption of certain species at the material's surface to initiate.

Finally, the higher surface-to-volume of nanomaterials allows using **less material**, which has environmental and economic benefits, as well as fabricating highly **miniaturized devices**, which can be portable and could use less power to operate.

Catalysis

A catalyst is a substance that increases a chemical reaction rate without being consumed or chemically altered. Nature's catalysts are called enzymes and are able to assemble specific end-products, always finding pathways by which reactions take place with minimum energy consumption. Man-made catalysts are not so energy efficient. They are often made of metal particles fixed on an oxide surface, working on a hot reactant stream (to reduce a phenomenon called 'catalyst poisoning' which occurs when species dispersed in the atmosphere, such as CO, occupy the active sites of the catalysts). One of the most important properties of a catalyst is its '**active surface**' where the reaction takes place. The 'active surface' increases when the size of the catalysts is decreased: the smaller the catalysts particles, the greater the ratio of surface-to-volume (**Figure 7**). The higher is the catalysts active surface, the greater is the reaction efficiency. Research has shown that the spatial organization of the active sites in a catalyst is also important. Both properties (nanoparticle size and molecular structure/distribution) can be controlled using nanotechnology. Hence, this technology holds great potential to expand catalyst design with benefits for the chemical, petroleum, automotive, pharmaceutical and food industry.

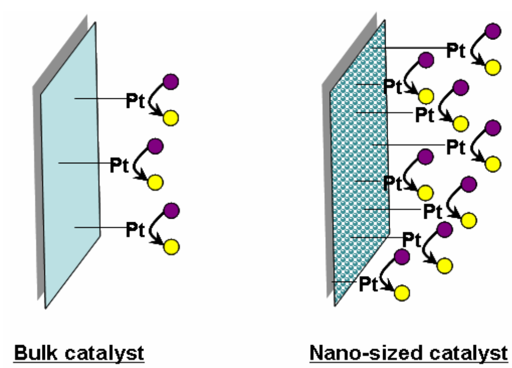


Figure 7. Schematic showing the increased active surface of a nano-sized catalyst (right) compared to a bulk catalyst.

Detection
The detection of a specific chemical or biological compound within a mixture represents the basis for the operation of numerous devices, like chemical **sensors**, biosensors and microarrays. As with catalysis, a detection reaction occurs at the material surface. The **rate**, **specificity** and **accuracy** of this reaction can be improved using nanomaterials rather then bulk materials in the detection area. The higher surface-to-volume ratio of nanomaterials increases the surface area available for detection with a positive effect on the rate and on the limit of detection of the reaction. In addition, nanomaterials can be designed to have specific surface properties (chemical or biochemical), tailored at a **molecular level**. This way, the active sites on the material surface can act as 'locks' to detect specific molecules (the 'keys'). **Figure 8** illustrates this concept.

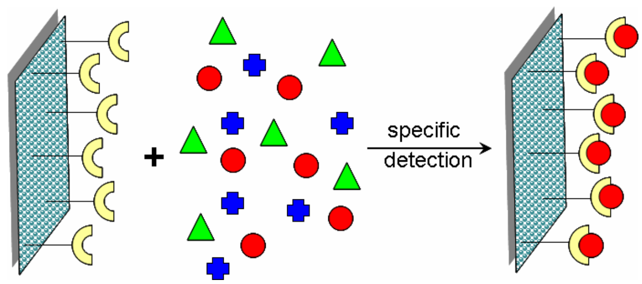


Figure 8. Schematic showing the specific detection of an analyte within a mixture by 'receptor' sites in a nanomaterial.

Scaling down using nanomaterials allows packing more detection sites in the same device, thus allowing the detection of multiple analytes. This scaling-down capability, together with the high specificity of the detection sites obtainable using nanotechnology, will allow the fabrication of super-small '**multiplex detection devices**'. Devices that can test and detect more then one analyte at the time will lower the cost of the analysis and reduce the number of devices needed to perform the analysis with an obvious economic benefit. Advancements in the field of nanoelectronics will also allow the fabrication of nanosensors capable of continuous, real time monitoring.

Nanotechnology is not all new

The interest in nanoscience is not all new. Researchers have been studying the atomic properties of matter for more then a century, and fields like colloidal science have been extensively investigated in the last decades. In a sense, the study of atoms and molecules is the basis of most scientific disciplines, such as chemistry, biochemistry and physics. Nanomaterials are not all new either: nanocrystals, nano-sized catalysts, magnetic nanoparticles have been long studied for years now, for a variety of applications. Some 'nano-tools' are not that recent either: for instance, the Atomic Force Microscope (AFM) and the Scanning Tunnelling Microscope (STM) techniques were first introduced to the scientific community in the mid 1980s. 'Nanoscience' is therefore an umbrella term that covers traditional disciplines as well as new and emerging ones.

So if it's not all new, why is it so special?
In recent years researchers have been able to uncover enormous potentials of nanoscience and nanotechnology thanks to a new set of analytical and fabrication tools. These have allowed the systematic investigation of nanomaterials and the realization that the exceptional properties of matter at the nano-scale level can be use to build new materials, systems and devices with properties, capabilities and functions that could not be achieved if bulk materials were used. In this context nanotechnology can be thought of as an extension of traditional disciplines towards novel ones that explicitly consider these new properties.

At the same time, in recent years new nanomaterials have been intentionally fabricated or discovered, novel nano-tools have been developed and old ones implemented, and novel properties of the matter at the nano-scale level have been discovered. For these reasons, nanoscience and nanotechnology shouldn't be seen as entirely new but rather 'work-in-progress science'. A 'work' that finds its roots in disciplines, like chemistry and physics, where a lot of fundamental knowledge is well established, and that progresses towards fields and applications where new knowledge is currently being created and collected.

For those reasons, nanotechnology should be seen as an **evolution**, not a revolution.

Bibliography and Web Sources

Project on Emerging Nanotechnologies of the Woodrow Wilson Center International Center for Scholars: http://www.nanotechproject.org/

National Nanotechnology Initiative (NNI): http://www.nano.gov

Nanotechnology in the European Commission www.cordis.europa.eu/nanotechnology/home.html. Specific documents are 'Towards a European Strategy for nanotechnology' (COM (2004) 338), and ´Nanoscience and nanotechnology: An action plan for Europe 2005-2009´ (COM (2005) 243).

Nanotechnology for the Life Sciences (10 volume set), Challa S. S. R. Kumar (Editor), Wiley-VCH, 2007.

V. Wagner, A. Dullaart, A-K Bock, A. Zweck, The emerging nanomedicine landscape, *Nature Biotechnology* 2006, 24 (10), 1211-1217.

Nanofabrication Towards Biomedical Applications: Techniques, Tools, Applications, and Impact, C. S. S. R. Kumar, J. Hormes, C. Leuschner, Wiley-VCH, 2005.

Nanoscience and nanotechnologies: opportunities and uncertainties, report by The Royal Society and The Royal Academy of Engineering 2004, http://www.nanotec.org.uk/

Nanotechnology: Basic Science and Emerging Technologies, M. Wilson, K. Kannangara (Author), G. Smith, M. Simmons, B. Raguse, Chapman & Hall/CRC, 2002.