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**See also separate file on CD with Hyperlinks to Mr. Kurzweil's references.

INTRODUCTION.

'**Nano**' keeps appearing in the media. Nanoscience and nanotechnology pop up in a myriad of forms. They are in technical papers ranging from medicine to all disciplines of engineering, and even in clothing catalogues and the financial news. Investment gurus predict enormous returns if you invest in this new technology. Some say it will be a larger influence on life than the application of computers. Others predict a $15 billion market for nanotechnology in the near future, then growing to a trillion.

In all this media coverage we found it difficult to get to grips with the subject, and separate myth from reality. Yet there appears to be sufficient momentum and interest that it deserves more study. So, in the Summer of 2004 the Central Canada Branch of the Institution of Mechanical Engineers decided to focus the 2004/2005 seasons program on learning more about the various aspects of, and prospects for nanoscience and nanotechnology. In particular we want to learn what it is all about, is there any substance behind the hype and what impact will it have for engineers.

The program has been very successful, with impressive talks from a wide variety of speakers who have covered many applications. In general the speakers spoke off-the-cuff from their computer full of PowerPoint slides rather than giving a set lecture. However, the speakers have kindly agreed to help us in producing summary notes of key aspects of their talks, and to our reproducing some of their slides.

Each lecture is covered in a chapter. Each chapter starts with the flyer announcing the talk and speaker, and is followed by our summary of the talk together with additional material from our studies. The final chapter summarizes our comments having listened to all the speakers as well as studying relevant literature. In addition we have included references and web sites for further study. We, the authors of this document are not experts in nanotechnology but generalist engineers.

The Canadian Nanobusiness Alliance co-sponsored the program, and we wish to thank their President, Neil Gordon for his help. In addition, some meetings were co-sponsored by BCS, SME and IEE.

Stephen C Armstrong.
Don S Lawson.
V C Mathur.

Canadian NanoBusiness Alliance
Alliance canadienne du commerce en nanotechnologie

IMechE CCB Programme 2004/2005

NANOTECHNOLOGY

The Science, Applications, Economic Impact, Way Forward

Overview

We have chosen a theme for next seasons technical programme. Nanotechnology is the science and technology at the atomic and molecular level - nanometric or 10^{-9}m. Nano science and technology covers many fields, from biology and medicine to material sciences and nano machines. It opens the opportunity for a new range of materials, huge advances in sensors, and a generation of more powerful computing capability. Nanotechnology is predicted to be the technology of the 21st century, and be even more pervasive than the development of computers. Many billions of dollars are being spent on development around the world. The US National Science Foundation estimates that by 2015 there will be a $1trillion global market for nanotechnology. This programme is aimed at cutting through the hype and presenting a useful introduction to nanotechnology for engineers, technologists, and scientists of all disciplines (Mechanical, Electrical, Chemical, Civil, Manufacturing, Industrial, Building, Aerospace, etc).

Programme Outline

Date	Subject	Location
21 Sep 2004	Overview – The underlying science, applications, trends, economic impact	University of Toronto
19 Oct 2004	Energy (generation, distribution & sources)	University of Toronto
16 Nov 2004	Transportation (space flight, commercial, military)	University of Toronto
03 Dec 2004	Computing applications – Photonics	Airport Board of trade, Dixon Road
18 Jan 2005	Lubrication for machines	Old Mill
15 Feb 2005	Materials technology	University of Toronto
18 Mar 2005	Medical applications and the engineering connections	Airport Board of Trade, Dixon Road
19 Apr 2005	Environment (soil, pollution control etc.)	University of Toronto
17 May 2005	The Way Forward – A Road Map for the Next 50 Years	University of Toronto

Why Should You Attend The Nanotechnology Lectures?

There are three reasons:

- First the subject is fascinating.
- Second, all the talks are by knowledgeable experts in their field. As a result attendance at the talks should qualify as meeting requirements for Continuing Professional Development (CPD). IMechE will be issuing a certificate to people who attend more than 7 meetings.
- And third, scientists and engineers have an obligation to ensure that the benefits of Nanotechnology are available in a timely manner to society, and that at the same time we do not descend into the nanohell that some worry about. This requires us to knowledgeably participate in the public debate to ensure that facts and logic prevail.

Programme open to Directors, Managers, Engineers, Scientists, Technologists and Government
Cost to cover printed material - $30; Students - $15 (in Total)
Flyers will be created for each lecture and will be posted at www.imeche-ccb.org
To register for the lecture series or for individual lectures, email: imechec@attglobal.net

CHAPTER 1.

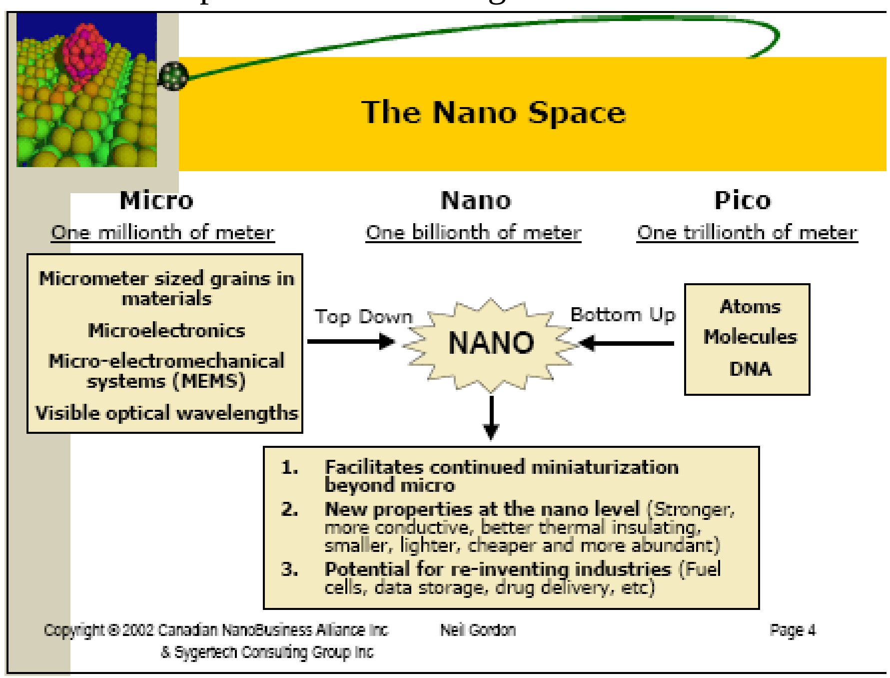
OVERVIEW – THE UNDERLYING SCIENCE, APPLICATIONS, TRENDS and ECONOMIC IMPACT.

Notes on the Lecture by Dr. Uri Sagman.

These notes cover the extensive briefing given by Dr. Sagman together with some material from his work with the Canadian NanoBusiness Alliance.

The nano world or nano space is shown in Fig.1.

Fig.1.

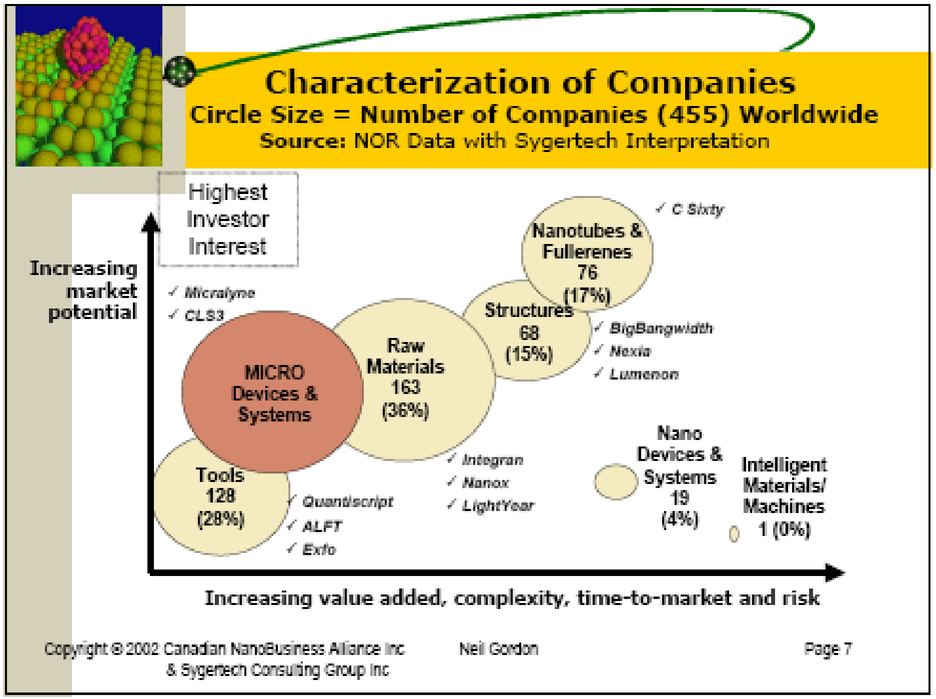


While nanotechnology is often considered as the science of the very small, there is a smaller world – the pico. A nanometer is 1 billionth of a meter. However most people now define nanotechnology as working in the range from 100nm to a fraction of 1nm. To put the nanoworld in perspective the sizes of materials found in nature are:-

Atom	0.1 nm
DNA (width)	2 nm
Protein	5-50 nm
Virus	75-100 nm
Bacteria	1000-10000 nm
White Blood Cells	10000 nm

The nanobusiness comprises 6 segments; tools for working at the nanoscale, nano raw materials, specific nano materials – Nanotubes and Fullerines, nano structures, nano devices & systems and Intelligent materials/Machines. The characteristic of companies in these sectors is shown in Fig. 2.

Fig.2.



One can question whether there is such a thing as the nanoindustry because it overlaps with microtechnology and is a merging of quantum science, biology and chemistry. Despite this, various estimates have been made of the size of the industry as shown in Fig.3.

Fig. 3.

Source	Now	2005	2010	2015
NSF	-	-	-	$1 trillion
In Realis	-	Up to $100 billion	Up to $800 billion	Up to $2 trillion
Evolution Capital	$20 – 50 billion	$150 billion	$1 trillion	-

The growth of nanobusiness is illustrated by the exponential growth of nano related patents.

Looking at the segments of nanotechnology in more detail –***Tools*** includes microscopy that permits visualization, and enables the manipulation of atoms. Tools include the Atomic Force Microscope (AFM), Scanning Tunneling Microscope (STM) as well as molecular modeling software. ***Raw Materials*** include nanoparticles and nanocrystalline materials. They can be used as biocompatible materials or coatings in drug encapsulation, bone replacements, prostheses and implants. ***Structures*** include quantum dots (which force atoms to occupy discrete energy states in biological markers) and dendrimers (branched polymers used for drug delivery, filtration and chemical markers). ***Nanotubes and Fullerenes*** –are the first ‘wonder materials’ of nanotechnology. They are forms of carbon, which are 100 times stronger than steel and one-sixth the weight, more conductive than copper, and can be safely used in some medical applications including artificial muscles, injection needles for individual cells, and drug delivery systems. ***Nanodevices and Systems*** are the evolution of microdevices, and biosensors and detectors that can be assembled as ‘lab-on-a-chip’. They offer the prospect of real time monitoring of biological conditions and near instant diagnosis. ***Intelligent Materials / Machines*** is a fascinating yet controversial area.

The applications for nanotechnology to medicine are shown in Fig. 4.

Nanomedicine Taxonomy

Biopharmaceutics
- Drug Delivery
  - Drug Encapsulation
  - Functional Drug Carriers
- Drug Discovery

Implantable Materials
- Tissue Repair and Replacement
  - Implant Coatings
  - Tissue Regeneration Scaffolds
- Structural Implant Materials
  - Bone Repair
  - Bioresorbable Materials
  - Smart Materials

Implantable Devices
- Assessment and Treatment Devices
  - Implantable Sensors
  - Implantable Medical Devices
- Sensory Aids
  - Retina Implants
  - Cochlear Implants

Surgical Aids
- Operating Tools
  - Smart Instruments
  - Surgical Robots

Diagnostic Tools
- Genetic Testing
  - Ultra-sensitive Labeling and Detection Technologies
  - High Throughput Arrays and Multiple Analyses
- Imaging
  - Nanoparticle Labels
  - Imaging Devices

Understanding Basic Life Processes

Fig.4.

Nanotechnology provides a wide range of new technologies for delivering drugs in the body. Some drugs are highly toxic and cause harsh side effects. Nano devices such as fullerenes can deliver drugs directly to the required destination in the body and then release the drug at a determined rate, directly to the affected cell. Drugs at the nanoscale compared with traditional microparticles have a larger surface area for the same volume, improved solubility and different structural properties. This technology can have a large role in tackling cancer, AID's, Parkinson's disease and ALS, to name just a few.

The fullerene is the nanoparticle most studied for drug delivery. It is built from 60 carbon atoms and is 1nm in size. The 60 atoms form into the strongest material in the universe. It is non-toxic and can become a 'molecular café' for delivering drug molecules. The 60 atoms form like a soccer ball Fig. 5.

Fullerene is short for Buckminsterfullerene and is named after the geodesic structures designed by Buckminster Fuller. Fullerenes are also called buckyballs.

Fig. 5.

Nanoparticles can be used as probes. Cancer antibodies can be attached to nanoparticles, which then attract them to cancer cells. Dyes are also attached to the nanoparticle and this makes them highly visible on a MRI. It has been claimed that this improves images by 50 times. Miniature imaging devices using nanotechnology are being developed for providing superior images to those from traditional devices.

Nanotechnology provides a new generation of biocompatible materials for repairing and replacing human tissue. Body material such as bone and teeth can only be repaired with material that the body sees as indistinguishable from the original. Nanomaterial has been developed that is biologically accepted by the body and can form the link between body cells and implants. This will make a dramatic reduction in the number of bone repairs that the body rejects.

The Genome Project was an impressive feat of research that catalogued DNA in a remarkably short time. Nanotechnology can now use that data to give tangible benefits. The process is one of *miniaturization* coupled with *parallel approaches* leading to *integration* and *automation*. Nanotechnology, together with biology will personalize medicine and change it from reactive to proactive. Prediction can come from the probabilistic DNA sequence. Prevention can come from systems to detect and prevent disease. And personalization can come from tailoring individual treatment based on DNA data and nanodata from a 'lab-on-a-chip' and other nano sensors.

Dr. Sagman has launched a Nanotechnology Clean Water Initiative. He sees clean water as one of the biggest single applications of nanotechnology. There are as many as 2 billion people who could face water scarcity by

2050. The Initiative has 3 branches – to make water safe, affordable and to find new supplies. Nanotechnology can help improve existing technologies by for example better filtration. Nanotools, materials and devices can all play a role, for example in killing off e-coli.

Nanotechnology applied to textiles can make them stain and water resistant as well as providing improved protection for bullet proof vests and better thermal insulation.

The increased surface area to volume of nanoparticles makes them more effective catalysts. When materials are produced there is a value chain as they move from mining to manufacture. For example copper mining is a $39B industry representing 0.4% GDP. Copper processing is a $374B industry representing 3.7% GDP. Manufacturing industries using copper is a $1720B industry representing 16.9% GDP. Nanomaterials could have a similar value chain.

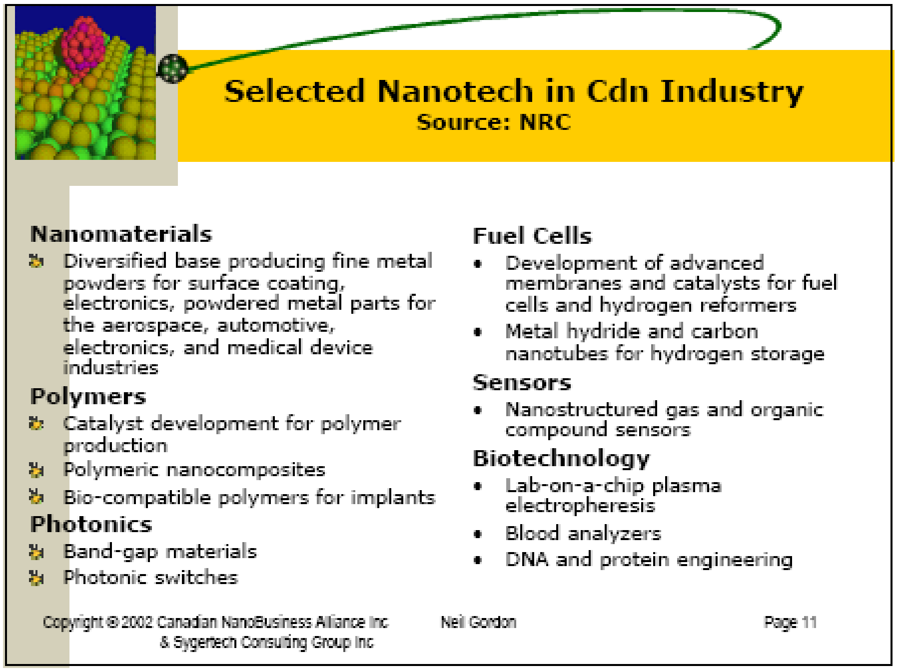
Nanotubes are already finding applications in cars. A small percentage of carbon nanotubes can increase the strength of polymers and can make them a conductor. This property allows electrostatic paint spraying, as used previously for metal fenders. Nanofibres can improve car tire performance.

The role of nanoscience and nanotechnology in Canada is shown in Fig.6.

Fig. 6.

Selected areas for Canadian nanotechnology are shown in Fig. 7.

Fig.7.



Few large-scale companies in Canada are involved in nanotechnology to date. And there is little visibility for the 150 to 200 small companies working in the field. Nano research funding per head of population in Canada is lagging other countries. A short-term and longer-term plans for Canada are shown in Fig. 8 & 9.

Fig. 8.

Fig. 9.


Long Term Considerations
From Kathryn Howard at BioNorth 2002
DG for Life Sciences, Industry Canada
Possible Goals for Canada in "Biotech" by 2010
1. Move from 3% to 10% of worldwide market for sales of biotech industry
2. Increase venture capital investment from $1 billion to $5 billion
3. Have 1 Canadian company in top 3 in world
4. Rank number 2 to US in Genomics
5. Natural bioproducts strategy to replace 5% of fossil fuels and petrochemicals
6. Position biotech as focused national clusters (less cities, less institutes)
Similar Goals are Needed Now for
Nanotech Success in Canada
Copyright © 2002 Canadian NanoBusiness Alliance Inc & Sygertech Consulting Group Inc
Neil Gordon
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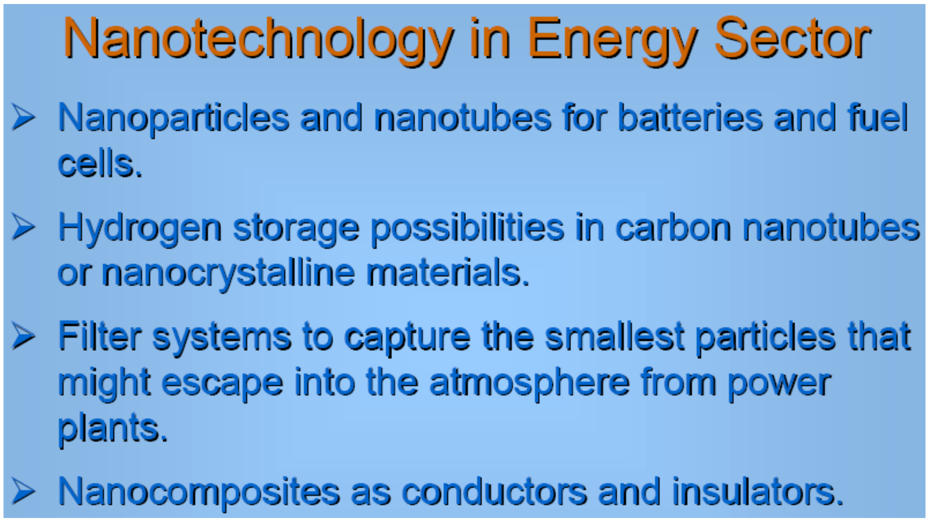
CHAPTER 2.

ENERGY – NANO COMPOSITES in POWER TRANSMISSION & DISTRIBUTION SYSTEMS.

<u>Notes on the lectures by Dr. Shesha Jayaram & Dr. Leonardo Simon.</u>

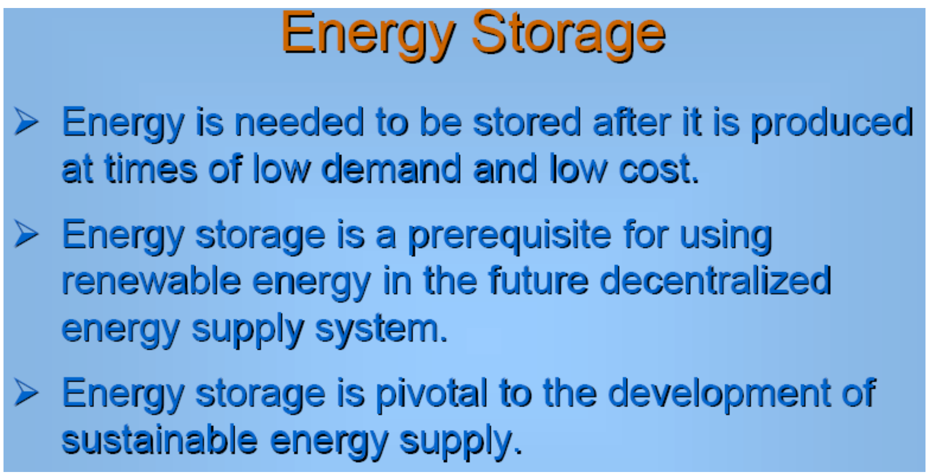
Dr. Jayaram started with an overview of the role of nanotechnology in the Energy Sector. Fig. 1.

Fig.1.



And in energy storage. Fig.2.

Fig.2.



The vastly increased ratio of surface area to volume at the nano size promotes surface effects that can markedly change chemical, electrical and mechanical properties. Some advantages of nanomaterials are shown in Fig.3.

Fig.3.

Dr. Jayaram pointed out that when people think about electrical systems they tend to concentrate on either the power plant or the end use of electricity. One element of the electrical system that is often overlooked is the large insulators. These are necessary to maintain electrical isolation of the high tension lines from the grounded towers as well as being components of transformer and switch gear. Typical materials for insulators are shown in Fig. 4.

Fig.4.

The respective advantages of the two main types are in Fig. 5, and the disadvantages in Fig.6.

Fig.5.

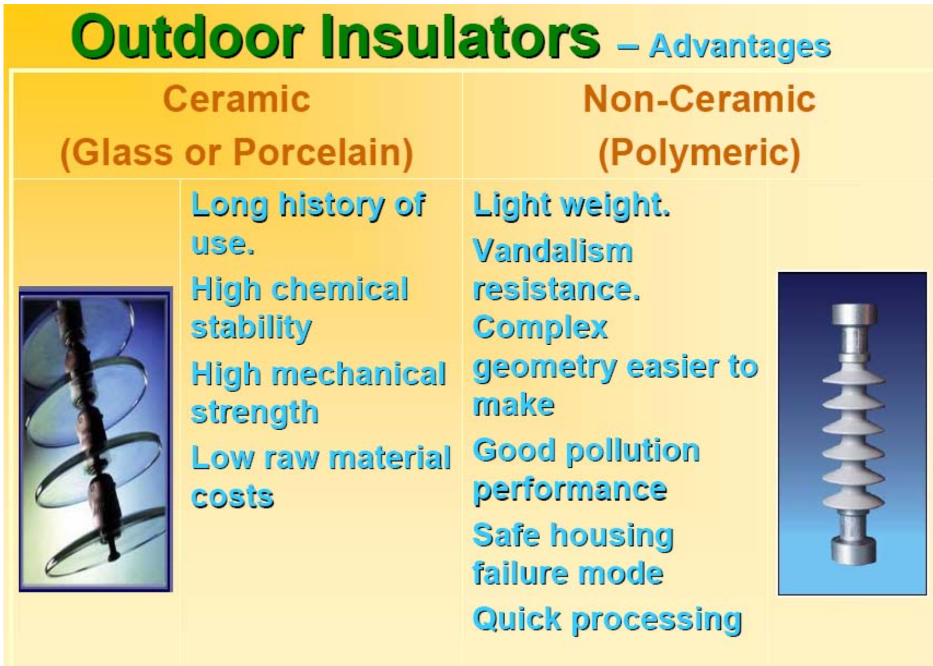
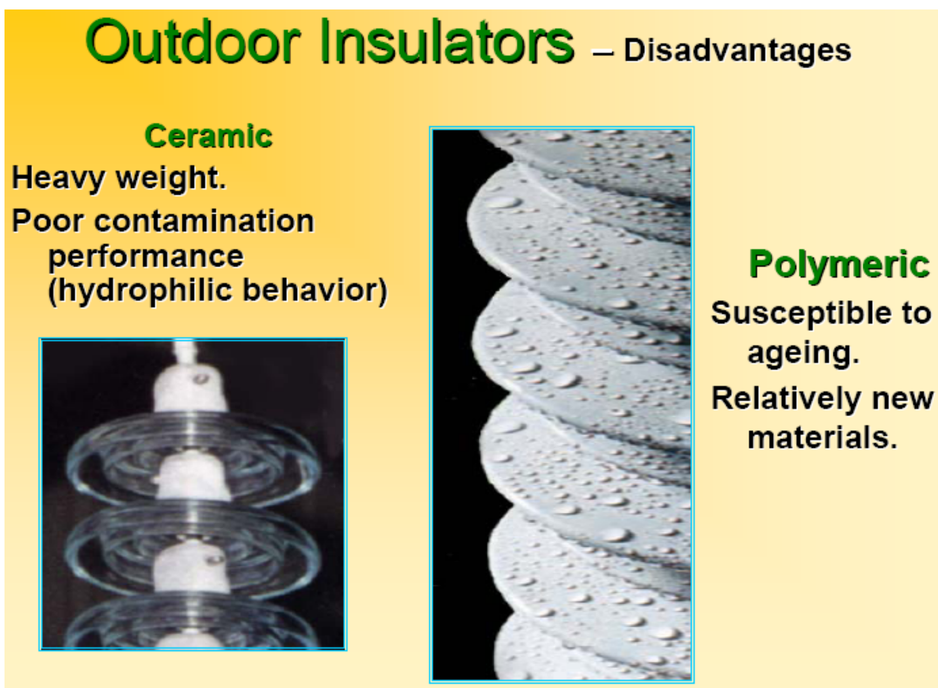


Fig.6.



The insulators are subject to a number of stresses – mechanical, electrical and environmental. The environmental stress comes from the sun, salt, ice, chemical and biological attack. Salt spray is not just at coastal sites but also from salt use on roads. Power lines close to major high-speed highways get contaminated from spray off the roads. Polymeric insulators age and can lose their hydrophobic action. Fig.7.

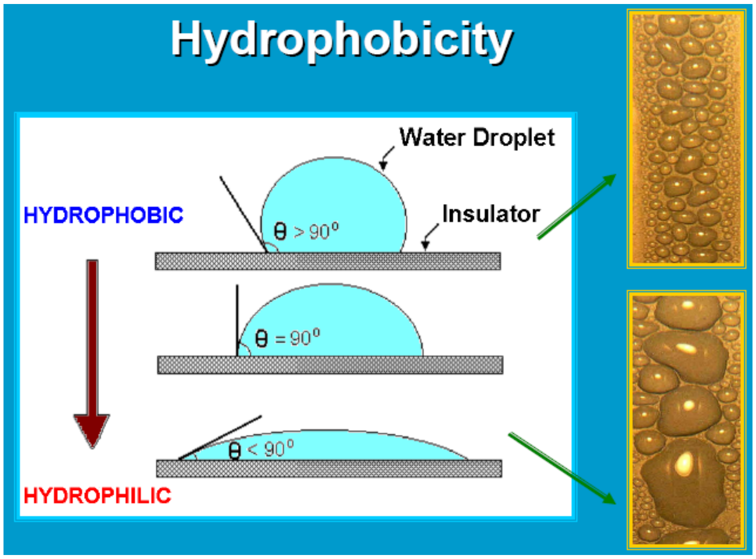


Fig.7.

The environmental stress and voltage combined with loss of hydrophobic property can lead to dry-band arcing. Fig.8.

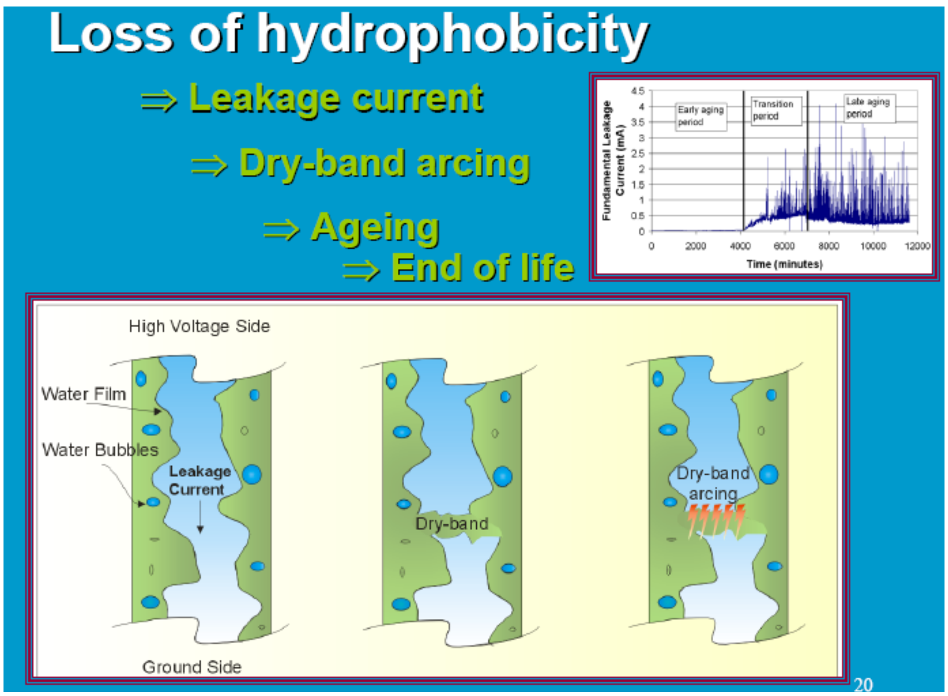
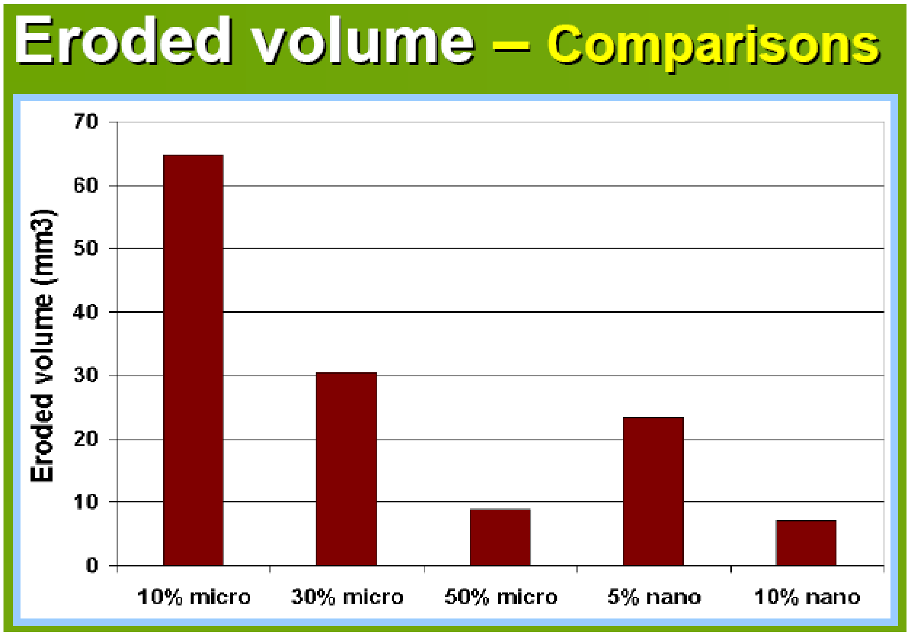


Fig.8.

Dr. Jayaram described work at the University of Waterloo that compared silicone rubber composites containing various amounts of either micro or nano sized fillers. The filler material was either 12nm fused silica or 5µm ground silica. The fillers improved the mechanical properties and chemical bonding; and reduced the cost. The comparison of the eroded volume under test is shown in Fig.9.

Fig.9.



In summary the nano filler significantly improved the erosion performance, but no significant improvement in thermal properties was found. The improvement in performance is thought to be more likely due to enhanced chemical bonding. More study is needed to fully understand the results.

Dr. Jayaram explained one feature of using nano particles – the problem of knowing what you have. One needs to know the distribution of size of the particles and whether they are coagulating into larger clumps. This tends to require Atomic Microscopy to assess the quality of the material you are using – as well as careful handling to ensure that the particles stay separate.

Dr. Leonardo Simon continued the lecture by first describing the vital tools for anyone working in nanotechnology – namely the scanning electron microscope, transmission electron microscope and atomic force microscope (more details in Chapter 10).

He then described the PEM fuel cell. PEM stands for Proton Exchange Membrane or alternatively Polymer Electrolyte Membrane. In the centre of a PEM fuel cell a polymer electrolyte membrane is sandwiched between an anode and a cathode. The membrane is between 15 and 20 microns thick. It conducts protons (charged ions) but not electrons. Current membrane materials have to be kept wet to function.

On the anode side of the membrane, hydrogen is introduced to a catalyst which strips off the electrons. The anode catalyst is usually platinum contained in a porous carbon electrode. The positive hydrogen ions, or protons can then flow through the membrane. On the cathode side of the cell oxygen in the form of air combines with the protons to form pure water – the only byproduct. Current flows from the anode to the cathode.

The power produced by a single cell is dependent on many parameters – temperature, pressure, materials and the form of the materials. Output from a single cell is around one volt.

Problems with fuel cells are the fact that the membrane has to be kept wet – in other words in a condition of weaker mechanical strength. Pressure differences across the cell can blow holes in the membrane. Contaminants can poison the cell. One contaminant is CO, which is very prone to poison the platinum catalyst. PEM cells typically operate around 80°C. they are lighter and smaller than other fuel cells and are preferred for transportation applications.

PEM fuel cells are a complex combination of materials. Nanotechnology brings a whole new dimension to the choice and form of materials. Nanonickel is a possible replacement for platinum. Electrodeposition of electrolytes is one promising line of research. Novel polyolefin material is being explored for the membrane. Hybrid materials are another area of study. In total, nanotechnology appears to have the potential to significantly improve and cheapen fuel cells.

Dr. Simon pointed out that another form of energy conservation is in developing better polymers that are stronger and can replace heavier material. As an example he quoted the changes in material use in a BMW car where, over the years, the percentage of weight in iron and steel has decreased from 75% to 55%. Polymers have increased from 5% to 20% of the car's weight. New stronger polymers can make a further impact. And the benefits are not just in automobiles – filled polymers can be used for beer barrels and food packaging.

Dr. Simon answered some questions.

Question – Can nanomaterials store hydrogen for hydrogen driven cars? Answer – Yes, but a lot more research is needed and commercial storage using carbon nanotubes may be 20 years away. Question – Are better polymers likely to be used because of lower cost or better properties. Answer – Both in various applications. For example a small addition of nano material has made some plastics much easier to extrude. And nano coatings on greenhouses have saved energy costs. Question – Could the developments in nano materials for sunscreens be used to extend the life of vinyl window frames by slowing their decay under UV rays? Answer – Probably, some small quantity of nanoparticles in the surface could absorb the UV light and extend the life of the frames.

CHAPTER 3.

TRANSPORTATION (SPACE FLIGHT, COMMERCIAL, MILITARY.)

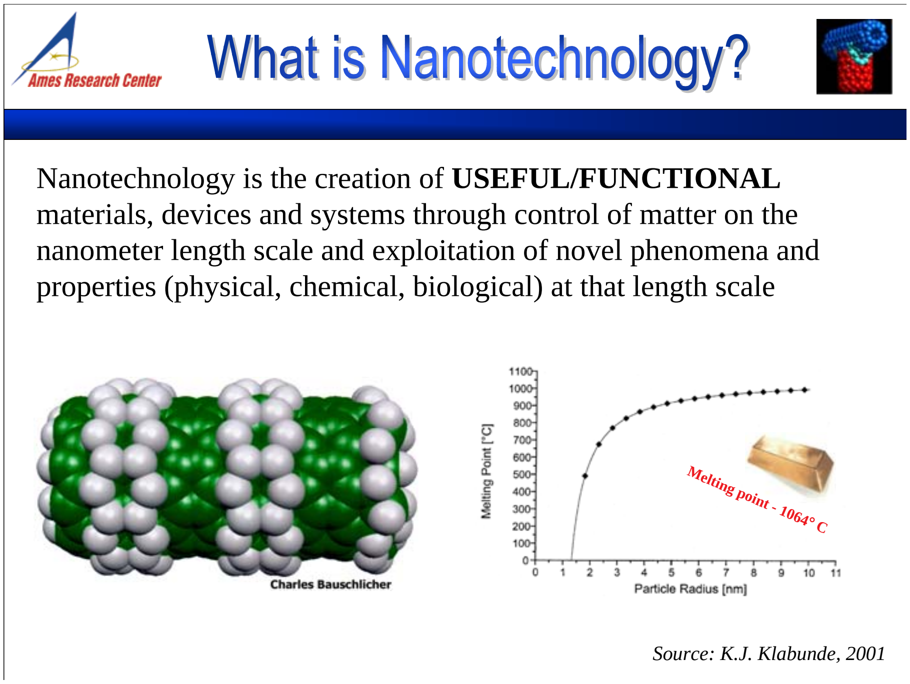
Notes on the Lecture by Dr. Meyyappan.

Dr. Meyyappan opened his talk by listing the areas of nanotechnology that he sees of interest to Mechanical Engineers (Fig.1.).

Fig.1.

His definition of nanotechnology is not just based on size but also that it should be useful and functional (Fig. 2.). The picture on the left of Fig. 2 shows a computer image of an idealized creation of atoms. The right hand picture shows how traditional physical properties change at the nano scale. The melting point of gold is markedly reduced as the particle size gets into the nano range. In this range the ratio of surface atoms to bulk atoms increases substantially. In material with strong chemical bonding, and where the structure changes with size, then there can be significant differences in physical and chemical properties as particle size is reduced. For example properties such as melting point, specific heat and surface reactivity change. When nano particles are consolidated into larger structures then new properties for the bulk material are possible – for example enhanced plasticity.

Fig.2.



Nanotech is an enabling technology likely to impact:-

- Materials and Manufacturing.
- Computing and data storage.
- Health and Medicine.
- Engineering.
- Environment.
- Transportation.
- National Security, and
- Space Exploration.

Carbon nanotubes are a key form of nanotechnology development (Fig.3.). This slide shows how the different forms of carbon nanotubes can be either metallic or semi-conducting, depending on chirality. In addition carbon nanotubes (CNT) have extraordinary mechanical properties, and many potential applications – as well as challenges, as shown in Fig. 4.

Fig. 3.

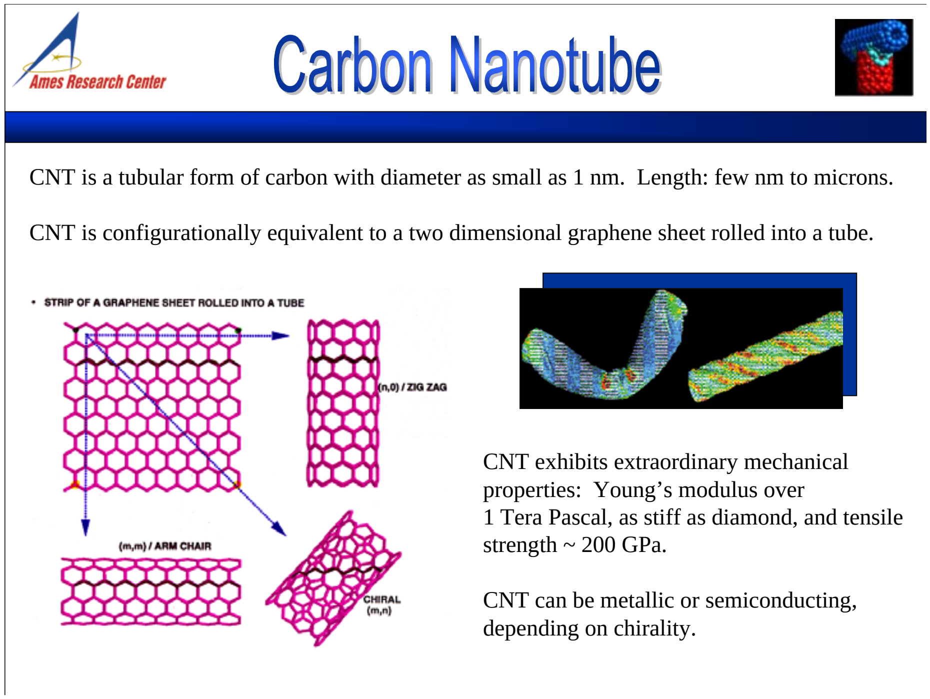
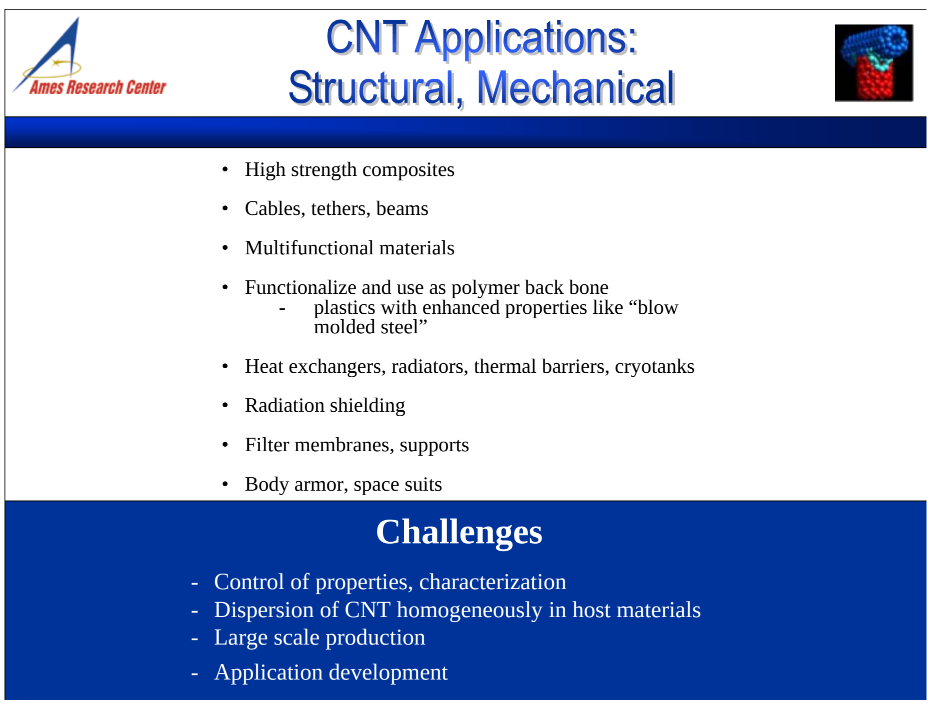
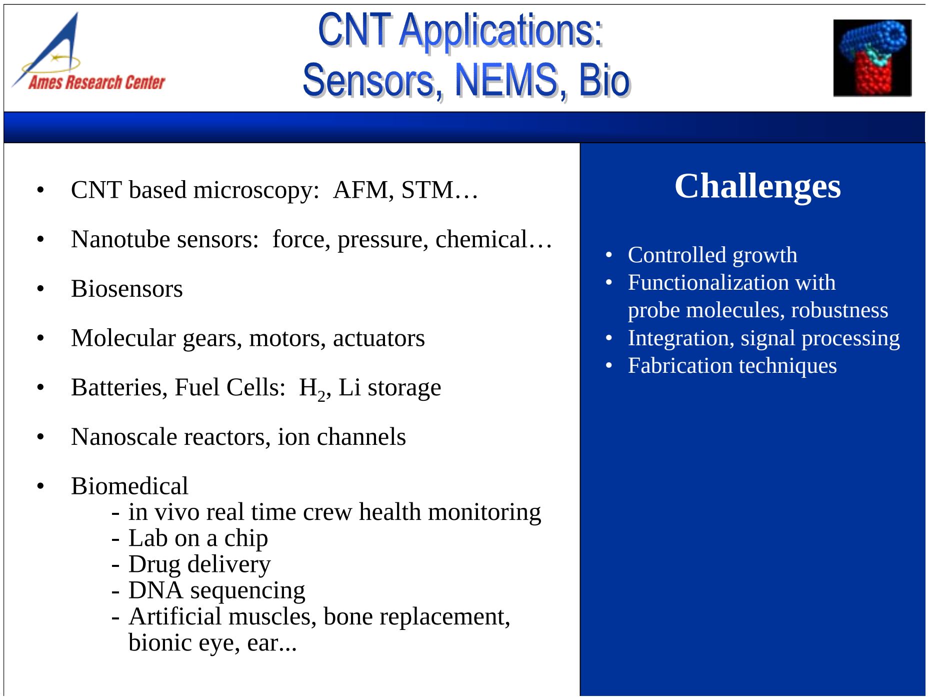


Fig. 4.



There are similar applications in the electronics field where carbon nanotubes can be used as interconnecting wires in nano-circuits. Carbon nanotubes open up a new world in sensors, Fig. 5.

Fig.5.



Carbon nanotubes have been grown by laser ablation since the early 1990’s. Manufacturing techniques have been following the experience in microelectronics by using hydrocarbon feed stocks and a catalyst at growth temperatures between 500ºC and 950ºC. Plasma reactors can also be used to grow nanotubes. High volume production of carbon nanotubes is still a developing technology. Some problems are having the nanotubes bunch up like ropes, or looking like a plate of spaghetti. In many applications one either wants specifically distributed nanotubes or be able to position individual tubes – and the challenge is to be able to do this economically.

Carbon nanotubes are effective in composites (Fig. 6.) and are already entering commercial application (Fig. 7.) Polymers can be made conducting by adding less than 1% by weight of carbon nanotubes. Carbon nanotubes in composites can also be effective magnetic shields. They can be used to produce thermal conductive coatings for example to deice aircraft surfaces.

Fig. 6.

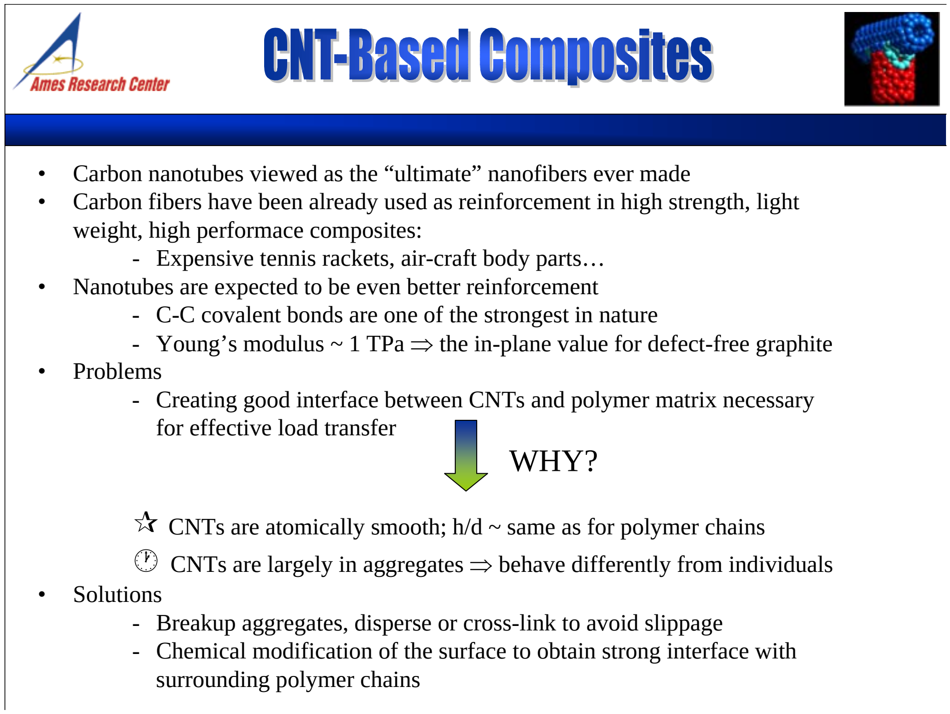
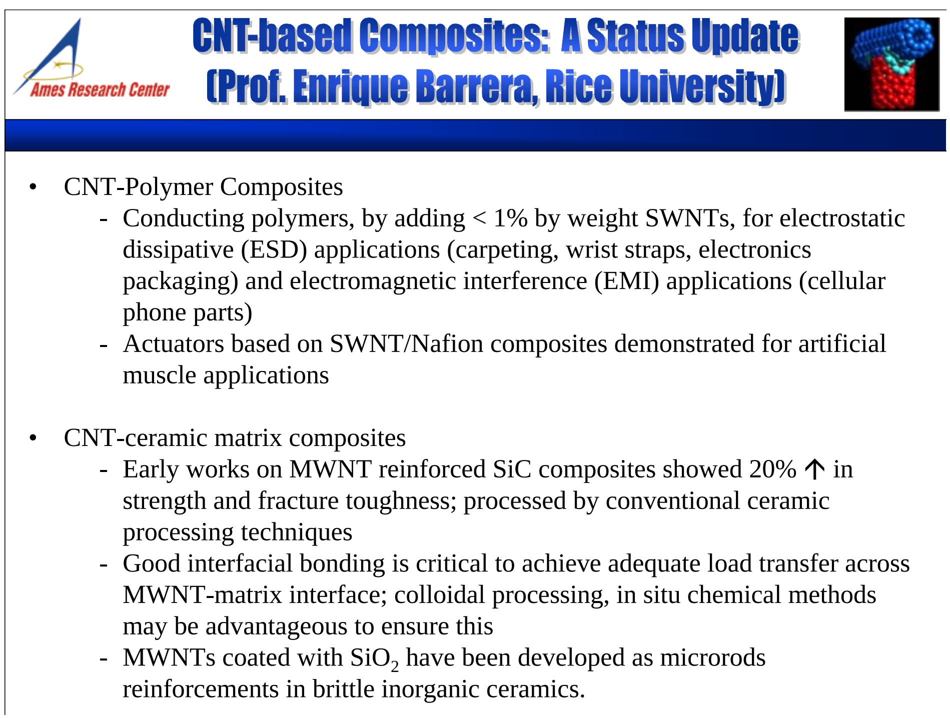


Fig.7.



(SWNT = Single Walled Nano Tube, MWNT = Multi Walled Nano Tube)

Carbon nanotubes have the potential to absorb hydrogen due to their porous structure and low density. This may help overcome a serious impediment to the commercialization of fuel cells – namely the safe and economic storage of hydrogen. The US Department of Energy has set a research target to store 6.5wt% or 62kg H_2/m^3. To date, several groups have confirmed the easy ability to achieve 1%, and some have claimed to get 5% to 8% but are struggling to demonstrate reproducible results.

Rechargeable lithium batteries using nanotubes instead of conventional graphite are able to store about 3 times more charge.

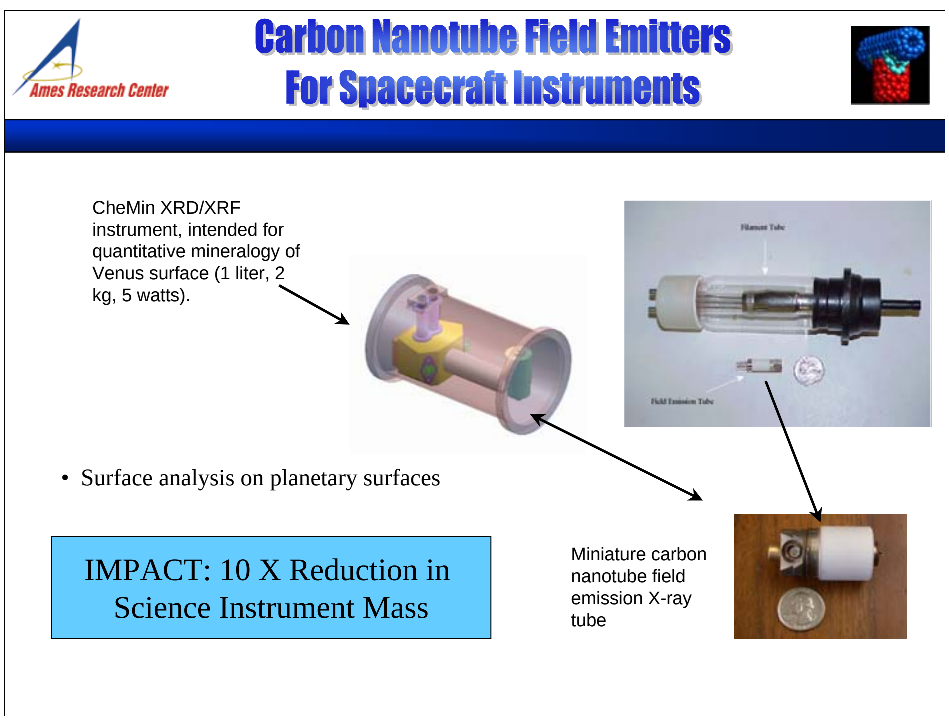
Nanotubes have potential application in :-

- Cathode ray lighting elements.
- Flat panel displays.
- Gas discharge tubes in telecommunication networks.
- Electron guns in electron microscopy, and
- Microwave amplifiers.

Working full colour flat tube panel displays and CRT lighting elements have been demonstrated in companies in both Japan and Korea. Samsung has produced a 32" prototype TV plasma display using nanotube technology.

Multiwalled carbon nanotubes can be used as electron sources and are ideal for miniaturization of instrumentation, such as the X-ray tube shown in Fig. 8. which has resulted in a 10 times reduction in mass.

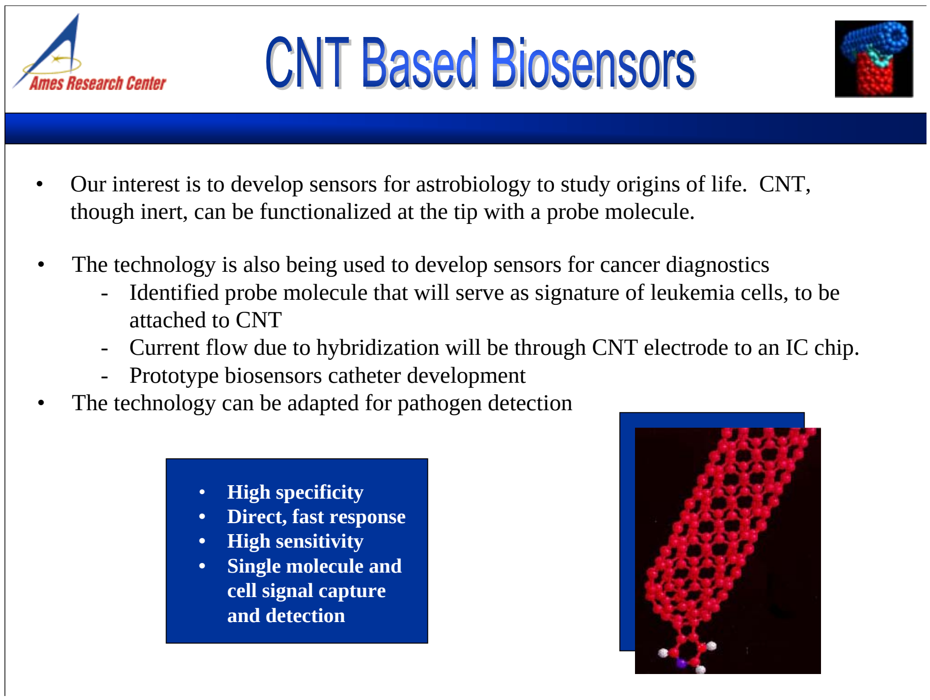
Fig. 8.



Multiwalled carbon nanotubes have found an application in Atomic Force Microscopy – an essential tool for studying nanoscience. The traditional silicon or tungsten probes wear out quickly, making it difficult to get repeatability of readings. The multiwalled carbon nanotube probe is robust and gives amazing resolution and repeatability of measurements.

Carbon nanotubes can lead to a new era of measurement tools for biology and medicine (Fig. 9.).

Fig. 9.



The right hand image shows a molecule attached to the tip of a carbon nanotube. This can result in a signal from a single cell. Every atom of a carbon nanotube is on the surface and is exposed to its environment. Any charge transferred to an atom of a nanotube can cause changes to its electrical properties, which can then be measured. For example a sensor for NO_2 has demonstrated a capability to detect levels down to 44ppb. This type of technology gives the potential to detect down to a single molecule. In biology a sensor can be designed with 30 dies on a 4" silicon wafer capable of giving instant readings for multiple biological and medical measurements.

Carbon nanotube strain sensors can be embedded in composite materials giving the ability for broad ranging non-destructive testing.

Nanotubes can be made from other materials than carbon. Boron nitride nanotubes are showing applications in nanoelectronic devices as well as composites.

Dr. Meyyappan summarized his talk in Fig. 10.

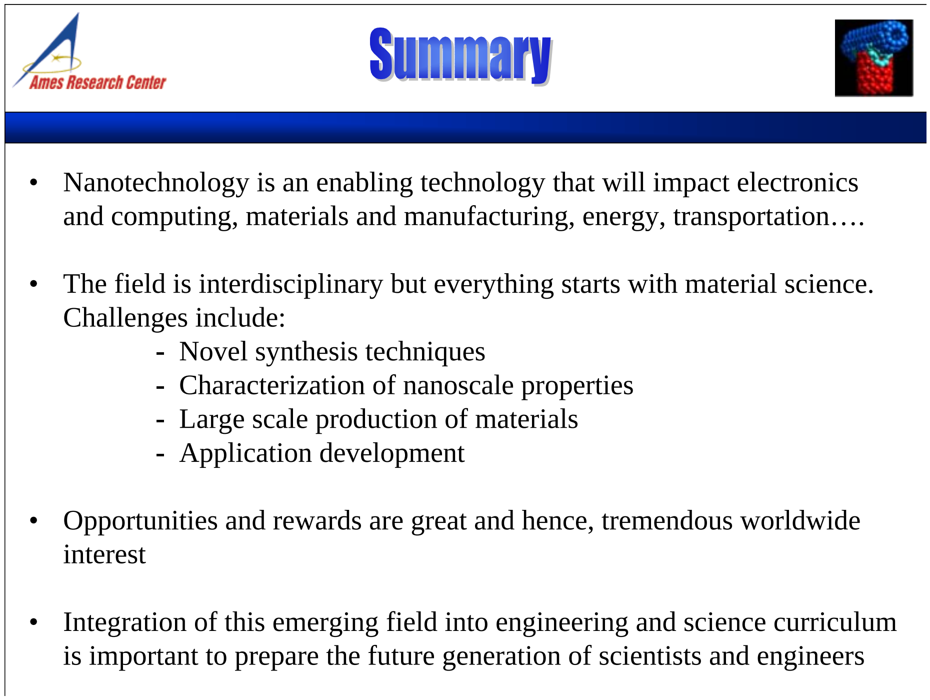


Fig. 10.

Dr. Meyyappan answered several questions after his talk:-

Q. How long can nanotubes be made?

A. Theoretically they can be made very long but in today's reality the catalyst poisons and typical lengths are around 100's of nm.

Q. What are the feed stock materials for large-scale production of nanotubes?

A. Methane is the preferred source and is cheap. The problem is controlling the production process.

Q. What are the environmental issues?

A. Nanotubes are smaller than cold viruses. With care they do not appear to be a health concern.

Additional information.

1. A description of the NASA Ames Center for Nanotechnology, of which Dr. Meyyappan is Director, can be seen at www.ipt.arc.nasa.gov/.
2. A talk by Dr. Meyyappan at Berkeley can be seen in Real Audio/Vision at nanoMa.rm.
3. Two books by Dr. Meyyappan;

Carbon Nanotubes : Science and Applications. ISBN 0849321115, 15 July 2004, CRC Press.
Introduction to Nanotechnology for Scientists and Engineers. ISBN 0471650420, to be published Feb. 2006 by John Wiley.

4. A Nanotech Gallery and links to Presentations and Reports is at www.ipt.arc.nasa.gov/gallery.html.

CHAPTER 4.

COMPUTING APPLICATIONS – PHOTONICS.

<u>**Notes on the lecture by Prof. Harry Ruda.**</u>

Prof. Ruda opened with some provocative questions – What is a computer? What is information? Can information move faster than light?

In the history of computing one of the milestones was the ENIAC computer first started in 1946. It was an early electronic digital computer built for the US Army Ordnance to compute ballistic firing. The equipment, power supply, cooling and IBM card reader input weighed in at 30 tons. But Prof. Ruda cautioned against seeing ENIAC in an old paradigm. It did establish standard circuitry with logical "and" and "or" elements.

Over the past three decades the computer has used ever more powerful, smaller and less expensive circuits. At the same time it has become more efficient and more efficient in its use of energy.

The development has followed Moore's Law. Gordon Moore, one of the founders of Intel made a prediction in 1965 that ***"innovations in technology would allow a doubling of the number of transistors in a given space every year"***. In 1975 he modified his prediction to doubling every two years rather than every year. In the three decades since then development has followed his prediction remarkably well. His Law is no natural law, but an observation that became a prediction.

This development has come about by continually moving to smaller sized components. Recent circuits use components around 130nm size, but production has already started on 90nm memory chips. This is getting close to the atomic dimensions of the components. At this scale electron flow can do strange things like tunneling, which can make conventional switches useless. So the development to smaller sizes is fast approaching a 'brick wall'.

However new technology is showing a way to proceed and maybe continue Moore's Law. Across this threshold the dominant laws change from classical physics to quantum.

Prof. Ruda introduced the concept of photonics – the technology of harnessing light and other forms of energy at the quantum size of a photon. Current photonic devices are made of rare materials that are difficult to fabricate, which makes their costs high. But development is likely to solve these problems and make photonics affordable. However this challenges another less well-known Moore’s Law that states that ***“manufacturing costs double every three years”.***

Optic based electronics might use quantum wells – layers of semi-conducting material and insulating material each only a few nanometers thick. Prof. Ruda concluded by questioning whether we could do away with conventional connections – like wires, and use optics. Can we get switching down to the level of a single electron?

CHAPTER 5.

WEAR PROPERTIES OF ELECTRODEPOSITED NANOCRYSTALLINE MATERIALS.

Notes on lecture by Dr. Daehyun Jeong.

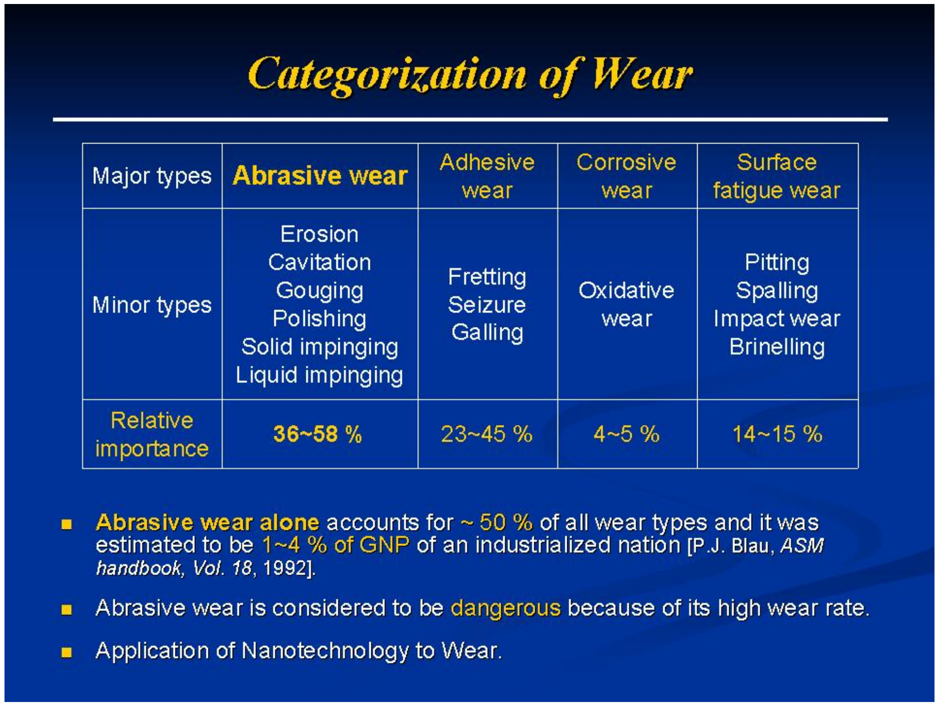
Dr. Jeong started by identifying Tribology problems. Fig. 1.

Fig.1.

He then placed the problem of wear in perspective. Fig. 2. and Fig. 3.

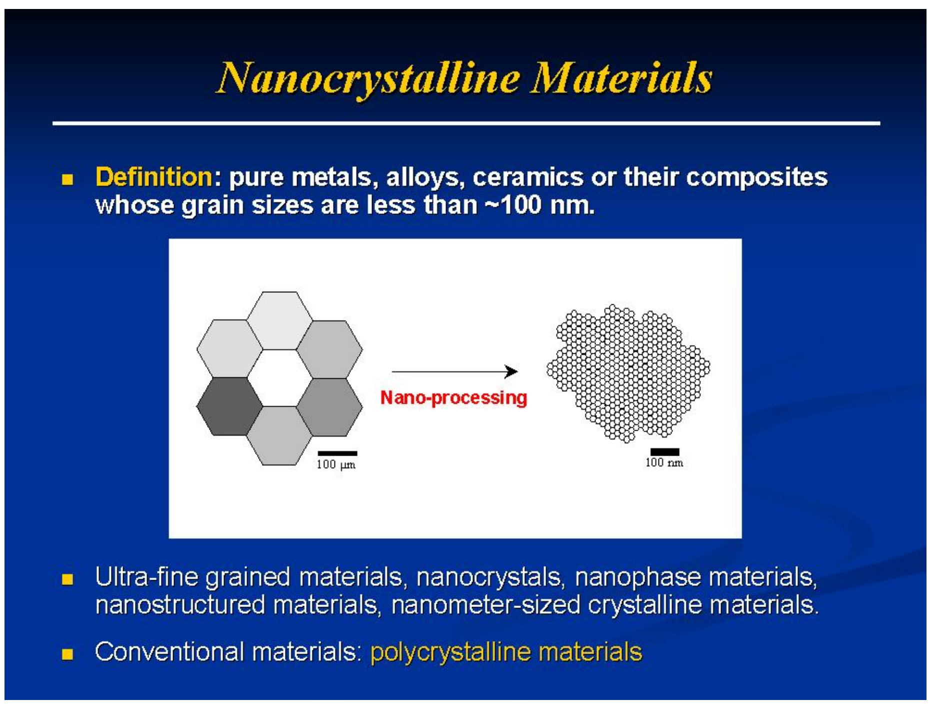
Fig.2.

Fig.3.



In crystalline structures the perfectly ordered crystal has the lowest free energy of solid material. Deviation from the perfectly ordered state comes from defects – vacancies, dislocations and grain boundary and inter-phase boundary. This leads to the basic idea for nanocrystalline materials, Fig.4.

Fig.4.



The volume fraction of intercrystalline components increases from 0.3% for polycrystalline material with a grain size of 1µm; to 50% for nanocrystalline material with a grain size of 5nm.

Nanocrystalline material can be produced in a variety of ways. Fig.5.

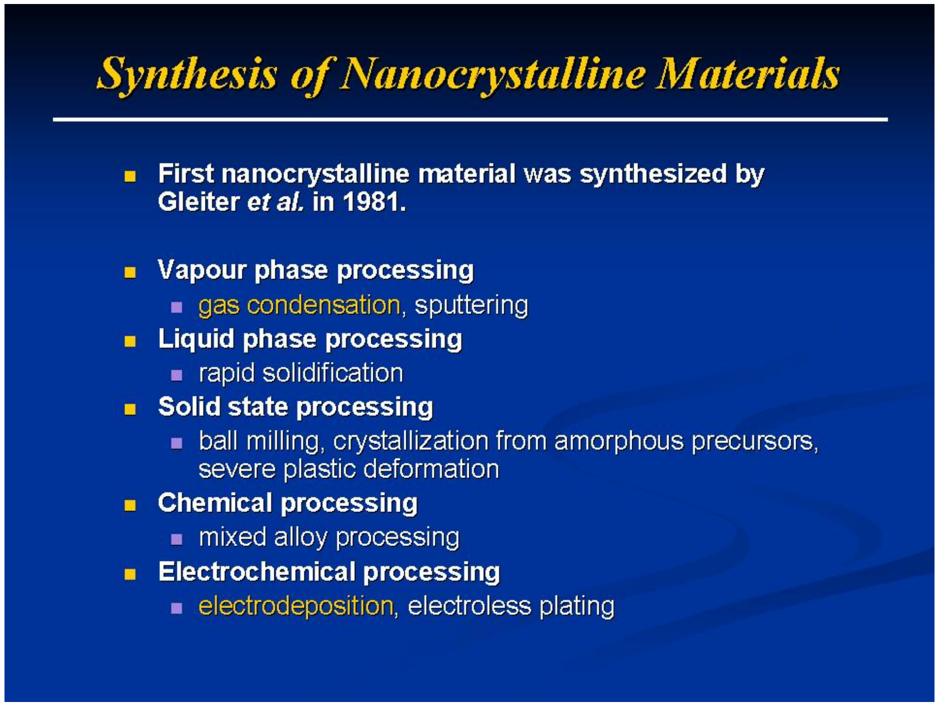


Fig.5.

Decreasing the grain size significantly improves hardness, yield strength, tensile strength and magnetic saturation. And the wear properties are similarly improved, Fig.6 & 7.

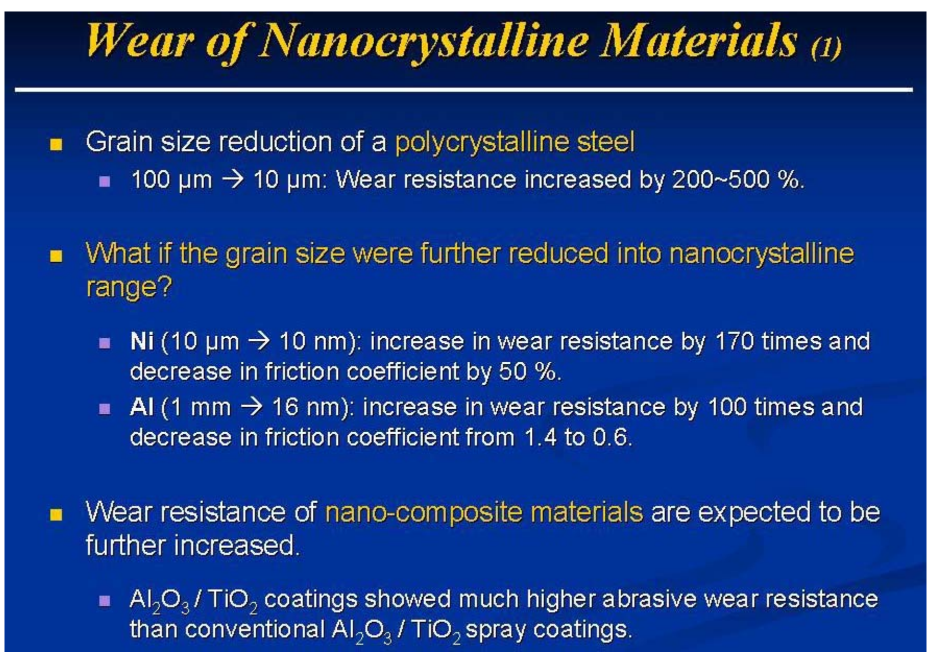


Fig.6.

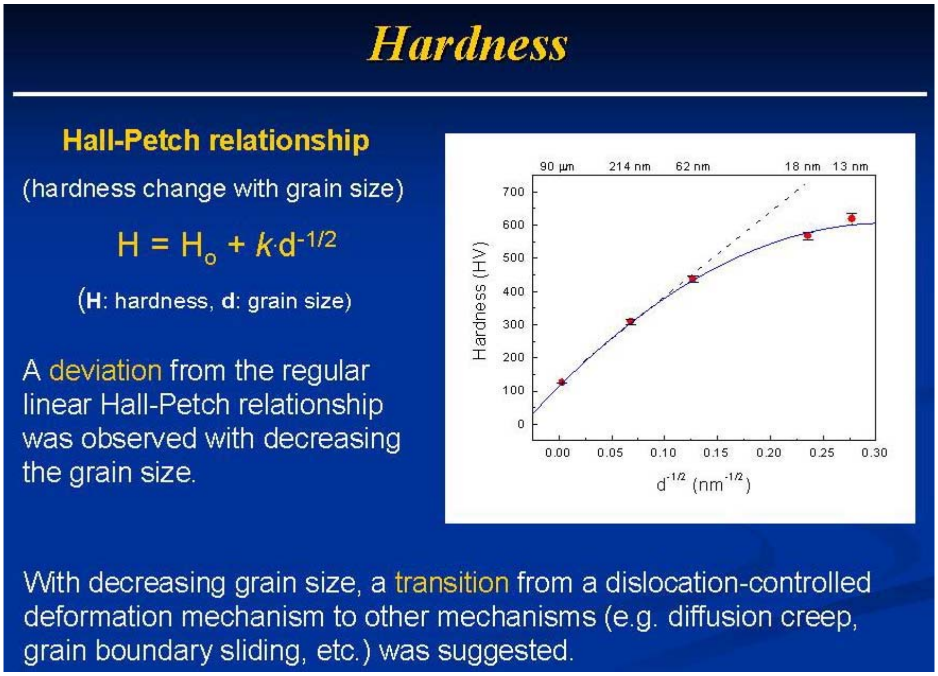
Fig.7.

A research program to better understand the abrasive wear properties of nanocrystalline materials used a systematic approach with standard wear test equipment under constant test conditions. The Taber wear test was used at room temperature. Fig.8.

Fig.8.

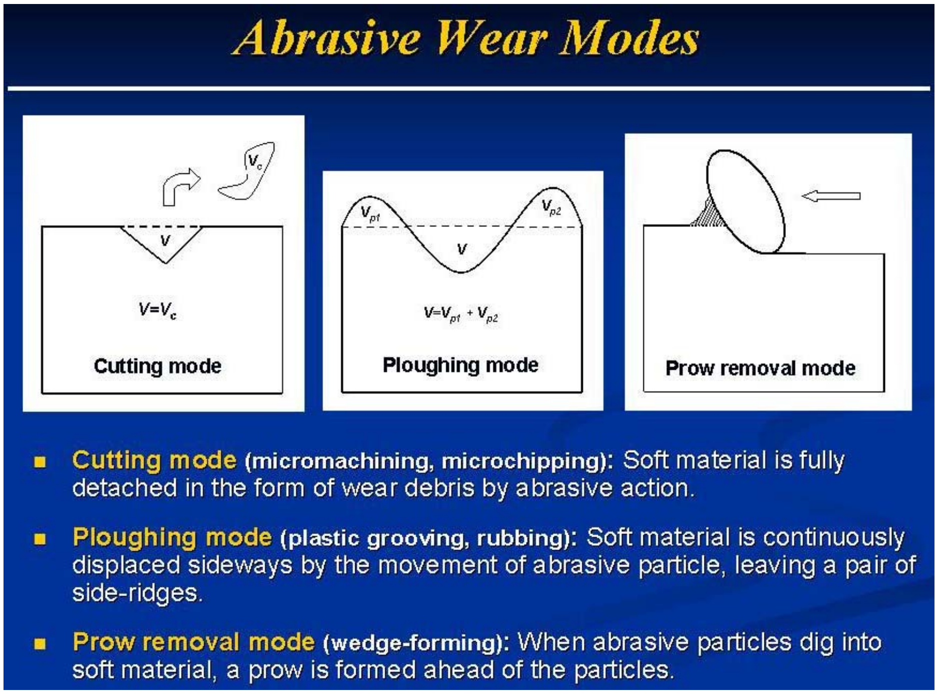
Hardness increases as grain size reduces, but deviates from the Hall-Petch relationship at the smaller grain size. Fig.9.

Fig.9.



The abrasive wear modes are shown in Fig.10.

Fig.10.



The different surface wear form for polycrystalline and nanocrystalline materials is shown in Fig.11 & 12.

Fig.11.

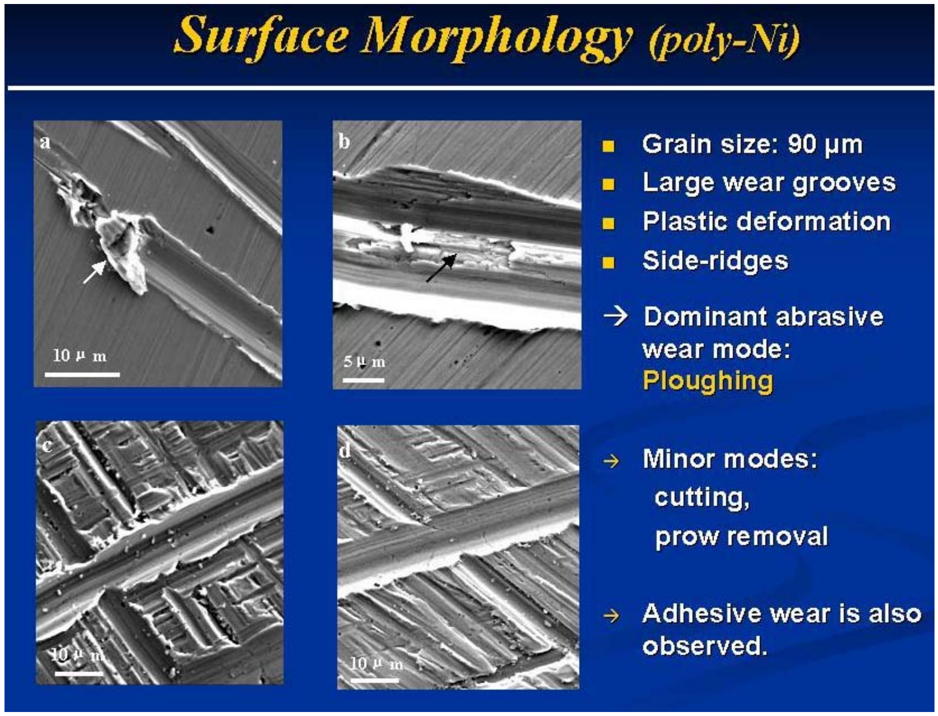
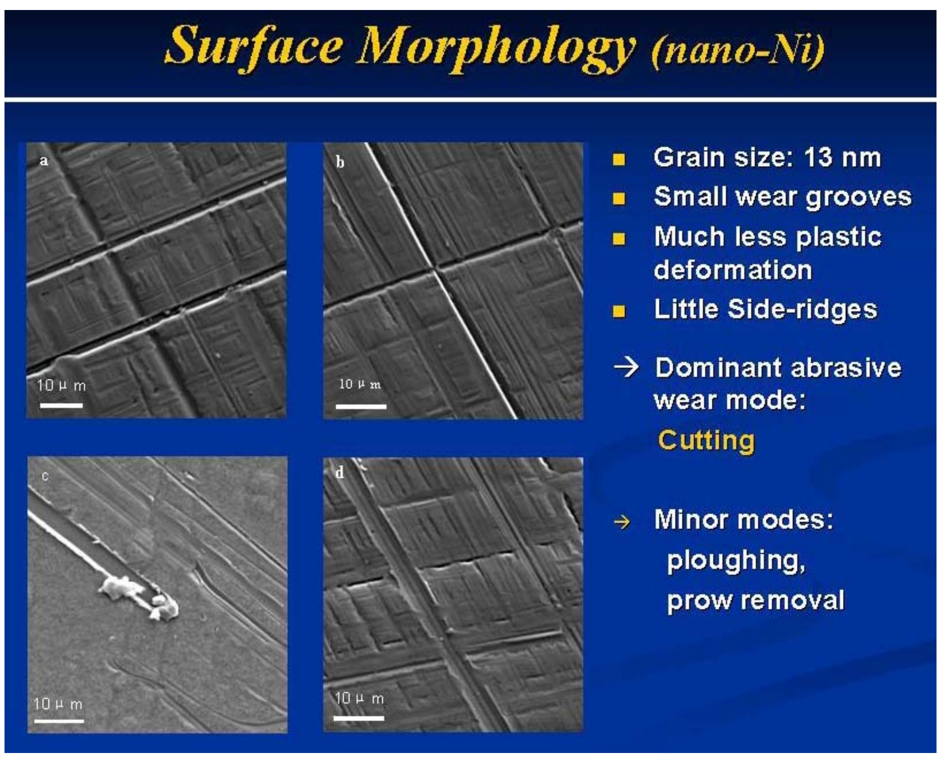
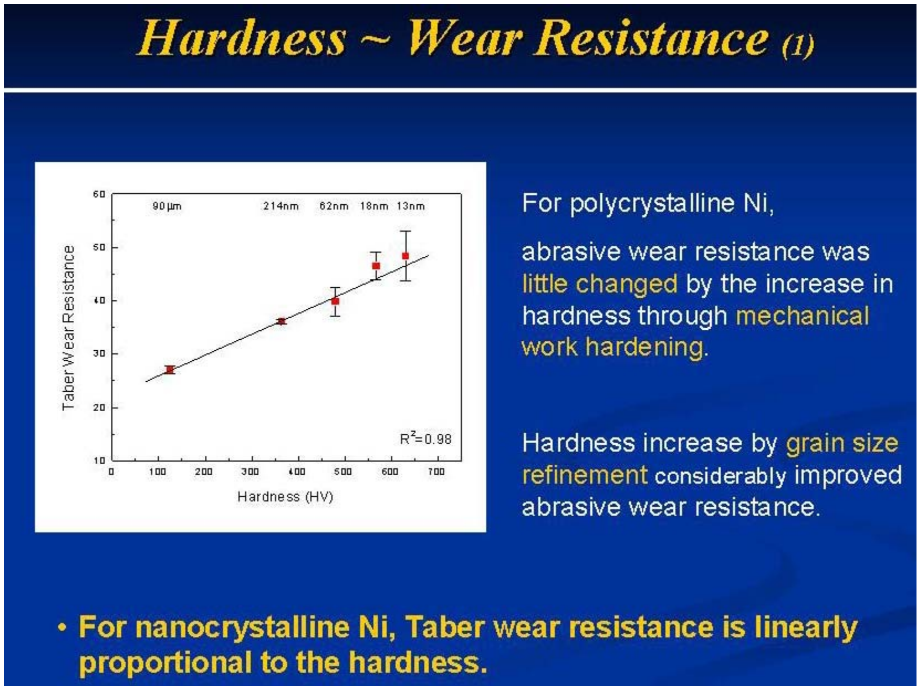


Fig.12.



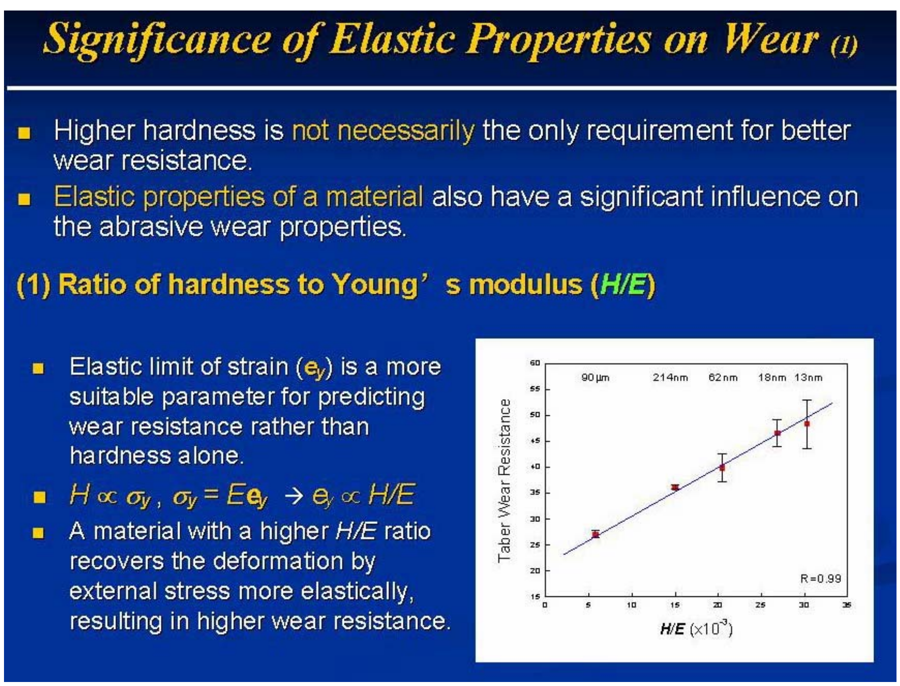
Reducing grain size from 90µm to 13nm resulted in a ~ 80% increase in the abrasive wear resistance. The relationship between hardness and wear resistance for polycrystalline and nanocrystalline materials is seen in Fig. 13.

Fig.13.



There is a transition in abrasive wear mode from ploughing dominating at 90µm grain size and 100 Vickers hardness, to cutting dominating at 13nm grain size and 600 Vickers hardness. The significance of elastic properties on wear is shown in Fig. 14.

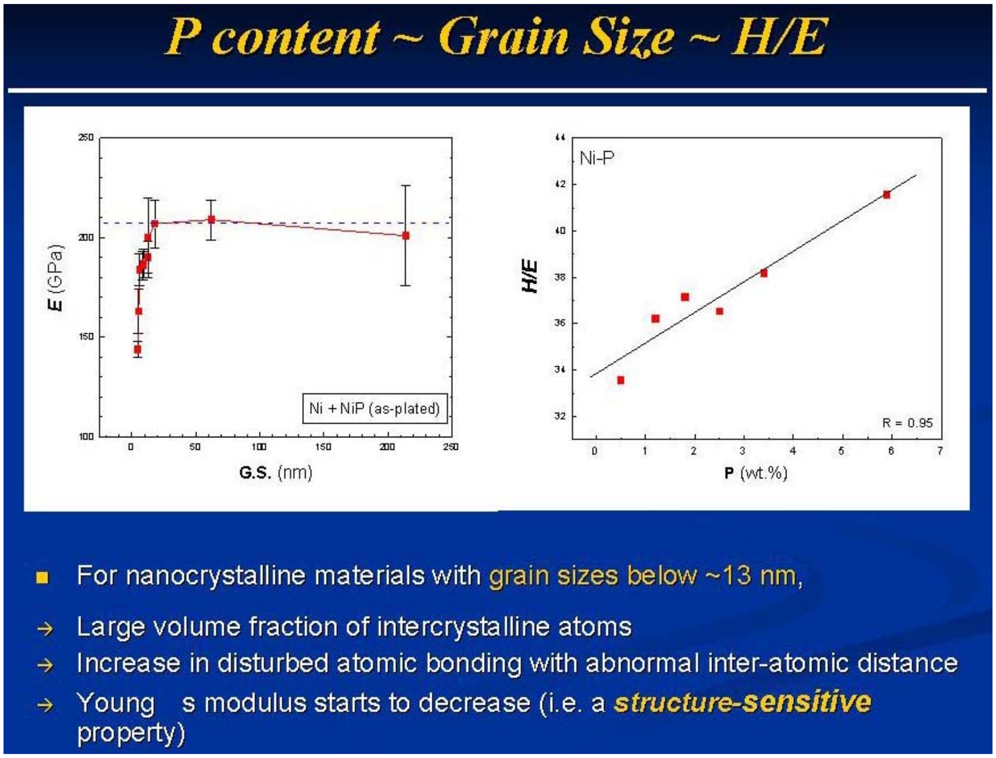
Fig.14.



The ratio of elastic deformation energy to total deformation energy represents the capacity of the material to absorb the deformation energy during indentation without exceeding the elastic limit on the surface. This ratio increases from ~ 13% at 90µm grain size to 32% at 13nm grain size – whilst wear resistance doubles.

Young's Modulus can decrease at very small grain size. Fig.15.

Fig.15.



Dr. Jeong described how a comparison between wholly nanocrystalline Ni-P and a combination of nanocrystalline and amorphous Ni-P did not behave as expected. The Ni-P amorphous phase was expected to have high wear resistance, but showed lower. So higher elastic properties do not always give better wear resistance – another parameter is needed to explain the anomaly.

A new parameter – Taber wear ductility – Fig.16 appears to correlate with wear resistance, Fig. 17.

Fig.16.

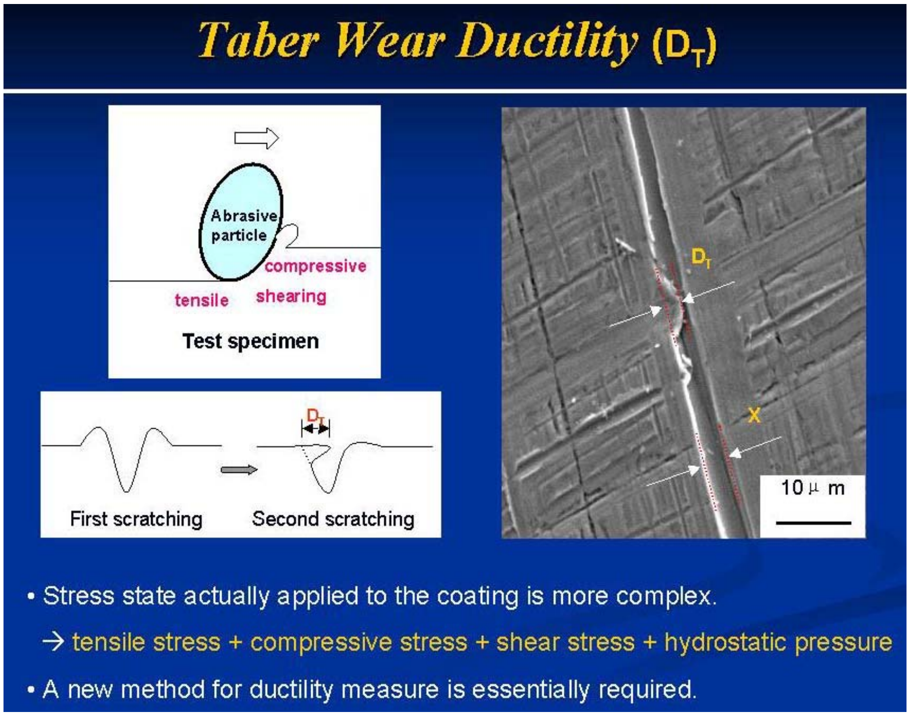
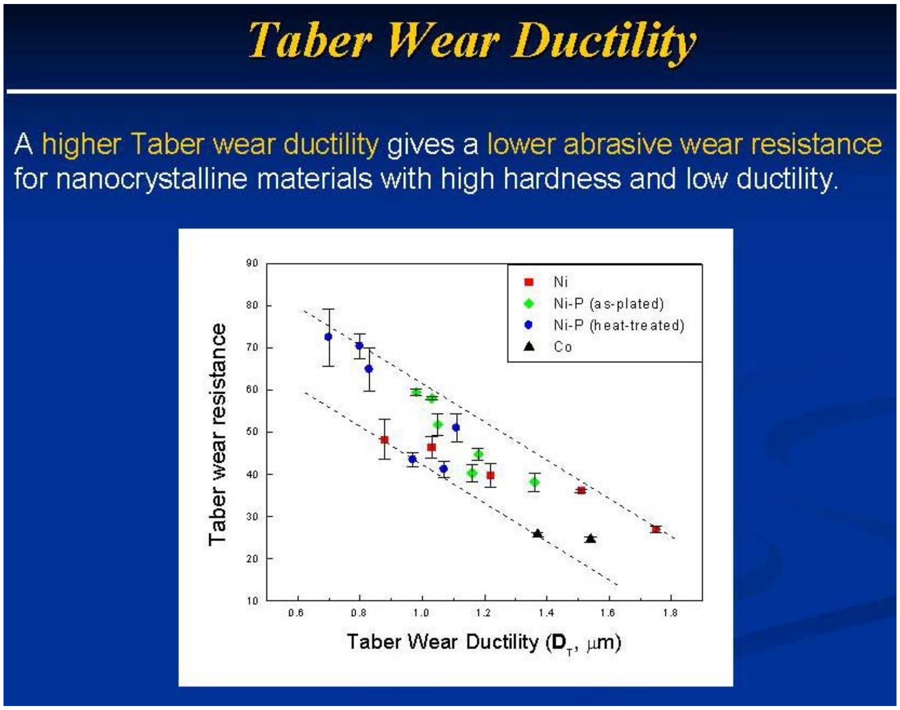


Fig.17.



Dr. Jeong’s summary is in Fig 18.

Fig.18.

And he mentioned that nano-nickel has already been used as a replacement for hard chrome on aircraft landing gear, and for repairing nuclear steam generator tubes.

In conclusion, he acknowledged the contribution of NSERC Canada and the University of Toronto.

CHAPTER 6.

MATERIALS TECHNOLOGY.

Notes on the Lecture by Dr. Francisco González.

Dr. Francisco (Paco) González gave the lecture on ***Electroplated Nanostructures***. He started by placing the 'nanotech world' in perspective (Fig. 1.) and giving his definition of nanotechnology (Fig. 2.)

Fig.1.

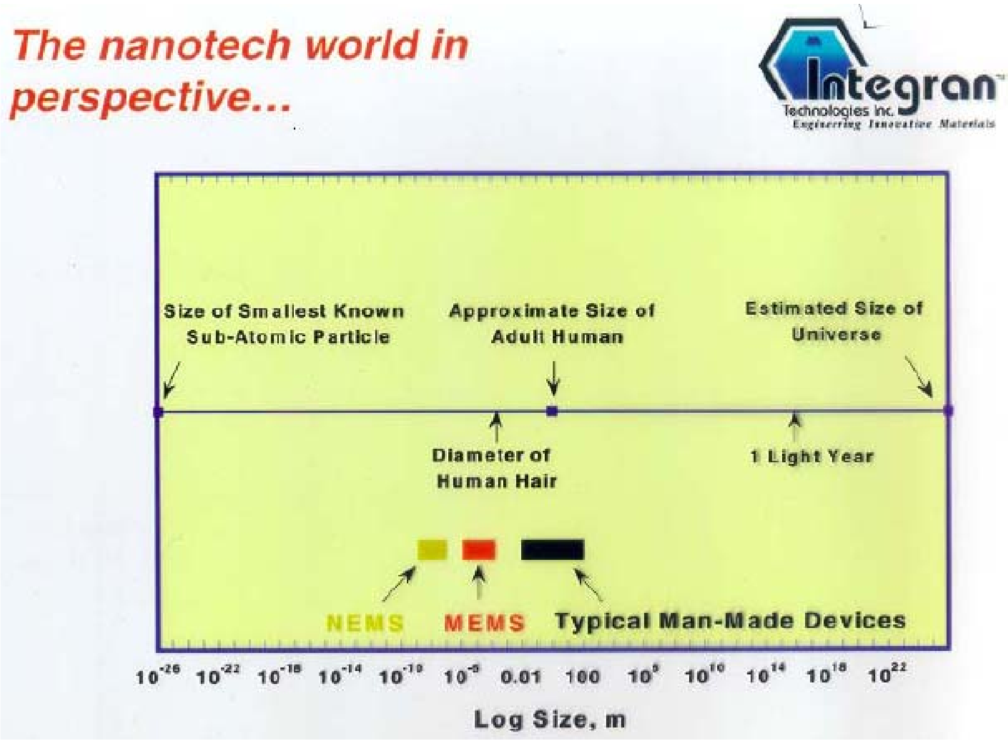
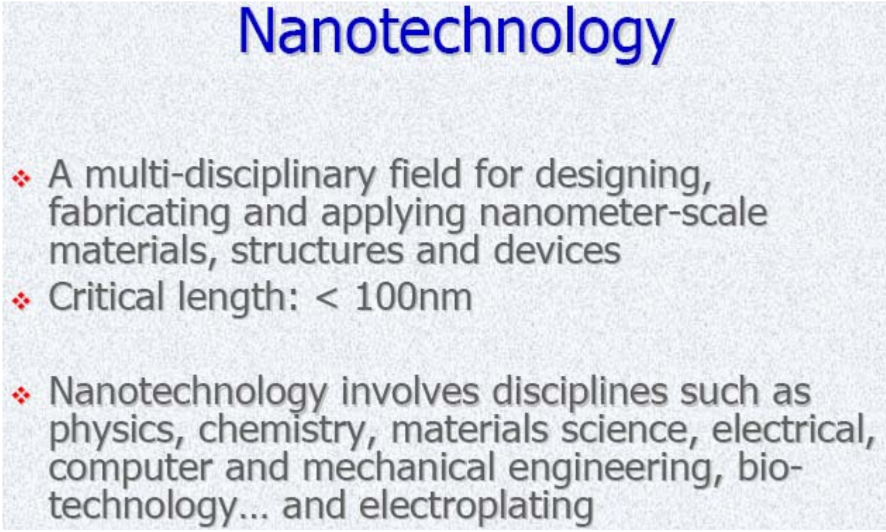


Fig. 2.



The various technical areas of nanotechnology are a ‘smorgasbord’ as shown in Fig. 3 (only the ones in red are covered in this talk) and the state of the art is shown in Fig. 4.

Fig. 3.

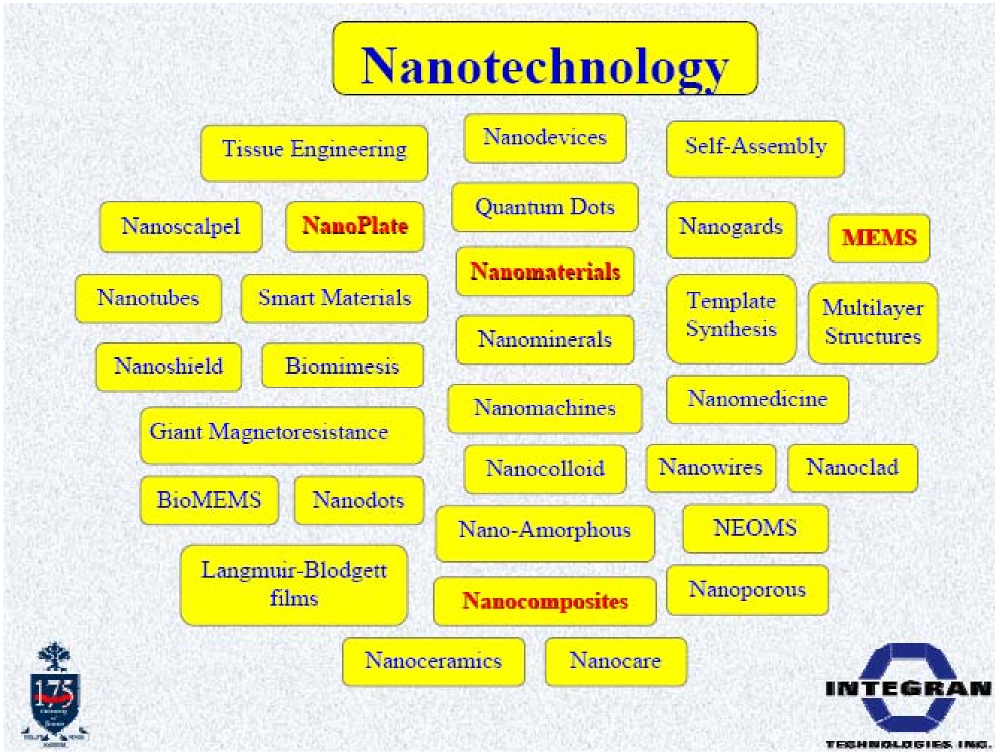
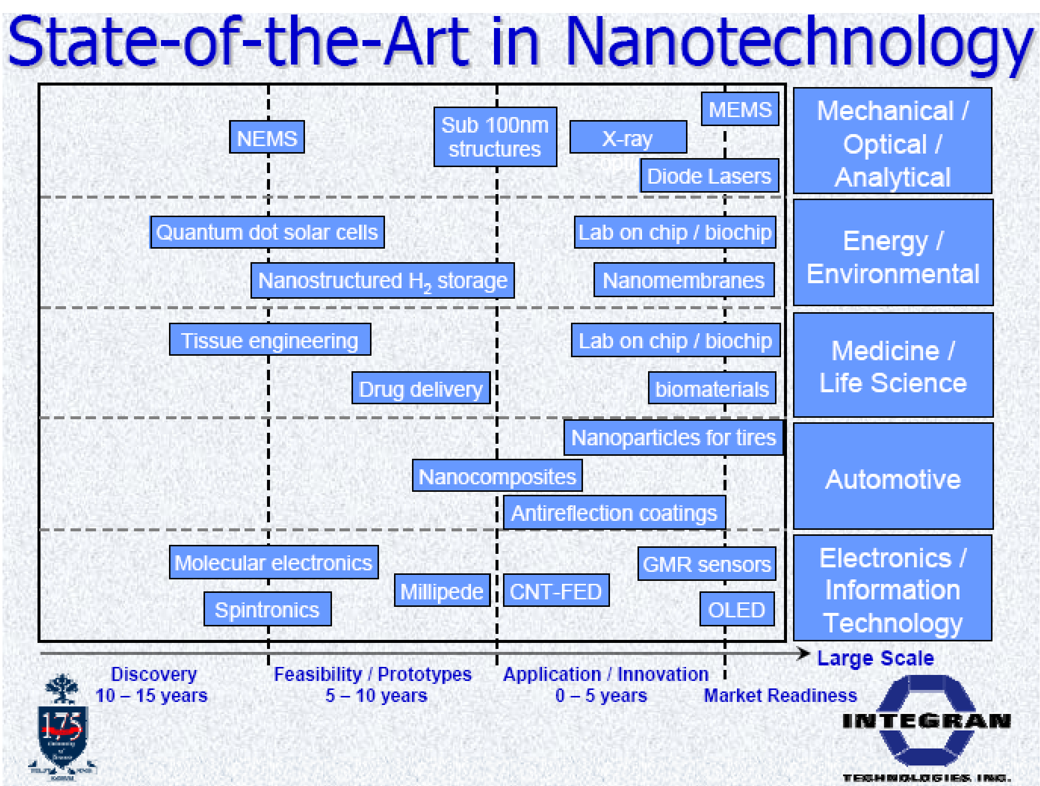


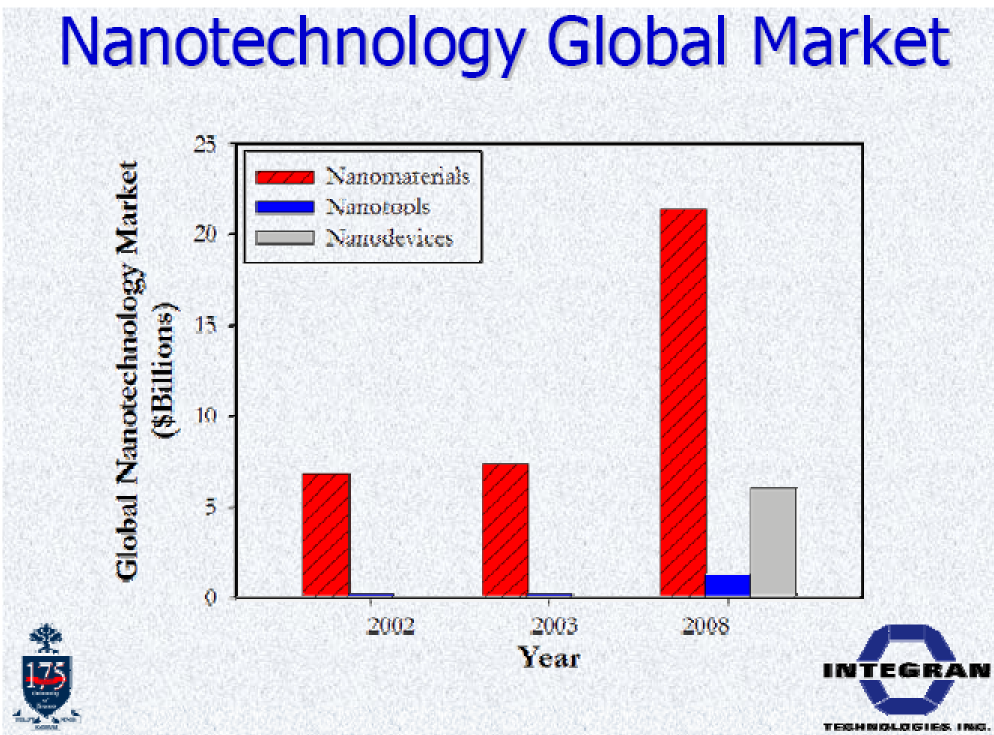
Fig. 4.



The market size is huge - (Fig. 5.) and (Fig. 6.).

Fig. 5.

Fig. 6.



We tend to think of the electronics industry when we talk about nano. Nanotechnology is already there, but there is also a large scope in other market areas.

One aspect of nanotechnology is molecular manipulation, where small mechanisms can be conceived to be assembled one atom at a time – as seen in the computer generated concept of a fine-motion controller formed out of 2596 atoms in Fig. 7.

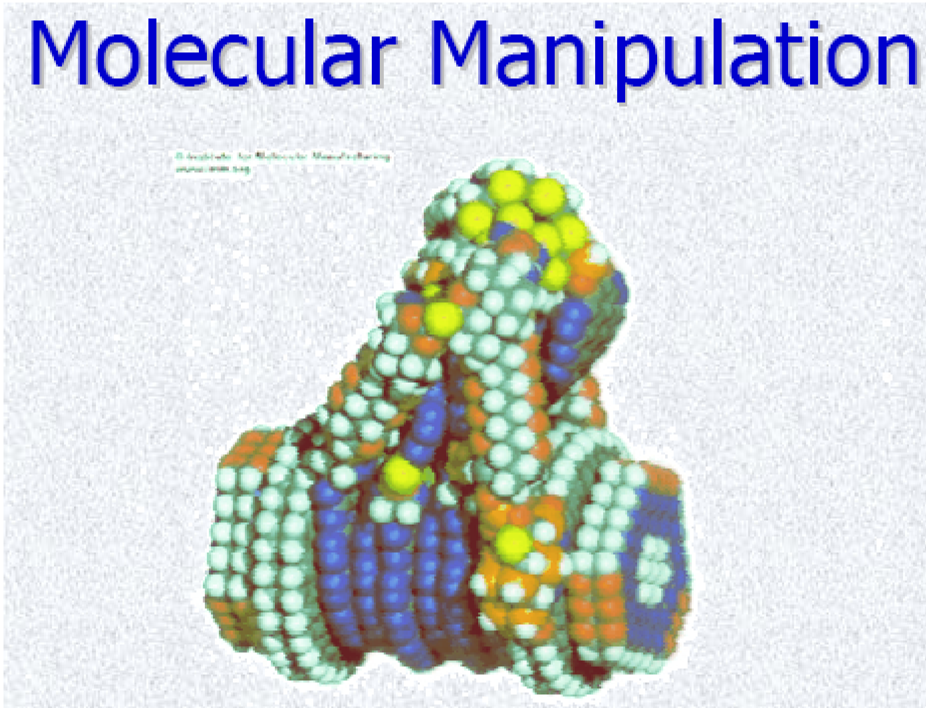


Fig. 7.

A more immediate application is in nano-synthesis (Fig. 8.)

Fig. 8.

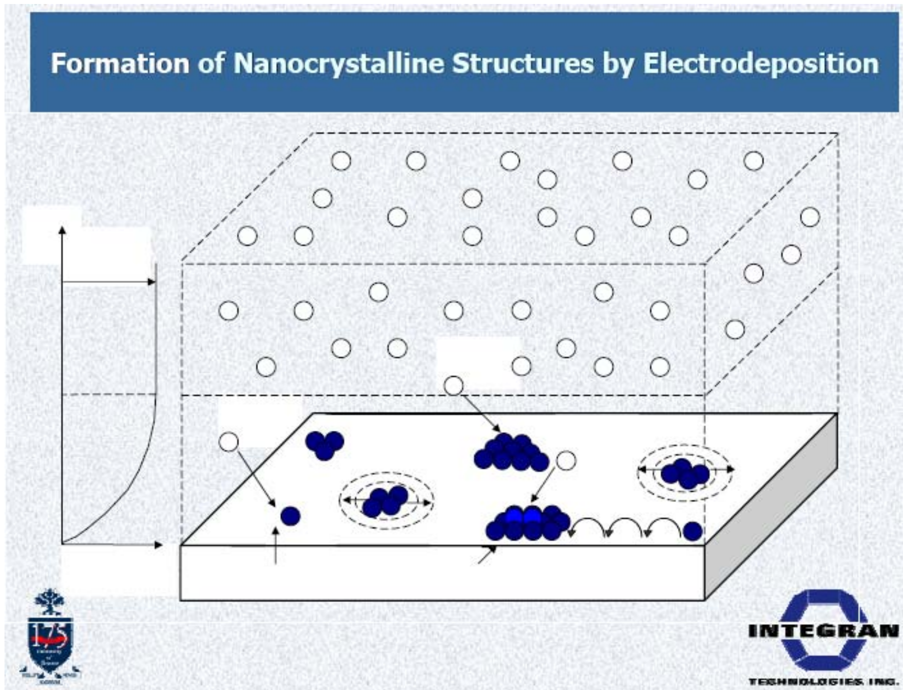
Approaches for Nano-Synthesis

Processing Route	Specific Examples
Vapour Phase Processing	Physical Vapour Deposition Chemical Vapour Deposition Inert Gas Condensation
Liquid Phase Processing	Rapid Solidification Atomization Sonication of Immiscible Liquids
Solid State Processing	Annealing of Amorphous Precursors Mechanical Attrition Equal Channel Angular Processing
Chemical Synthesis	Sol-gel Processing Precipitation Inverse Micelle Technology
Electrochemical Synthesis	Electrodeposition Electrodeposition Under Oxidizing Conditions Electroless Plating

INTEGRAN TECHNOLOGIES INC.

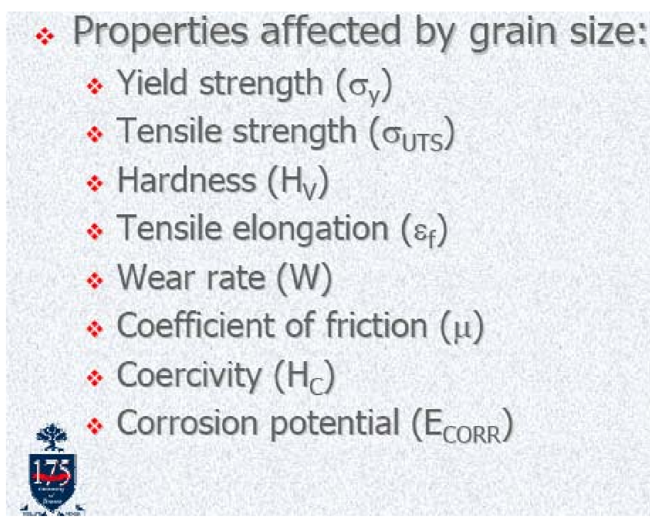
Dr González concentrated his talk on **electrodeposition**. As an introduction, he pointed out that defects make metals weaker than the theoretical limit. Conventional metal forming leaves a ‘garbage dump’ of defects at grain boundaries. Defects affect corrosion. In nanodeposits the defects are the grain boundaries themselves and this affects the corrosion performance. Fig. 9 shows a process of forming nanocrystalline structures by electrodeposition. The process is a development of traditional electroplating, but using pulsed current and special chemistry to deposit nano sized grains. Grain nucleation is enhanced with respect to grain growth and, as a result, small grains are formed.

Fig. 9.



At nano grain size the grain boundary/grain interior volume fraction is much higher than in conventional polycrystalline materials. This affects the mechanical properties, some of which are listed in Fig. 10.

Fig. 10.



Properties not affected by grain size are heat capacity, saturation magnetization, thermal expansion coefficient and Young's modulus. Examples of changed properties for nano sized grain material are shown in Fig's 11, 12, 13, 14, and 15.

Fig. 11.

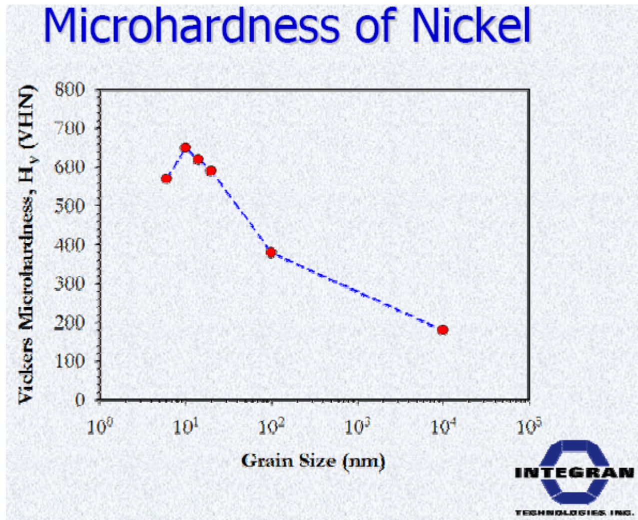


Fig. 12.

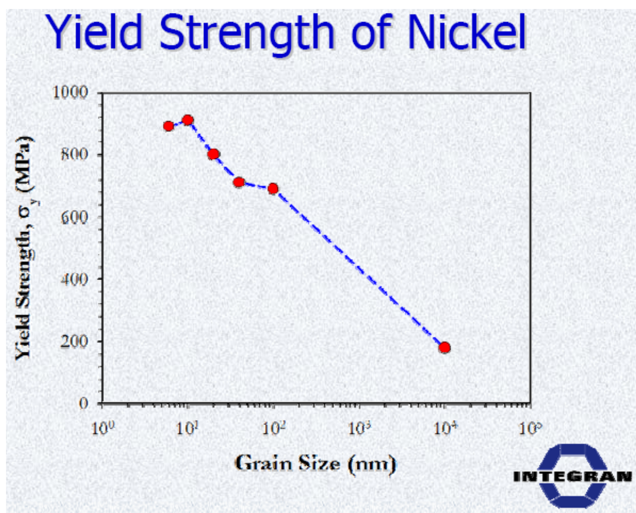


Fig. 13.

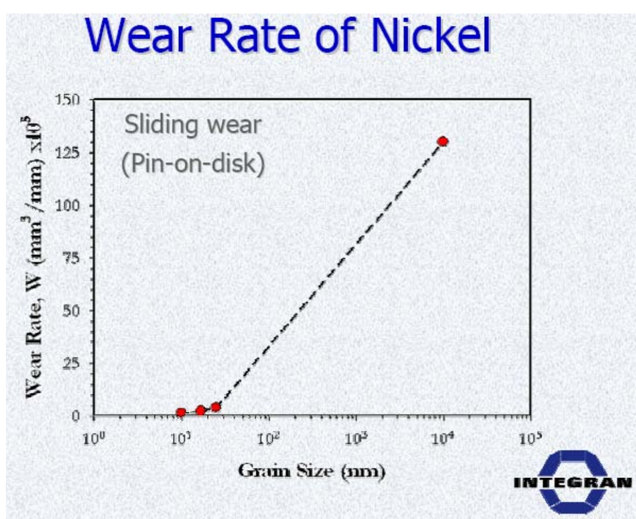


Fig. 14.

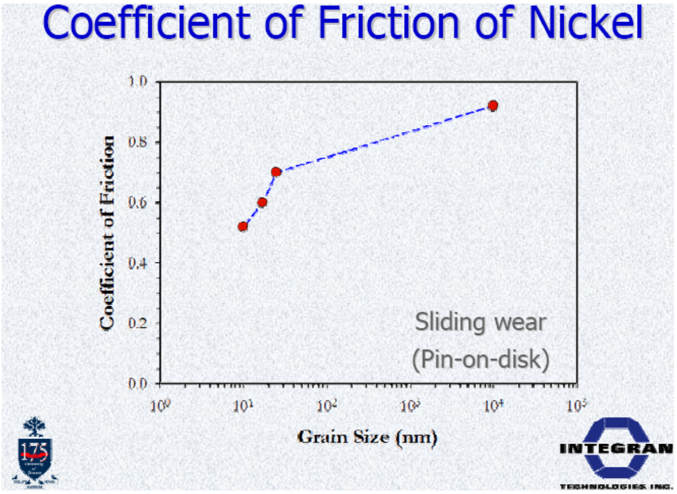
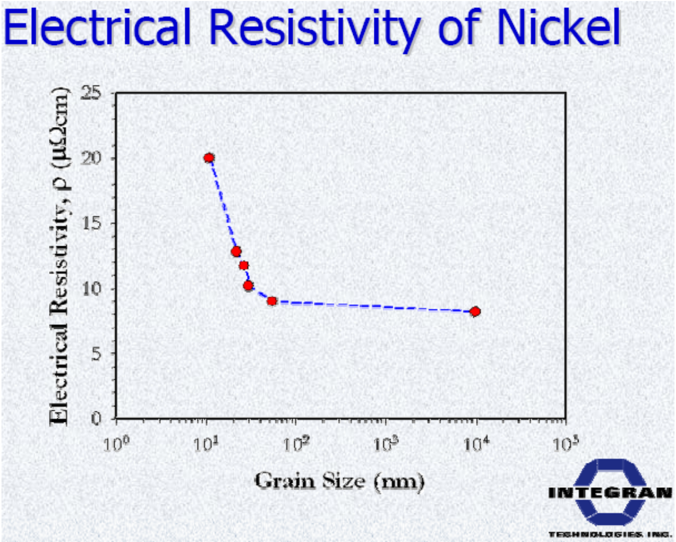
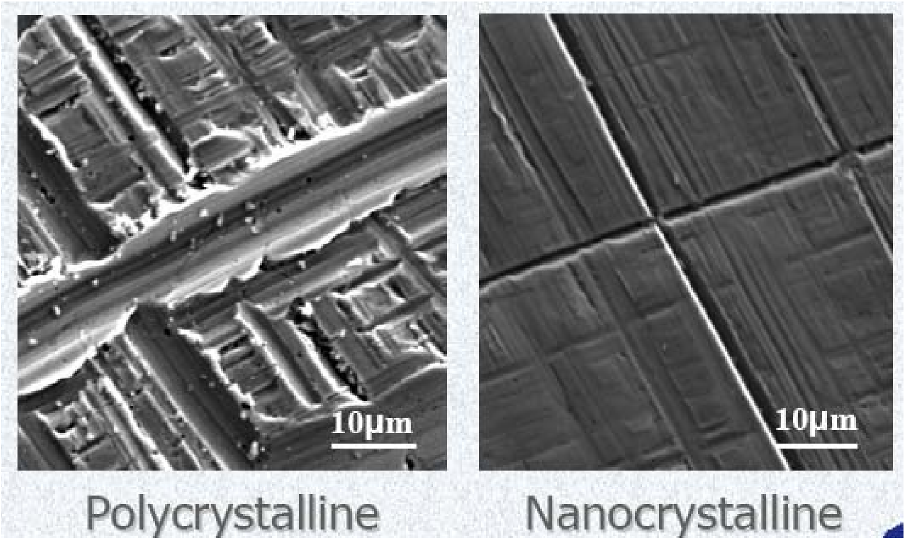


Fig. 15.



The surface of nickel after wear tests is quite different for nanocrystalline nickel than for conventional polycrystalline material Fig. 16.

Fig. 16.



Examples of nanoplate materials are in Fig. 17. The technology can be applied as coatings, or via electroforming to produce cost effective micro and macro scale complex components.

Fig. 17.

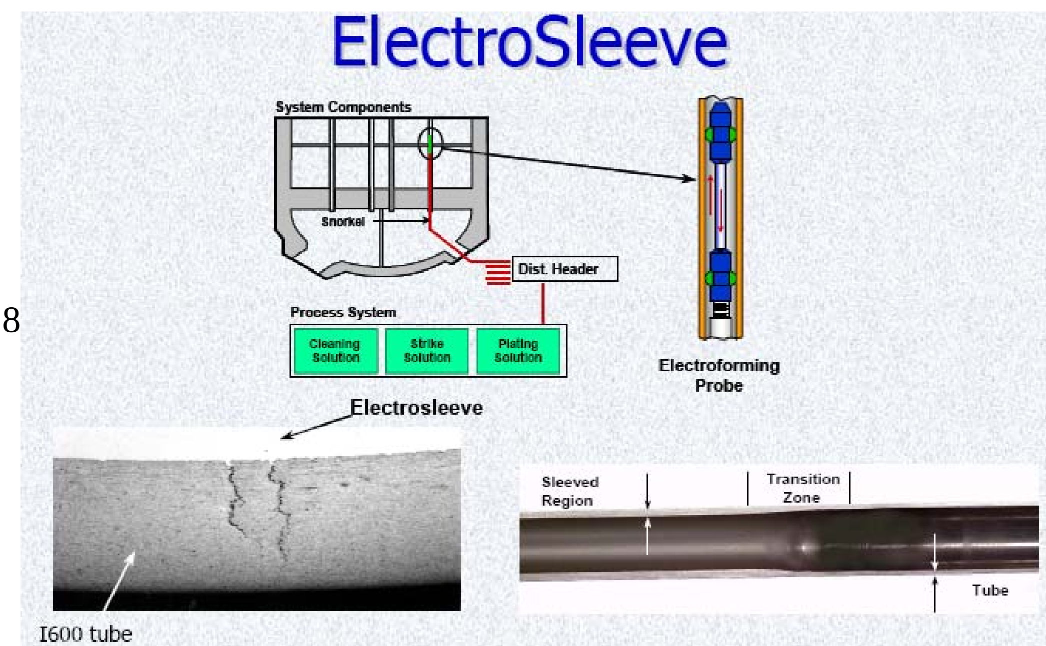
Examples of NanoPlate Materials

Pure Metals	Ni, Co, Cu, Pd, Au, Sn, Pb, Zn
Alloys	Ni-P, Co-P, Ni-Fe, Co-W, Zn-Ni, Ni-Co, Ni-Mo
Composites	Ni-SiC, Ni-B_4C, Ni-Ni_3P, Co-SiC, Co-Al_2O_3, Co-Teflon

<u>Pickering Nuclear Steam Generator Repair.</u>

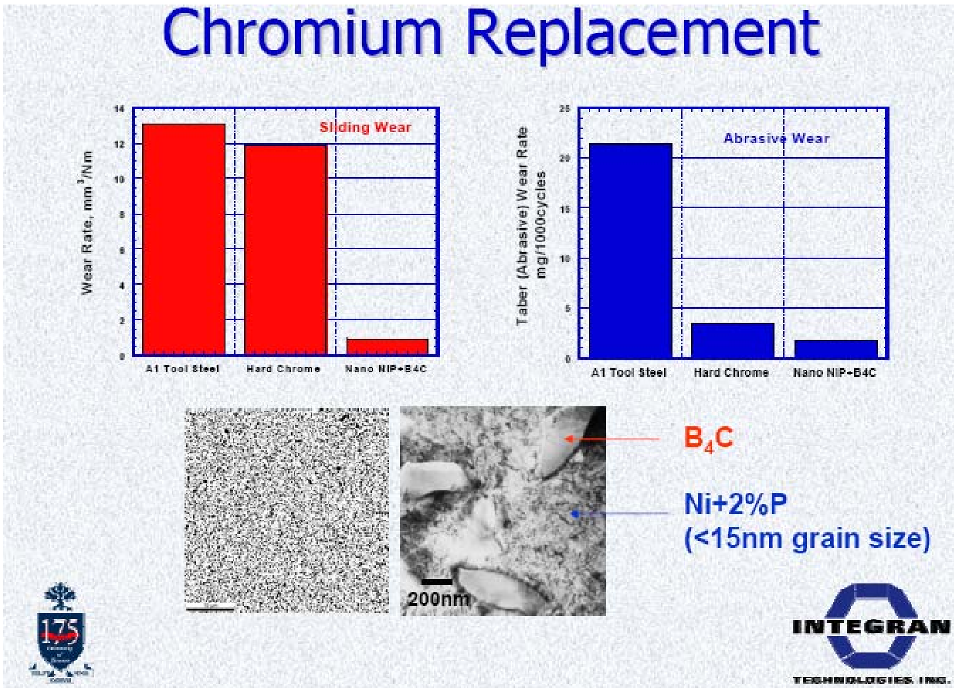
An impressive example of the capability of nano electrodeposition is in the repair of nuclear (Inconel 600/ Monel 400) steam generator tubes. These tubes were degrading because of abnormal conditions in the operating chemistry. The traditional approach would have been to plug the degraded tubes. This action would have reduced the heat transport capability, and eventually would have led to the need to re-tube or completely replace the steam generators – all at immense cost. By repairing the tubes and fully restoring their structural properties, the units could continue to operate without having to be de-rated. The process involved a probe with two fittings, which was developed to seal off the degraded (cracked or wasted) section of the tube. The probe was used to deposit a nanocrystalline sleeve inside the tube. The probe was removed and the sleeved tubes returned to service.

Fig. 18



Nanodeposition can be used for corrosion and wear resistant coatings, for example nickel on carbon steel. Other examples are plating to produce soft magnetic foils, nanofoam as a lightweight material, and a nanosandwich for armour applications. Nanonickel/nanocobalt can replace traditional chromium plating (Fig. 19.)

Fig. 19.



Nickel with Teflon can produce self-lubricating nano-composites. Nanotechnology can help in producing microelectromechanical systems (MEMS), by processes such as LIGA and NIL (Fig. 20.)

Fig. 20.

Fig. 21 shows the principle of the LIGA process, while Fig. 22 and 23 show the end results – note the size of the components.

Fig. 21.

Fig. 22.

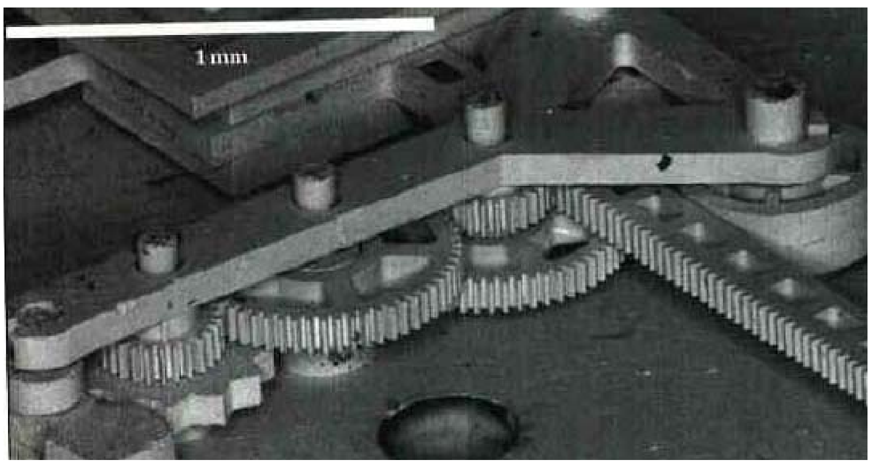
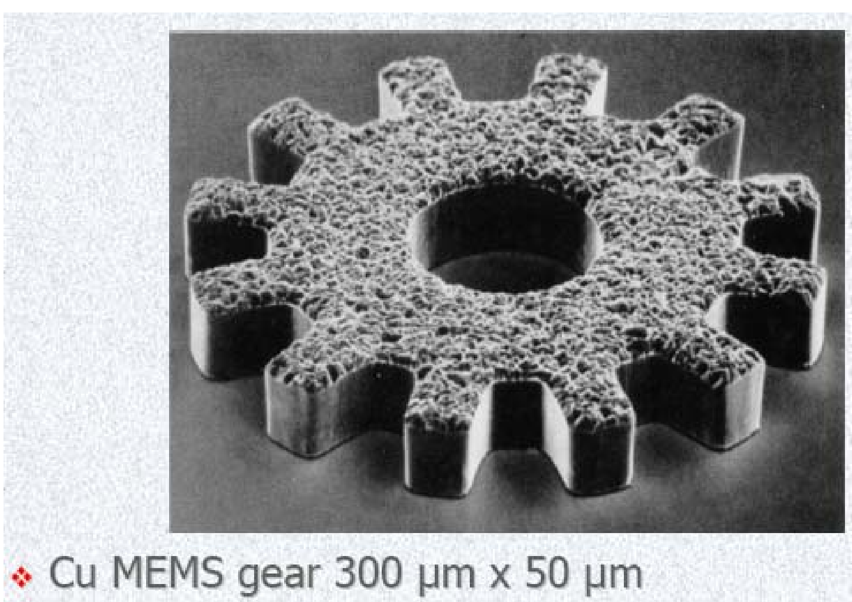


Fig. 23.



Dr. González proceeded to show the difference between conventional electrodeposits and nano-electrodeposits. In conventional electrodeposits there is strong grain anisotropy, with hardness around 2GPa. With nano-electrodeposition there is no grain shape anisotropy and hardness is around 7GPa. The property enhancements of nano are seen in Fig. 24 and 25.

Fig. 24.

PROPERTY CHANGE IN Ni

Property	Conventional †	Nano-Ni 100nm	Nano-Ni 10nm
Yield Strength, MPa (25°C)	103	690	>900
Yield Strength, MPa (350°C)	–	620	–
Ultimate Tensile Strength, MPa (25°C)	403	1100	>2000
Ultimate Tensile Strength, MPa (350°C)	–	760	–
Tensile Elongation, % (25°C)	50	>15	1
Elongation in Bending, % (25°C)	–	>40	–
Modulus of Elasticity, GPa (25°C)	207	214	204
Vickers Hardness kg/mm^2	140	300	650
Work Hardening Coefficient	0.4	0.15	–
Fatigue Strength, MPa (10^8 cycles/air/ 25°C)	241	275	–
Wear Rate (dry air pin on disc), μm^3/μm	1330	–	7.9
Coefficient of Frictionality (dry air pin on disc)	0.9	–	0.5

Fig. 25.

GRAIN SIZE EFFECTS

Performance Indicator / Grain Size	10μm	1μm	100nm	10nm
Specific Strength (σ_y / ρ)	1	2.2	3.4	4.6
Elastic Energy Storage (σ_y / E)	1	4.8	11.7	21.5
Thermal Shock Resistance ($\sigma_y / E \cdot \alpha$)	1	2.2	3.5	4.9
Wear Resistance (1/W)	1	1.6	3.7	52

Dr. González summarized his talk in Fig. 26 and 27.

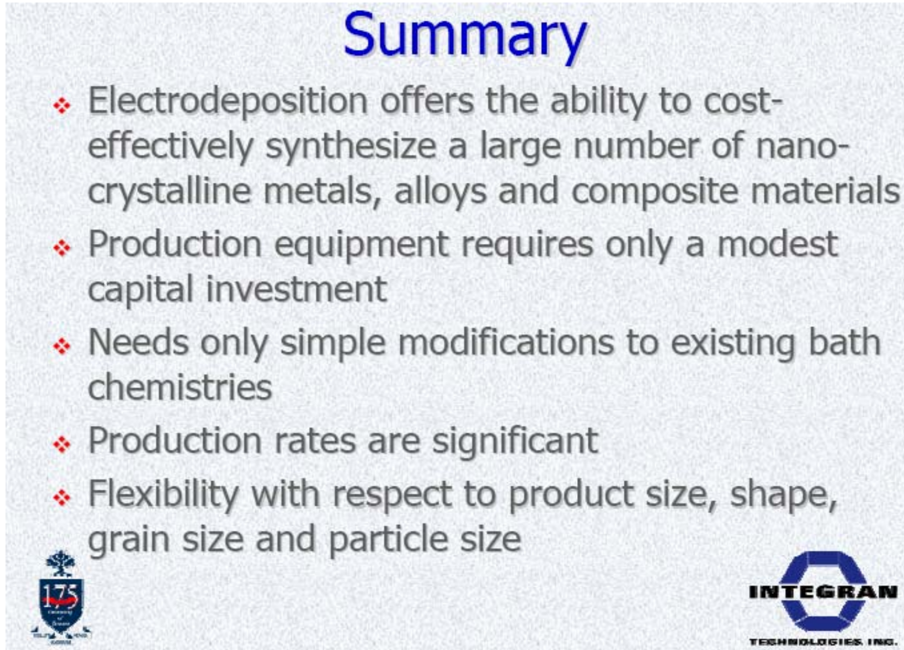


Fig. 26.

Fig. 27.

Additional information.

1. Integran web site, www.integran.com. has technical data as well as company data.
2. Some good explanatory slides and video about nanotechnology and nanomaterials are at the University of Wisconsin web site http://mrsec.wisc.edu/Edetc.
3. An array of nanomaterial products are in the slide show of A Sugunan and K Ramamurthy, at www.nano.ait.ac.th/nano/2004/Download/Assignments/NanoMaterials.pdf.

CHAPTER 7.

MEDICAL APPLICATIONS.

Notes on the Lecture by Dr. Eric Marcotte.

Dr. Marcotte started his talk by posing the questions ***What is Nanotechnology?*** and ***What is Nanomedicine?***

Nanotechnology deals with materials and systems that:-

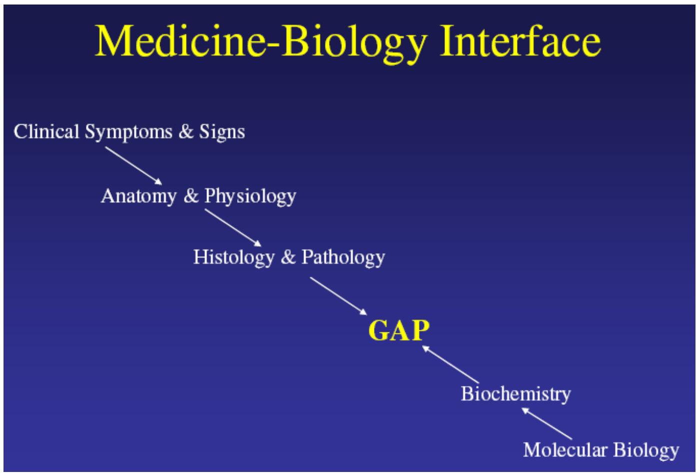
- Have at least one dimension in the range 1nm to 100nm.
- Have properties that are qualitatively different because of that scale length (ie quantum mechanical effects, etc), and
- Are designed through processes that exhibit fundamental control over physical and chemical attributes of molecular scale structures.

The first applications of nanotechnology are in tools for imaging and manipulating single molecules and atoms. The first commercial applications are in sunscreens and stain resistant clothing – 'nanopants'. L'Oreal is said to hold more nano patents than any other company. 'Nanopants' are for sale in all major stores and clothing catalogues – they seem ready to take over the world!

When nanomedicine is mentioned, most people immediately think of nanobots travelling through the body doing surgery and clearing debris from arteries. Dr Marcotte showed several illustrations of mechanical looking robots – nanobots. They are all science fiction – with the emphasis on 'fiction'. Eric Drexler can probably be blamed for starting the idea, which was enthusiastically taken up by science fiction writers and illustrators. In Dr Marcotte's view people are wasting their time dreaming up this fanciful fiction, as well as distorting the public image of nanomedicine.

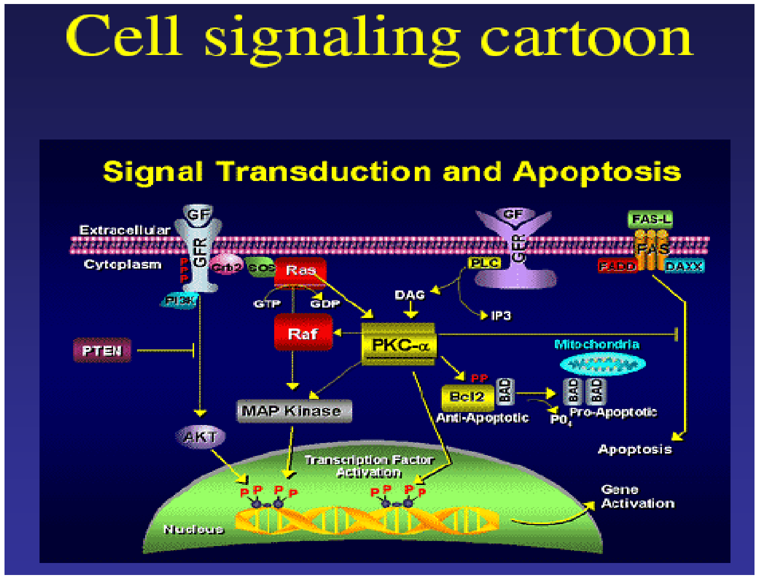
Nanomedicine has no simple and unifying definition, and is an amalgam of different approaches and perspectives. Nanomedicine is helping to fill the gap between traditional medicine and biology (Fig. 1.)

Fig. 1.



The action within cells can be simply depicted in the cartoon (Fig. 2.) but in fact it is a much more complex biochemical and electrochemical interaction.

Fig. 2.

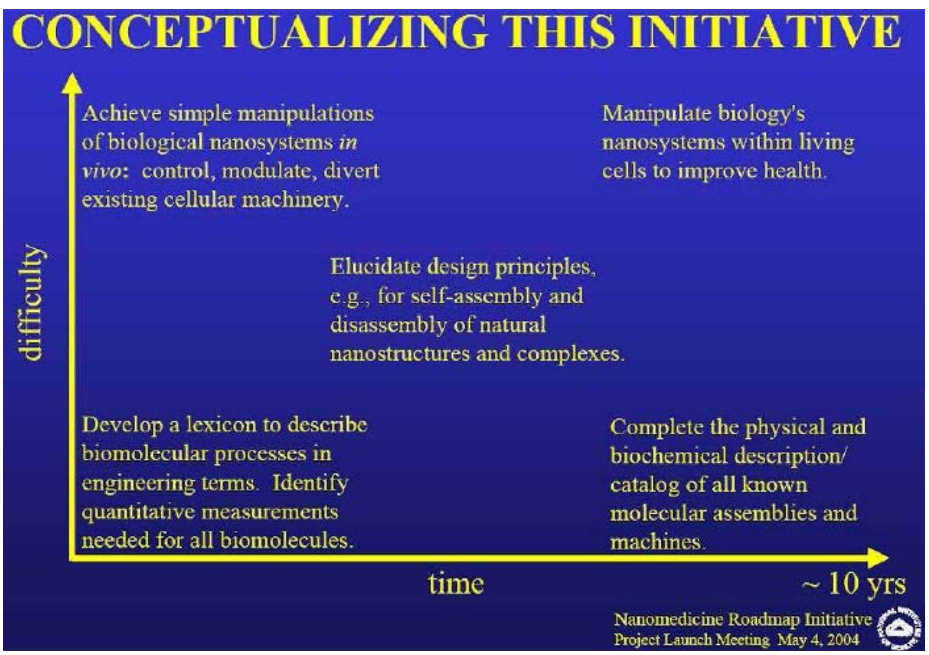


The National Institutes of Health (NIH) in USA have a roadmap for nanomedicine with three branches to:-

- Characterize quantitatively the physical and chemical properties of molecules and nanomachinery in cells,
- Gain an understanding of the engineering principles used in living cells to “build” molecules, molecular complexes, organelles, cells and tissues, and
- Use this knowledge of properties and design principles to develop new technologies, and engineer devices and hybrid structures, for repairing tissues as well as preventing and curing disease.

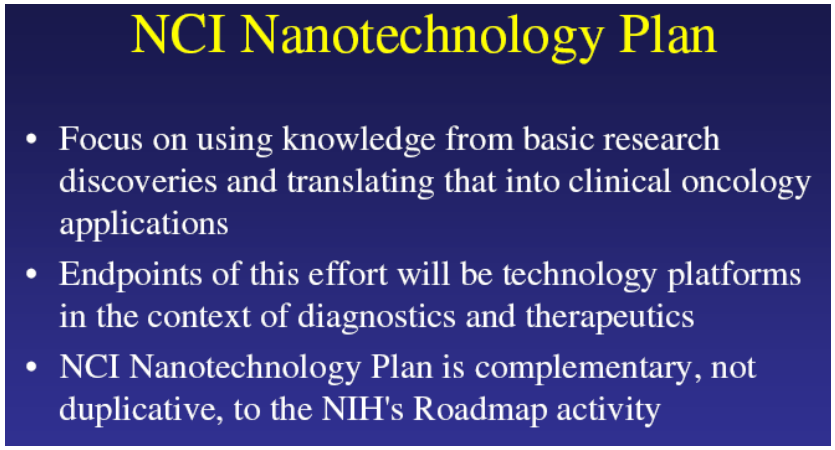
This roadmap is conceptualized in Fig. 3. The task of manipulating biological nanosystems within a decade is a tough challenge.

Fig. 3.



The National Cancer Institute (NCI) of USA has a nanotechnology plan that compliments the NIH plan (Fig. 4.)

Fig. 4.



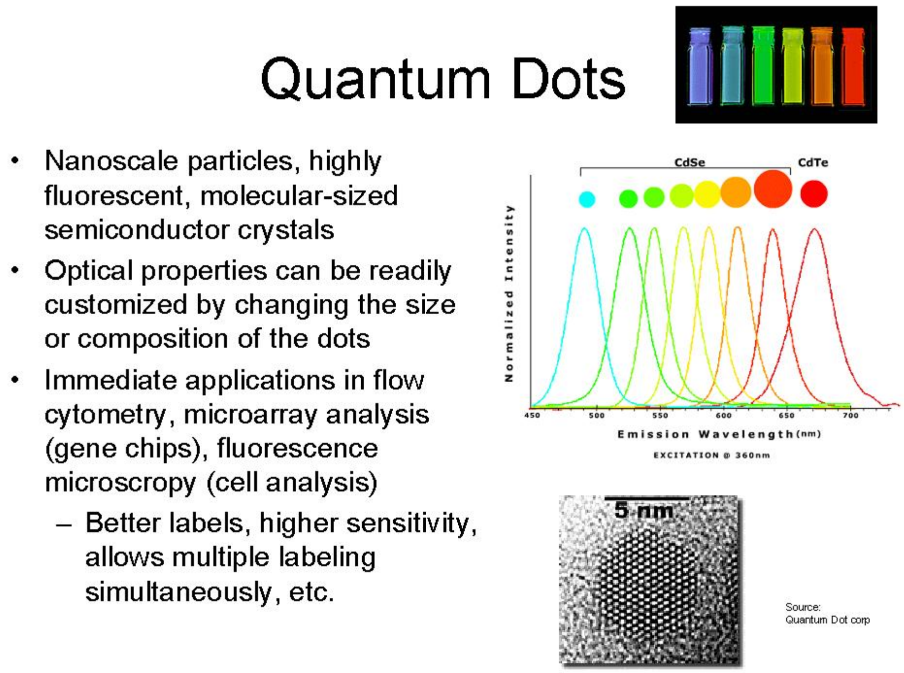
The Canadian CIHR approach to nanomedicine is :-

- Specialized biomedical measurement or intervention – at a molecular or cellular scale – needed to treat diseases and restore function.
- Integrated with Regenerative Medicine, which seeks to regenerate or repair injured tissues and organs through natural or bioengineered means, and
- Multi-disciplinary research approach with close integration of the physical and applied sciences with biomedical and clinical research balanced with consideration of the social, cultural, and ethical perspectives of human health.

<u>What really is Nanomedicine - 1. Diagnostic tools.</u>

The 'Holy Grail' search is to find real-time, non-invasive, *in vivo* and *in situ* imaging. Current technologies are computer tomography, single photon emission computed tomography, positron emission tomography, magnetic resonance spectroscopy, magnetic resonance imaging, electron beam tomography and ultrasound. An emerging technology is optical coherance tomography, which provides high-resolution images, in real time. Interestingly it was developed from components originally created for the fibre optic communications industry. Another new technology is based on quantum dots (Fig. 5.) Quantum dots have a near term application as 'bar codes' for biological applications, genomic detection and mapping, and tagging and tracking cells for immunoassays. In the longer-term, quantum dots may be used for homogeneous whole blood analysis with hand held instruments, *in vivo.* Warren Chan at the University of Toronto is using quantum dots in tissue remodeling, early cancer diagnosis, guidance during tumor detection and potential applications in stem cell research.

Fig. 5.

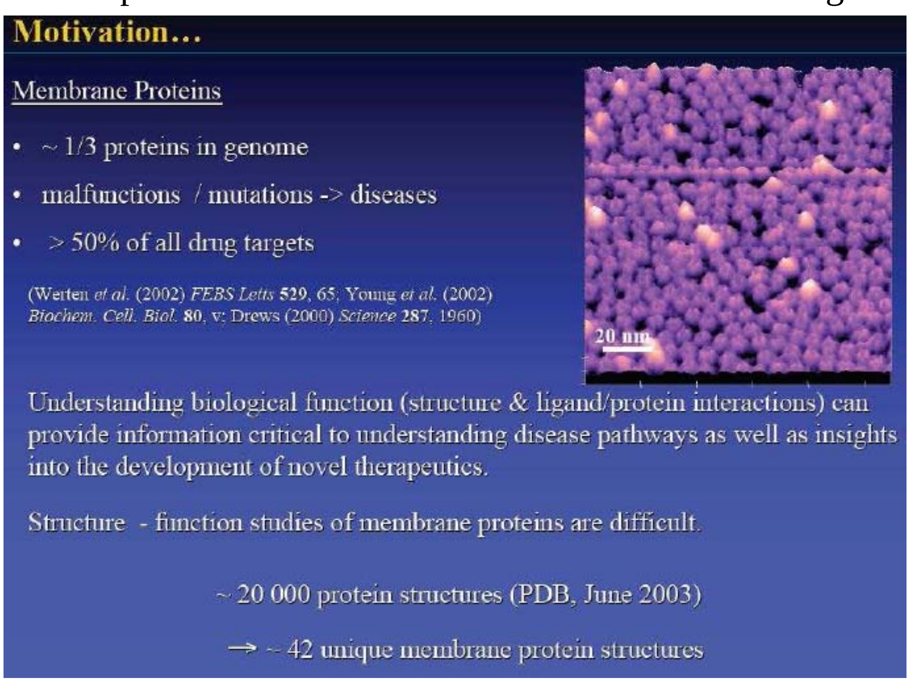


Quantum dots have a broad range of potential biological applications such as diagnostic and imaging tools in the fields of circulation, neuroscience, cancer, infection and immunity, and genetics.

What really is Nanomedicine – 2. Instrumentation for basic biological research.

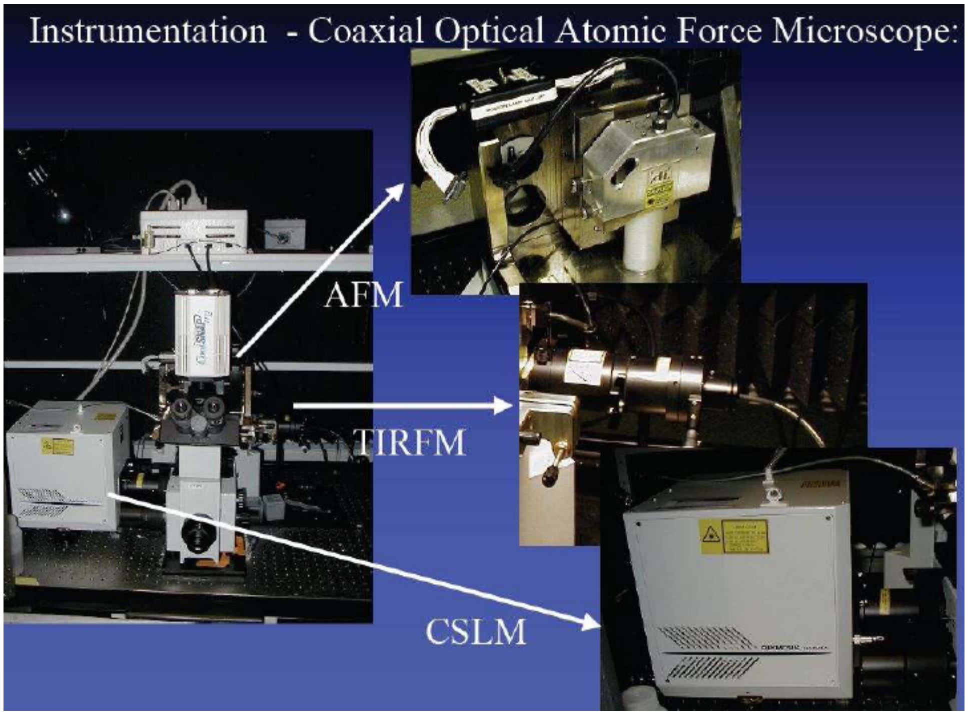
Dr. Marcotte used examples from recent Nanomedicine Workshops held in Canada. The first example was the work of Christopher Yip on the mapping of protein-protein interactions at membrane interfaces using an Atomic Force Microscope. The motivation for this work is shown in Fig. 6.

Fig.6.



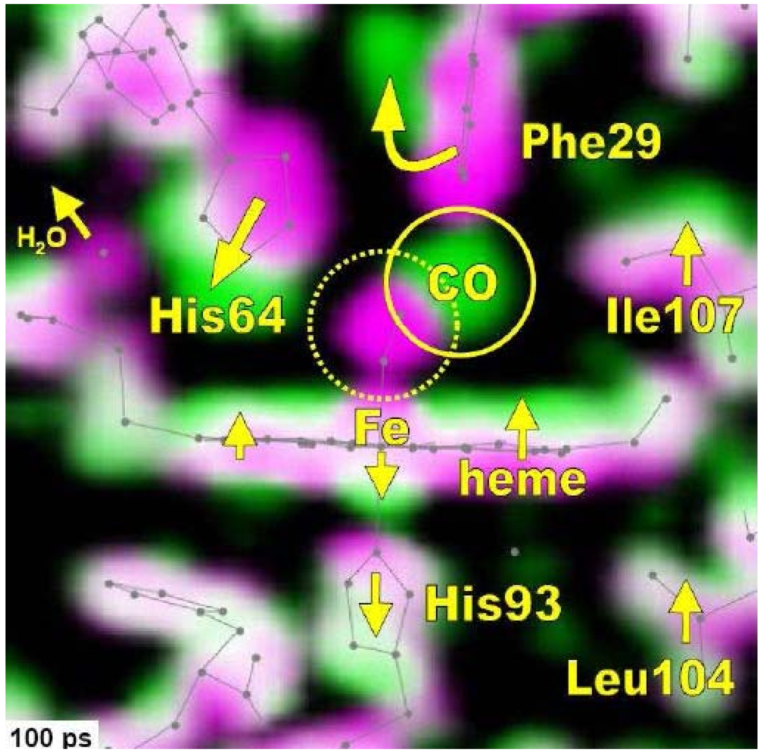
This work compliments the traditional approach and allows a greater understanding of the inner working of the cell. The instrumentation used is a combination of Atomic Force Microscope (AFM), Total Internal Reflection Fluorescence Microscopy (TIRFM) and Confocal Scanning Laser Microscopy (CSLM) as seen in Fig. 7. TIRFM allows single molecule fluorescence. CSLM can provide high level resolution of skin at the cellular level without resorting to surgery. (Editors note – TIRFM has also been used for short fatigue crack growth studies in aluminium alloys www.ryerson.ca/~avarvani/CSLM.htm.)

Fig.7.



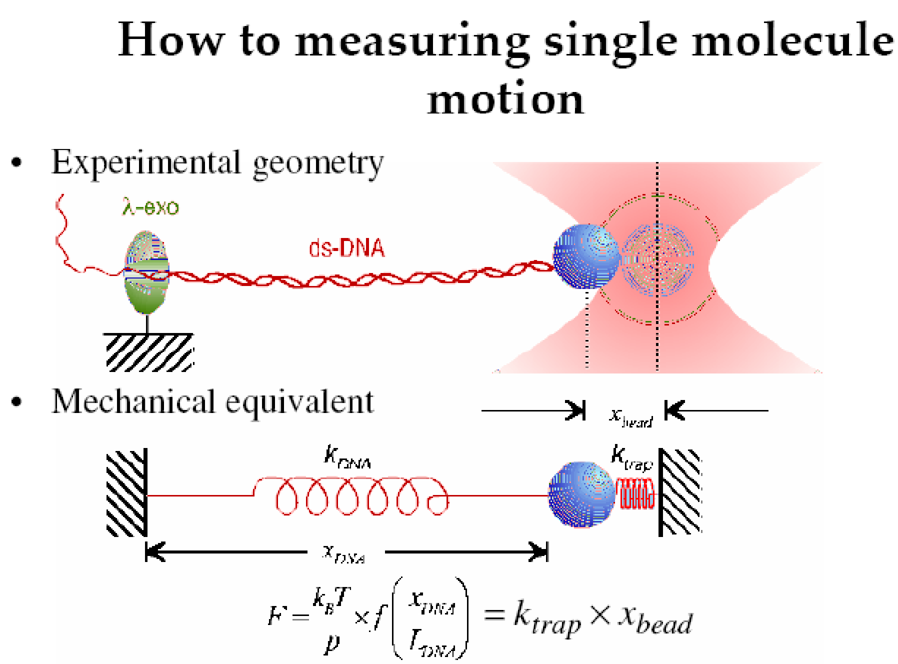
Another example is the impressive achievement of a team from NIH and Rice University led by Philip Anfinrud. They made it possible to watch a protein function. They used the synchrotron at Grenoble to provide picosecond X-ray crystallography. A laser pulse of a trillionth of a second was aimed at a myoglobin protein to break the chemical bond between it and a molecule of carbon monoxide. Then a series of still images were taken 10 billionth of a second apart. They were stitched together to create a moving picture showing the protein expelling the carbon monoxide molecule. Fig. 8 is one frame, the overlaid framework and dots show the bonds and atoms forming the protein. Being able to watch a protein at work gives an increased understanding of the engineering within a protein. One benefit of this research could be the development of controlled release of oxygen from artificial blood. Myoglobin is a small bright red protein – common in muscle cells, which gives meat much of its red colour. It is important in binding with oxygen. The mechanism by which it releases oxygen into the blood is key to our body's metabolism.

Fig. 8.



In another example the work of a team led by Thomas Perkins of the University of Colorado watched single enzymes move along DNA. Optical tweezers were used to measure the motion of single molecules (Fig. 9.)

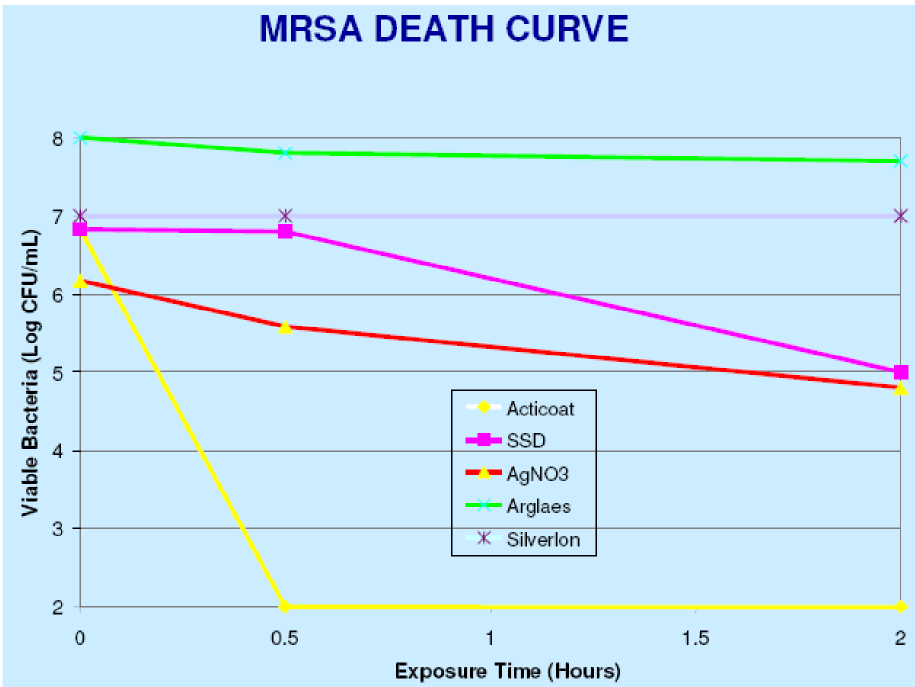
Fig. 9.



What really is Nanomedicine – 3. Clinical Applications.

Dr. Marcotte described the work of Prof. Robert Burrell at the University of Alberta on antimicrobiological properties of silver. Silver has been known for its antimicrobial properties for centuries. It was used as a defense against typhoid and anthrax in the 19th century. During the 20th century its use declined with the advent of cheaper antibiotics. Nanocrystalline silver is now shown to have dramatic improvement over conventional silver treatment. Fig. 10 shows how the death rate of MRSA bacteria is significantly greater and faster with nanocrystalline silver (Acticoat). MRSA, commonly described as 'superbug', is shorthand for any strain of staphylococcus bacteria that are resistant to one or more conventional antibiotics.

Fig. 10.



Dr. Marcotte showed comparative photographs of a patients leg where skin lesions had been treated for 10 years with conventional treatment compared with 60/70 days with Acticoat. With the short-term nano treatment only about half the lesions were present and those that were looked far less inflamed.

The final example was of improved eye surgery using femtosecond laser laminations taken from the eye to correct corneal problems.

In summary, nanomedicine is evolving in three areas; diagnostic tools, instrumentation for biological research and in clinical applications. And nanomedicine has nothing to do with nanobots roaming inside the human body!

Following the lecture Dr. Marcotte answered some questions. One asked 'What is the cost of the new measurement tools?' Dr. Marcotte said that sometimes the cost has been reduced from previous techniques, but it is not easy to give a simple answer without debating the proportion of research costs that should be included. Another question raised the issue that so many different styles and sites of expertise are involved. Dr. Marcotte agreed, and said that it is important to try to bring together and combine a range of disciplines. In a University setting this is not always easy with different departmental agendas and styles. The key is to encourage cross training and exchange postings.

Aditional information.

1. Background on CIHR is at www.cihr-irsc.gc.ca. Abstracts of papers from the 2nd Annual Nanomedicine Workshop held in Toronto, Feb. 2004 are at www.regenerativemedicine.ca/nanomed2004/Participant%20Kit.pdf.
2. Nanomedicine activities of NIH are at http://nihroadmap.nih.gov/nanomedicine/index.asp.
3. Background on the NCI roadmap and nanomedicine plan is at www.nci.nih.gov/researchfunding/NIHRoadmapFAQs.
4. Further information on the work of Prof. Warren Chan at the University of Toronto is at http://128.100.71.175/research.htm.
5. A short summary on nanomedicine is at the web site of the San Francisco Medical Society, www.sfms.org/sfm/sfm1104c.htm.
6. "Nanotubes glow, even within biological cells", summary note on work at Rice University at http://media.rice.edu/media/NewsBot.asp?MODE=VIEW&ID=6854&5nID=523123998.

CHAPTER 8.

ENVIRONMENT (SOIL, POLLUTION CONTROL, ETC)

<u>Notes on the lecture by Dr. Shesha Jayaram.</u>

Dr. Jayaram based her talk primarily on pulse power applications in food processing, cell biology and genetic engineering, and air purification. As well as considering the nano scale of length, Dr. Jayaram introduced the concept of 'nanotime' – pulsed power with pulses of nanosecond dimension.

Pulsed power can be an alternative to pasteurization for food processing – without the need for heat, which tends to affect some food properties like altering the taste. Traditional steam treatment has advantages and disadvantages, Fig. 1.

Fig. 1.

Steam treatment is so well accepted that it is hard to introduce other technologies. New technologies have to show a clear advantage to be considered. An electrical sterilization treatment is summarized in Fig. 2.

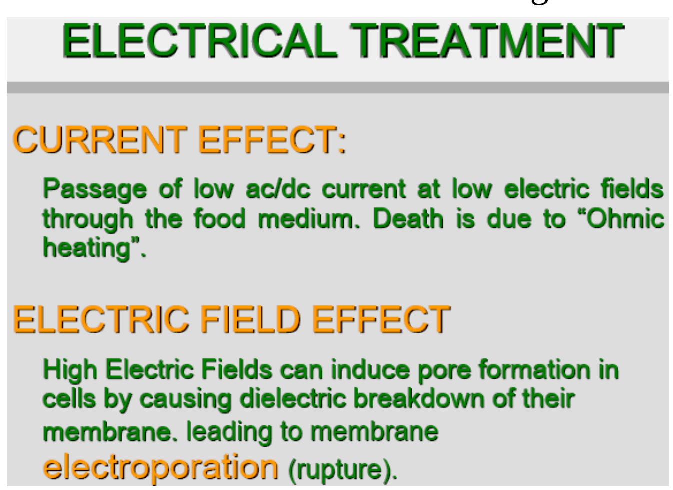
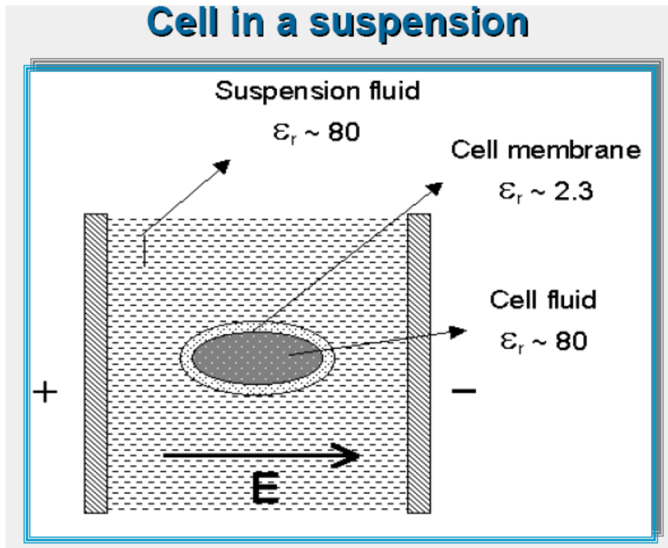


Fig. 2.

Electroporation occurs from a nanosecond to a millisecond time frame and produces negligible heating. There is debate on the science – electroporation might work either due to electromechanical phenomena or via a secondary process after pore formation is initiated in the cell membrane. The concept is shown in Fig. 3.

Fig. 3.



Bacterial cells have internal fluid and components such as chromosomes contained inside the membrane. A short electric pulse can rupture and cause a dielectric breakdown of the membrane Fig. 4 & 5.

Fig. 4.

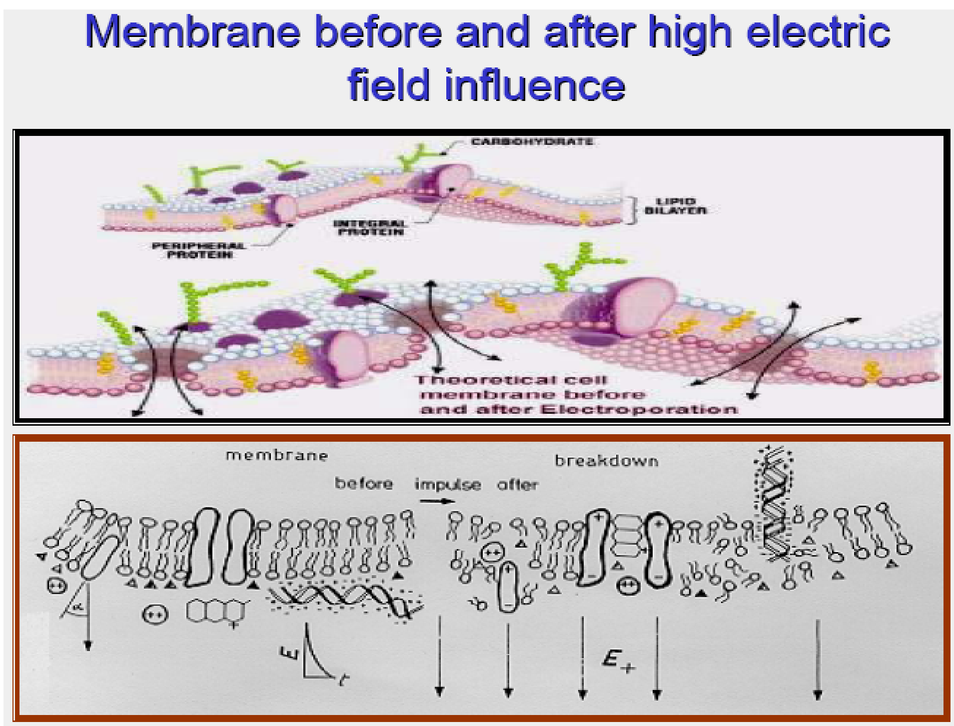
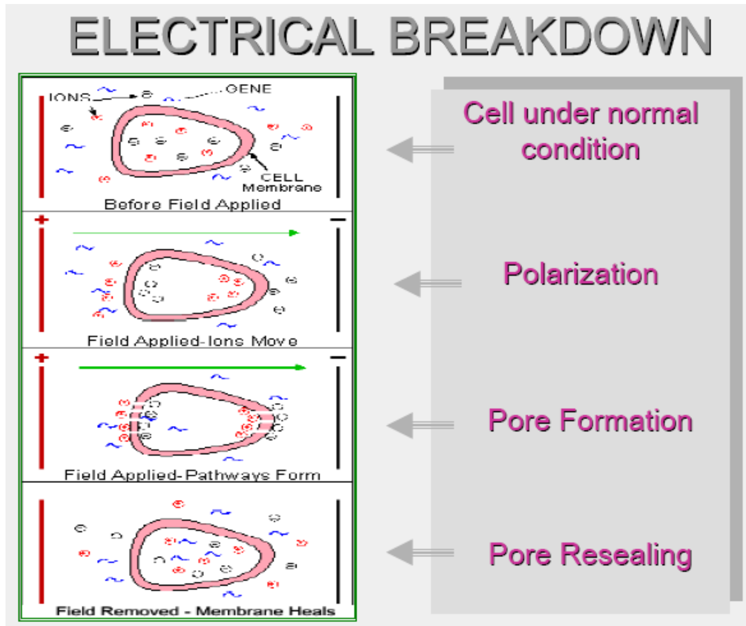
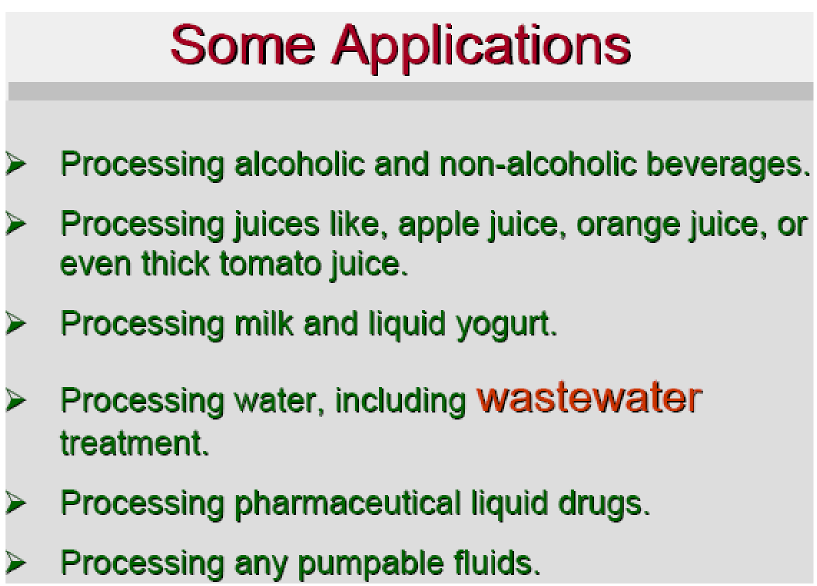


Fig. 5.



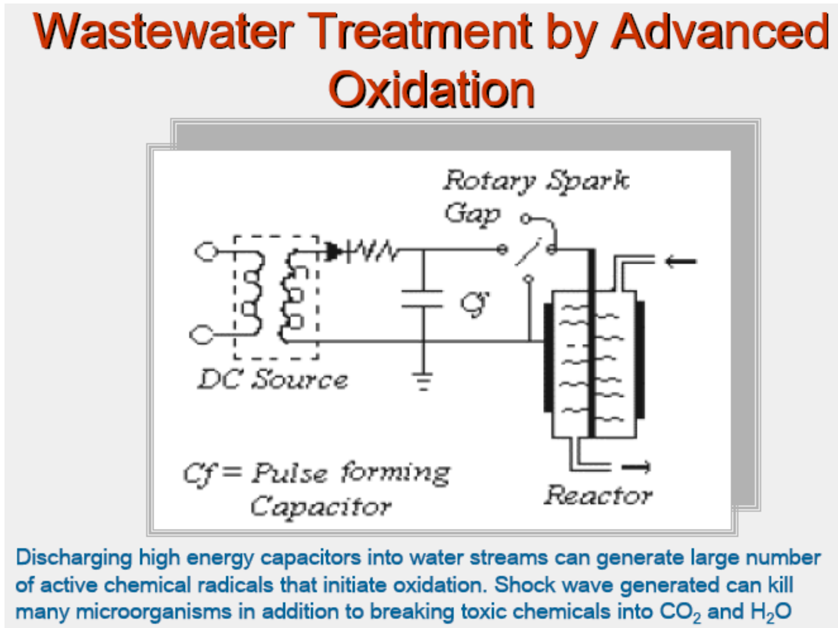
Depending on the field strength and pulse duration, there can be either reversible or irreversible breakdown. Membrane rupture appears to stop bacterial growth (like e-coli) even though the cell contents are released. A 10 to 30 kv pulse for 10 to 30 nanoseconds appears to be the range to stop bacteria from multiplying. The challenges are to design the power supplies and treatment chamber, and to be able to measure the pulse to ensure that the process is working. Following laboratory scale tests, the issues now are to create an effective design for large scale (thousands of liters/hour) processing, and to get an adequate electrical field throughout the treatment zone. The fluid flow has to be uniform and laminar. Some potential applications are shown in Fig. 6.

Fig. 6.



Until the underlying science is clear, there is still the question "How well can pulsed power breakdown micro-organisms and toxic chemicals?" A concept for wastewater treatment is shown in Fig. 7.

Fig. 7.



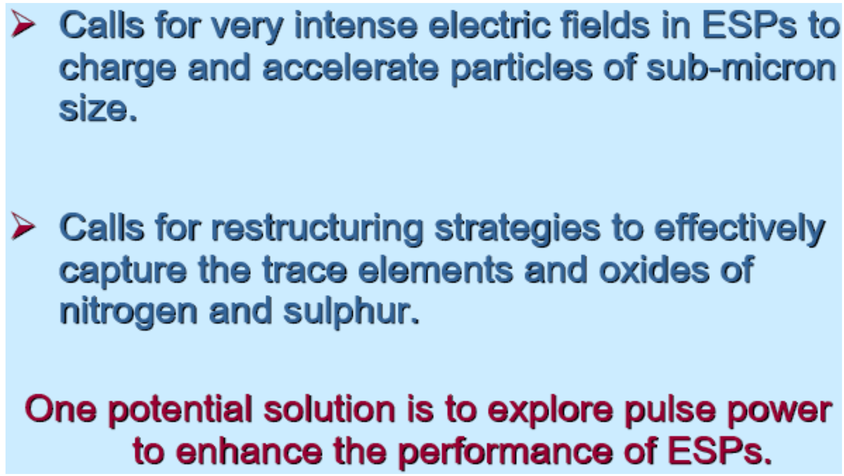
Ultra short pulses, less than the charging time of the membrane can enable intracellular manipulation – which might be used to improve wound healing. Similarly it has been observed that healthy and leukemia cells are affected in different ranges. This might lead to the ability to target the leukemia cells whilst leaving the healthy cells unaffected.

The second part of Dr. Jayaram's talk concentrated on modifing electrostatic precipitators with pulsed power for improving the environment. Traditional electrostatic precipitators are being challenged in various areas as shown in Fig. 8 & 9.

Fig. 8.

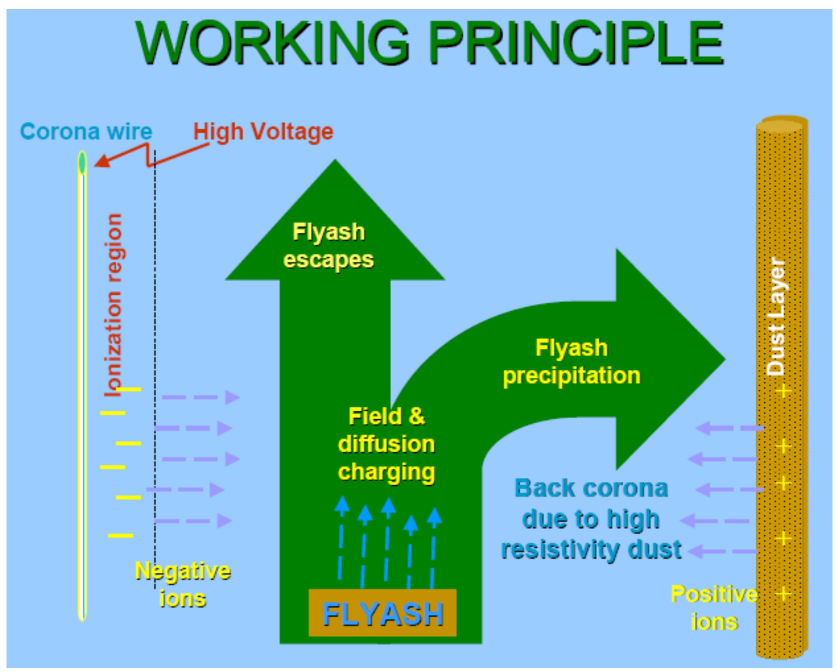
- Particulate Contamination from utility boilers and other industrial plants.
- Growing concerns about the removal of particles of "Respirable size.
- Growing concern about the removal of mercury in particular and other trace elements.
- Growing concern about the emission of oxides of nitrogen and sulphur.

Fig. 9.



While the efficiency of electrostatic precipitators is high when measured by the weight of particles removed, there is growing concern that the smaller particles that get through might be harmful for the environment. The working principles of electrostatic precipitators are shown in Fig. 10.

Fig. 10.



The back corona can reduce the effectiveness of dust collection. Adding pulsed power can be flexible as the voltage, pulse shape, pulse width and repetition rate can all be controlled. The benefits of adding pulsed power to electrostatic precipitators is shown in Fig. 11.

Fig. 11.

Usefulness of Pulse Power

- Suppressing Back Corona – more efficient than other methods.
- Pulse Corona is effective in oxidizing mercury; thus helping in capturing trace elements.
- Pulse power is also been found useful in reducing emission of oxides of sulphur and nitrogen.

Dr. Jayaram answered a question on the economics and status of pulsed power sterilization. Work at Ohio State University has estimated the cost of steam sterilization at 6¢/l. Pulsed power is now predicted to be around 7 to 8¢/l, but they estimate that with development it could reduce to 3 to 4¢/l. They are also doing food taste surveys and have prototype commercial sized plant under test.

She provided a bibliography of related papers as follows:-

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E. J. M. van Heesch, A. J. M. Pemen, , P.A..H Huijbrechts, P.C.T. van der Laan, K.J. Ptasinski, G.J. Zanstra, and P. de Jong, "A fast pulsed power source applied to treatment of conducting liquids and air," *IEEE Trans. Plasma Science*, vol. 28, no. 1, pp. 137-143, Feb. 2000.

Additional information.

1. A good summary by US FDA, June 2000, is the report " Kinetics of Microbial Inactivation for Alternative Food Processing Technologies – Pulsed Electric Fields." At http://vm.cfsan.fda.gov/~comm/itf-pef.html.
2. Another summary of pulsed electric field processing is at www.divtecs.com/, click on *Papers* then *Pulsed Electric Fields.*

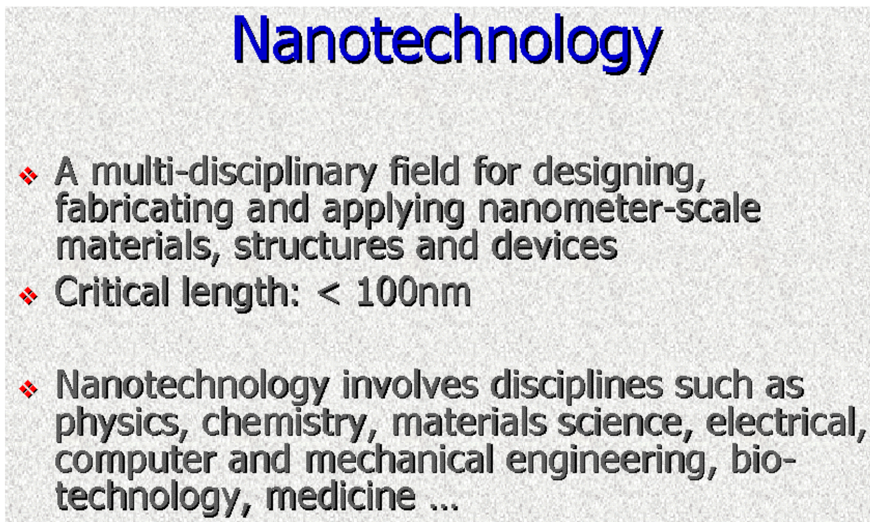
CHAPTER 9.

THE WAY FORWARD – A ROAD MAP FOR THE FUTURE.

<u>Notes on the lecture by Prof. Uwe Erb.</u>

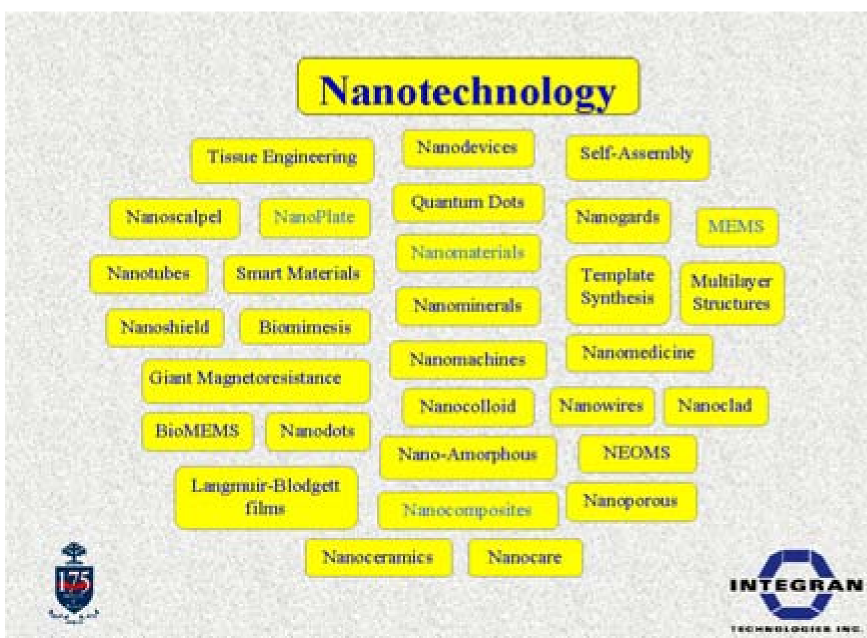
The last lecture of the series was by Prof. Uwe Erb who quickly summarized nanotechnology and then followed with his views on the areas showing the greatest potential. The definition of nanotechnology, which he uses, is in Fig.1.

Fig.1.



Nanotechnology covers a wide range of areas Fig.2.

Fig.2.



R&D funds are being spent in many countries with the expectation of a share in the predicted $1T commercial business by 2015. And the work is not just in the large developed countries – for example smaller countries in Asia-Pacific are all engaged in R&D where they aim to find niche areas for exploitation. (See Table 4 in attachment A) The scale of activity worldwide is reflected in the large range of scientific journals now available on the subject – and the number of patents (Fig.3.)

Fig.2

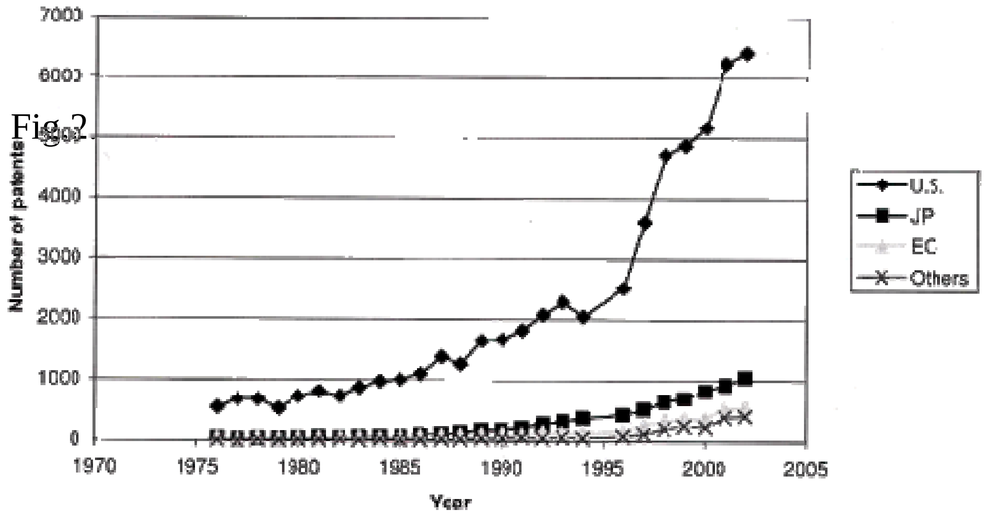


Fig. 3 Number of nanotechnology patents per four regions (1976–2002). The leading ten countries in 2002 were: U.S., 6425 patents; Japan, 1050; France, 245; UK, 100; Korea, 87; Taiwan, 86; Netherlands, 66; Australia, 61; Switzerland, 55; Italy, 44. The survey was taken using the USPTO database in April 2003 [13].

Popular commercial magazines such as BusinessWeek are now reporting that while ***"there's still plenty of hype,...nanotechnology is finally moving from the lab to the marketplace."*** (Feb 14 2005) To emphasize their view Prof. Erb commented that nearly every clothing store is now advertising shirts and pants with nano-treatment. A few examples of nano materials in the marketplace are shown in Fig. 4.

Fig.4.

Product Name	Company	Product Description
Nanocare	Nano-Tex (US)	Stain-Resistant fabrics
Nanoceram	Argonide Nanomaterials (US)	Alumina nanofibres
Nanoclay	Southern Clay Products (US)	Nanocrystalline clay additives
Nanograin	Nanodyne Corp. (US)	Ceramic, metal and composite powders
NanoPhaze	Nanophase Materials Corp. (US)	Metals and ceramic powders
NanoPlate	Integran Technologies (Can.)	Electroplated metals, alloys, composites
NanoSurface	Advanced Surface Eng. (US)	Nanocrystalline ceramic coatings
NanoTek	Nanophase Technologies (US)	Nanocrystalline metals and oxide powders
Nucryst	Nucryst Pharmaceuticals (Can.)	Anti-microbial silver nanocrystals
Vitroperm	Vacuumschmelze (Germany)	Nanocrystalline soft magnets
Amplate	Fidelity Corp. (US)	Amorphous/nanocrystalline electrodeposits
Finemet	Hitachi Metals (Japan)	Nanocrystalline soft magnets

However there is also lots of hype and gimmicks where ‘nano’ is attached to the name where there is no nanotechnology involved. One example shown was a small box of matches labeled ‘nano’!

On the other hand Fig. 5. shows an example of nano-electroplated material on top of foam to provide a material for armour applications.

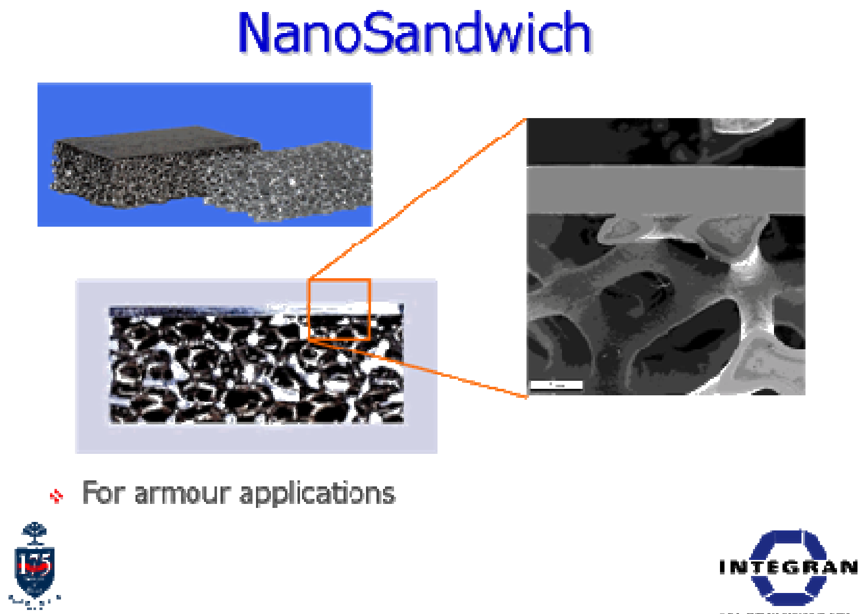


Fig.5.

Prof. Erb sees four areas having great potential for the future. (Fig.6.)

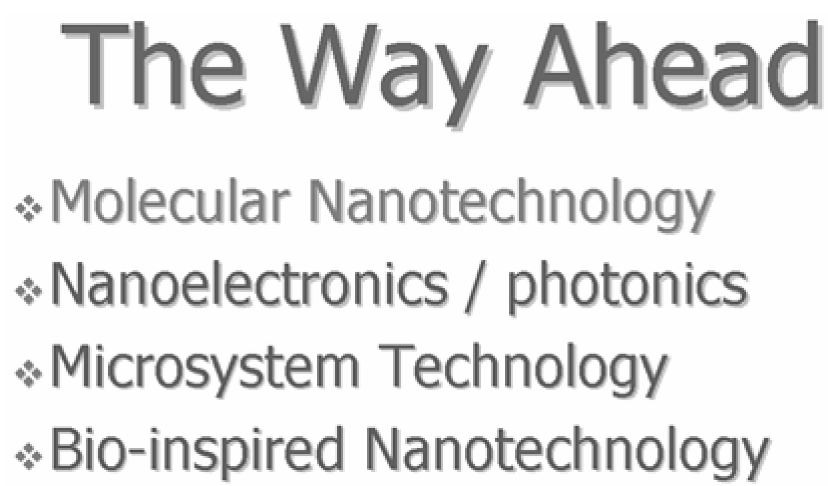


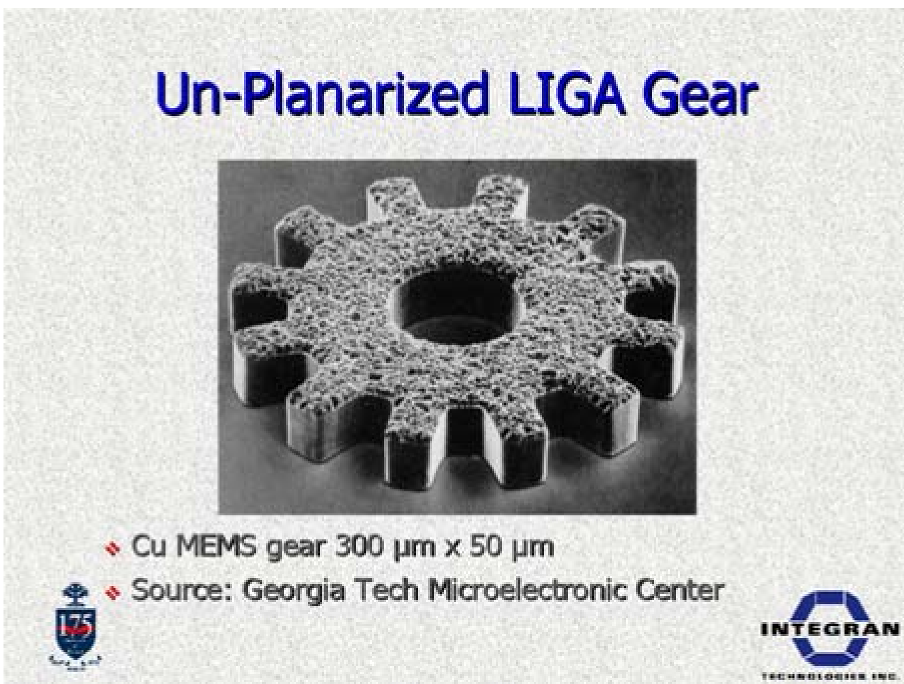
Fig.6.

Whilst IBM researchers were able to spell out ‘IBM’ with Xenon atoms in 1989 and since then researchers have positioned atoms with Atomic Force Microscopes, nevertheless molecular manipulation and building components atom-by-atom has still not reached reality. In Prof. Erb's view it may take another 10 to 15 years to see significant progress in this area.

In electronics and photonics there are great expectations. Research is focusing on how electrons behave when size is reduced to that of quantum dots – the size where quantum physics rules. Making and manipulating quantum dots will be the key to the development of new and faster integrated circuits.

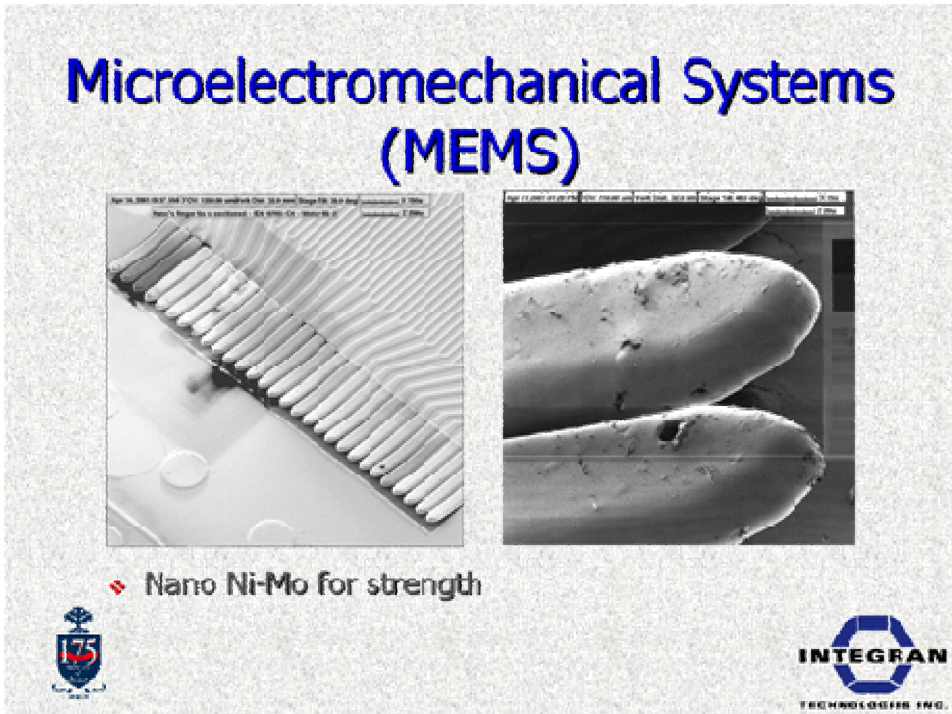
Developments in microsystem technology is being led by materials that have nano-sized grains. The improvements in material properties are shown in attachment B. Prof. Erb showed two examples where nanotechnology can improve Microelectromechanical Systems (MEMS). In Fig.7. an un-planarized micro-gear is seen to have few grains along each tooth. As a result the mechanical properties of the tooth are dependent on the orientation of just a few grains. If the gear was made by nano-electrodeposit then there would be many more grains along each tooth and hence more consistent and improved mechanical properties. The net result is better giving more predictable performance, and longer life. Further details are in attachment B.

Fig.7.



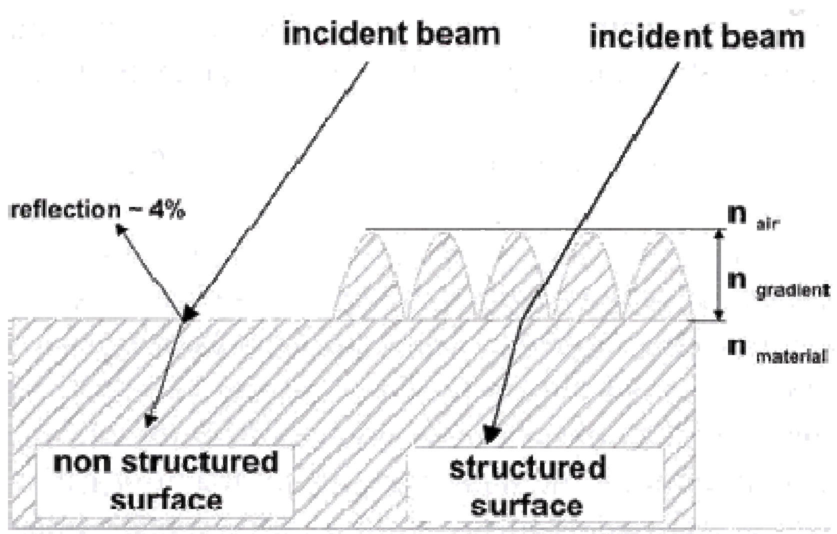
The second example is the small contact springs used for testing computer chips. (Fig.8.) Traditional manufacture results in few grains per spring and hence variable 'springiness' depending on the grain orientation. With nano material there are many more grains per spring and hence more consistent 'springiness'.

Fig.8.



The 4th Way Ahead is 'bio-inspired nanotechnology'. An example is to match the technology used in the eye of a moth to see in the dark. The moth needs to capture the maximum light and not loose any by reflection. The surface of the moth's eye is covered with semi-spheres around 200-250nm in diameter, similar to what is shown for a man-made structured polymer surface (Fig.9.)

Fig.9.



Comparison of light hitting on a planar or nanostructured PMMA surface.

The nano-structured surface effectively stops the light lost in reflection. The same technology appears to work in producing non-reflecting glass, and the properties can be tailored to wavelength.

Another bio-inspired development uses the lotus leaf effect. The lotus leaf never gets dirty. The nano-rough surface tends to be non-wetting, and when the droplets run off they collect any particles of dirt. (Fig.10.) The physics is still not fully understood.

Fig.10.

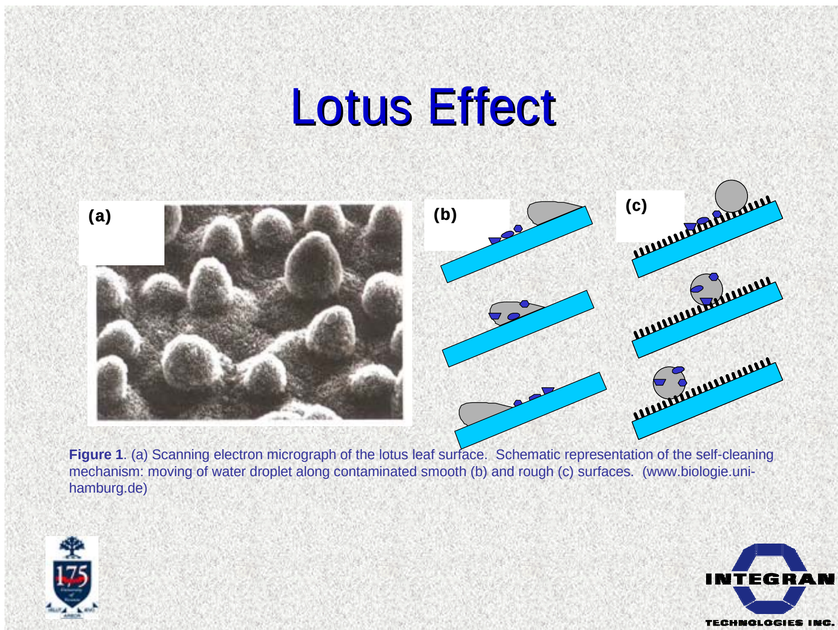
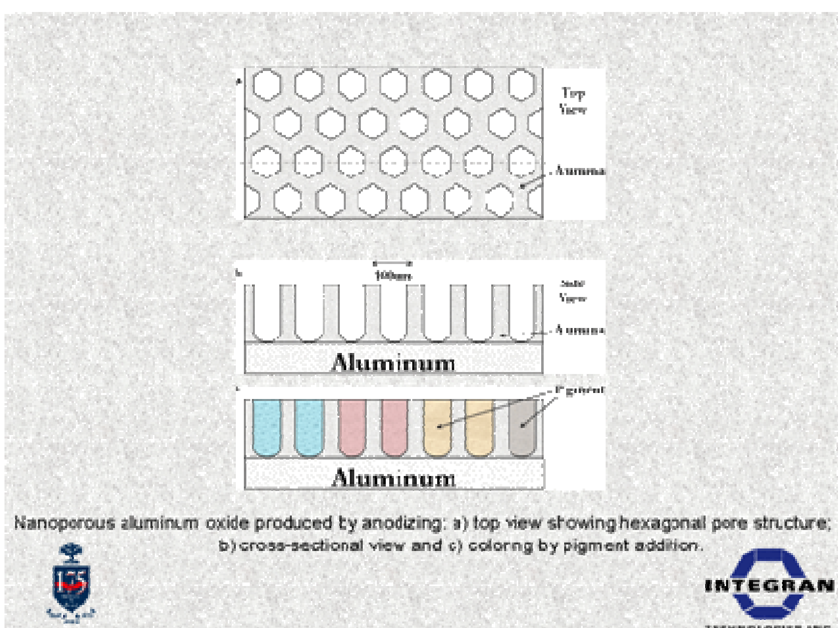


Figure 1. (a) Scanning electron micrograph of the lotus leaf surface. Schematic representation of the self-cleaning mechanism: moving of water droplet along contaminated smooth (b) and rough (c) surfaces. (www.biologie.uni-hamburg.de)

For many decades anodized aluminium surfaces have been used to create different coloured objects by filling the oxide pores with pigment. Aluminium oxidizes in a regular nano-sized hexagonal pattern. (Fig.11.)

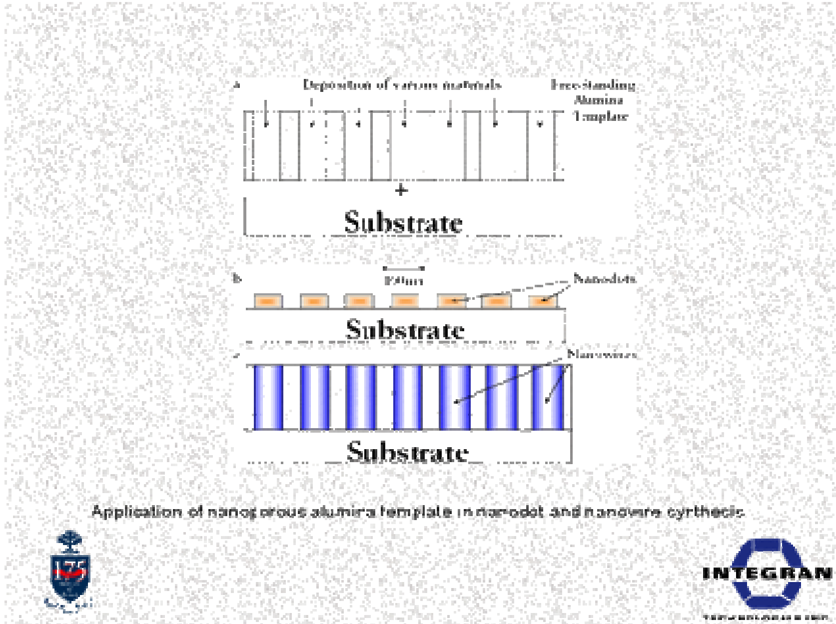
Fig.11.



Nanoporous aluminum oxide produced by anodizing: a) top view showing hexagonal pore structure; b) cross-sectional view and c) coloring by pigment addition.

This effect can be used to make nano-wires and nano-dots. (Fig.12.)

Fig.12.



In summary, nanotechnology is a fascinating new technology that can lead to the next industrial revolution. (Fig.13.)

Fig.13.

The impact on society can be enormous with developments in clean water and fuel cells to name just a couple. It is not easy to predict which area to invest in, but the technology offers a great career choice for students.

However there are some concerns. (Fig.14.)

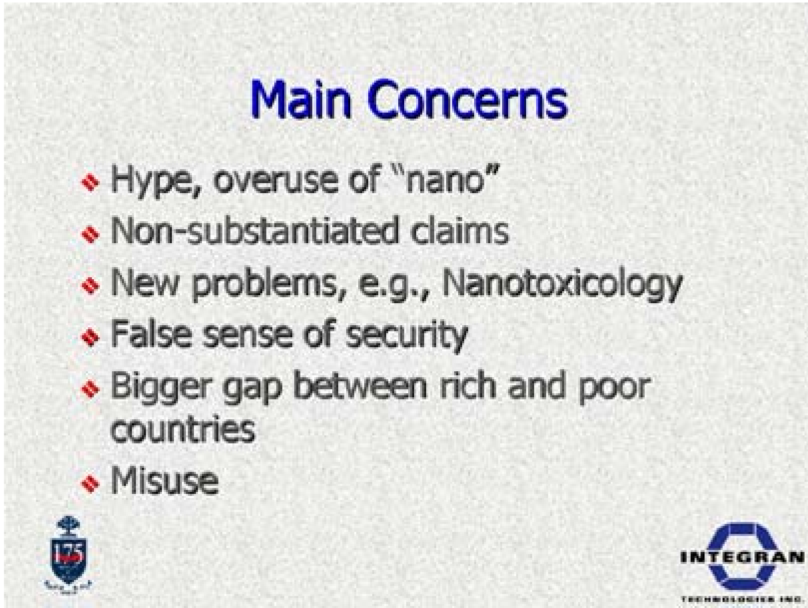


Fig.14.

Hype and the over use of the prefix “nano” clouds real development. And it is important that potential issues such as toxicity are researched in parallel with other research.

Prof. Erb concluded his presentation by acknowledging the support from the Natural Sciences and Engineering Research Council of Canada.

DISCUSSION AND QUESTIONS.

Question – what is the optimum depth for electroplated nano-material? Answer – it is dependent on the application, for example the wear rate likely to be experienced.

Question – how do you get small grains, past technology has always produced large grains? Answer – traditionally there is a competition between nucleation and growth, and growth wins. The trick is to find the right conditions that favour nucleation. It’s the control of electricity, temperature and chemistry – process related parameters.

Question – can Inconel properties be varied to suit the application? Answer – yes, by changing the crystal size. Large crystals are the lowest energy state and atoms have plenty of time to go to low energy. The solution is to not give them time to go to the low energy state.

Question – can nano-materials be tailored to best suite the product application? For example a metal to metal seated valve needs a combination of wear, friction and sealing properties. Answer – yes, but it is currently dependent on how much one can spend on developing the specific nano-material. And some materials are not easy to electro-deposit due to carcinogenic chemicals in their formulation.

Comment – it is a surprise to see Korea amongst the leading countries in the future of nanotechnology. Response – that is the result of investment and by being technology driven.

Question – should we worry the same about nano-structured components as particles, and have we been exposed to nano-particles already? Answer – Carbon Nanotubes are just carbon but have been shown to cause cancer in rats. More work is needed to understand the situation. Nano-sized particles are available in nature, and soot from man-made activities has been around for years. In Jamaica there are the Red Mud Lakes where bauxite was mined. The particles stay in suspension – a nano-soup!

A brief discussion took place on the effect of different plating processes on grain size. It appears that the technology is complex and that some information is proprietary.

ELECTROPLATING IN THE CONTEXT OF WORLDWIDE NANOTECHNOLOGY INITIATIVES

(CHAPTER 9 ATTACHMENT A)

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Abstract

This paper deals with two important issues of interest to the electroplating and surface finishing industries. In the first part a summary is presented on recently established nanotechnology initiatives in various countries around the world. Program funding levels and core activities will be compared to provide a basis for assessing business opportunities for various industries. The second part of the paper looks at specific examples of nanostructures made by electrochemical methods currently at various stages in their development, or already in use. These include electrodeposition of monolithic pure metals and alloys, multi-phase composites, compositionally modulated multilayers, template manufacture by anodizing for nanodot and nanowire synthesis and electroplating of components for microelectromechanical systems.

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1) Worldwide Nanotechnology Activities

Nanotechnology is a relatively new multidisciplinary field in which many of the unusual physical and chemical effects observed only on the nanoscale (typically less than 100 nm) are utilized to create new materials, devices and objects with outstanding properties and functions never seen before. Nanotechnology includes several subdisciplines which can be summarized as shown in Fig. 1. The various subfields have their origin in different disciplines and were initially developed by scientists and engineers with different backgrounds. For example, nanostructured materials were originally developed by physicists and materials scientists, while bio-inspired nanotechnology was the domain of chemists and biologists.

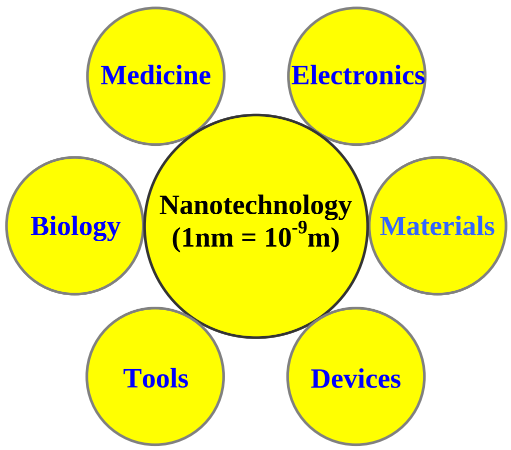

Figure 1: *Main focus areas of nanotechnology*

Today's' nanotechnology approach requires the breakdown of traditional barriers between these fields and strong collaborative efforts of people with quite different but complementary skill sets.

Table 1: Comprehensive Research Programs in Nanotechnology with Funding in Excess of US $ 100 Million/Year [Adopted from Ref. 1]

Country	Date Initiated
United States	January 2000
Japan	July 2001
South Korea	July 2001
European Community	March 2002
Germany	May 2002
Taiwan	September 2002

The enormous long term potential of nanotechnology in revolutionizing our approach to technology, which would ultimately result in increased productivity, a deeper understanding of nature and a better quality of live, was recognized in the late 1990's in many different countries. Table 1 [1] summarizes various comprehensive research programs in nanotechnology with government funding levels in excess of US $ 100 million per year, established after 2000.

President Clinton's initial nanotechnology initiative was launched in 2000 and was later enhanced under President Bush to become the 21st Century Nanotechnology Research and Development Act [e.g. 2]. Table 2 [1] shows a breakdown of funding levels for various Federal Departments or Agencies for 2000-2005 within the US National Nanotechnology Initiative (NNI). Over this period the total funding level increased by more than 360% to close to US$ 1 billion for 2005.

Table 2: Contributions of Key Agencies to NNI [Adopted from Ref. 1]

Federal department or Agency	FY 2000 Actual ($M)	FY 2001 Actual ($M)	FY 2002 Actual ($M)	FY 2003 Actual ($M)	FY 2004 Est. ($M)	FY 2005 Est. ($M)
National Science Foundation (NSF)	97	150	204	221	254	305
Department of Defense (DOD)	70	125	224	322	315	276
Department of Energy (DOE)	58	88	89	134	203	211
National Institutes of Health (NIH)	32	40	59	78	80	89
National Institute of Standards and Technology (NIST)	8	33	77	64	63	53
National Aeronautics and Space Administration (NASA)	5	22	35	36	37	35
Environmental Protection Agency (EPA)	-	6	6	5	5	5
Homeland Security (TSA)	-	-	2	1	1	1
Department of Agriculture (USDA)	-	1.5	0	0	1	5
Department of Justice (DOJ)	-	1.4	1	1	2	2
Total	270 (100%)	465 (172%)	697 (258%)	862 (319%)	961 (356%)	982 (364%)

Similar growth rates were observed in other countries such as Western Europe and Japan (Table 3, [1]). The total worldwide spending on nanotechnology reached US$ 3 billion by the year 2003.

Table 3: Estimated Nanotechnology R & D Expenditures During 1997-2003 (in U.S. $ millions/year) [Adopted from Ref. 1]

Region	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
West Europe	126	151	179	200	225	400	600
Japan	120	135	157	245	465	700	810
USA	116	190	255	270	422	600	774
Others	70	83	96	110	380	550	800
Total	432	559	687	825	1492	2347	2984
(% of 1997)	100	129	159	191	346	502	690

The funding comparison for Asia-Pacific countries presented in Table 4 [3] clearly shows that even smaller countries such as Australia, New Zealand or Singapore invest heavily in selected areas of nanotechnology R & D.

China, Taiwan and South Korea have established very aggressive programs with South Korea alone contributing US$ 1 billion over the five year period 2003-2007.

Table 4: Funding for Asia-Pacific countries in 2003 (For period 2003 – 2007) [Adopted from Ref. 3]

Country	**Population**	**Funding (5y)**	**Priority**	**Policy coordination**
Australia	19.2 million	100 M	BIO, IT	Common Core Facilities
China	1.2 billion	300 M+	MAT, ME	National and Regional Centers
Hong Kong	6.7 million	30 M	MAT, IT, EN	Centers of Excellence
India	1.0 billion	20 M+	MAT, MEMS	Centers of Excellence
Korea (South)	48.3 million	1 B	MAT, EL, BIO	National Centers and Core Facilities
Malaysia	21.8 million	23 M+	MAT	Centers of Excellence
New Zealand	4 million	50 M	MAT, EL	Centers of Excellence
Singapore	4.2 million	60 M	MAT, EL, BIO	Centers of Excellence
Taiwan	21.5 million	500 M	MAT, EL, MEMS	Common Core Facilities
Thailand	62 million	25 M	MAT, MEMS	National Centers

BIO = Biomedical, EN= Energy, EL=Electronics, IT=Information Technology, ME=Molecular Electronics, MAT=Nanomaterials, MEMS= Microelectromechanical Systems

The expected returns on investment in nanotechnology are huge. Table 5 [2] gives a breakdown by area of the projected market size by 2015, totaling US$ 1 trillion. The largest sectors are nanostructured materials and electronic components which probably reflects the relatively long nano research activity in these areas. For example, nanostructured materials were already introduced in the early 1980's [4] with considerable research efforts throughout the 1980's and 1990's. It was also during this period when most of the early fundamental work on nanostructured electrodeposits was carried out [5].

Table 5: Projected Nano Market Size by 2015 [Adopted from Ref. 2]

Materials	US$ 340 billion
Electronics	US$ 300 billion
Pharmaceuticals	US$ 180 billion
Chemicals	US$ 100 billion
Aerospace	US$ 70 billion
Sustainability	US$ 45 billion
Healthcare	US$ 30 billion
Nanotech Tools	US$ 20 billion

In view of the great potential for new business opportunities arising for the electroplating industries from the worldwide activities in nanotechnology, in particular nanostructured materials, AESF established the Nanomaterials Subcommittee in 2002. A first comprehensive paper on "Nanotechnology Opportunities for Electroplating Industries" was published by Plating and Surface Finishing in 2003 [6] and full day sessions on Nanomaterials were held at the 2003 SUR/FIN in Milwaukee and 2004 SUR/FIN in Chicago. It was also in 2004 that the Nanomaterials Subcommittee was accorded full Committee Status.
The remainder of this paper deals with specific examples looking at current and future application areas for electroplating and surface finishing industries in nanotechnology.

2) Monolithic Metal Nanostructures

Synthesis methods for the production of monolithic electrodeposits with crystal sizes less then 100 nm have been developed since the early 1980's. One of the earliest systems that was extensively studied was Ni-P [7, 8], using bath formulations very similar to the ones developed by Brenner et al. [9], and direct current plating. Particular emphasis was on electrodeposits with very narrow grain size distributions and average grain sizes in the 5-50 nm range. An example of such a structure is shown in Figure 2. In the late 1980's emphasis shifted towards more complex alloy systems (e.g. Ni-Fe, Co-Fe, Ni-Mo, Zn-Ni, Ni-Fe-Cr, etc.) and the application of pulsed current deposition of pure metals such as Ni, Co or Cu [10, 11].

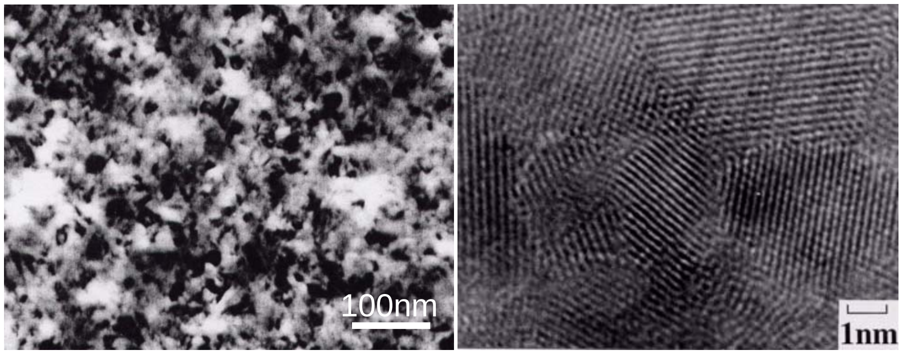

Figure 2: *Bright field (left) and high resolution (right) electron micrographs of nanocrystalline Ni with equiaxed grain shape and narrow grain size distribution*

During electrodeposition, two competing factors control the grain size of the electrodeposit. When a metallic ion in solution is reduced on a substrate it can either contribute to the nucleation of a new crystal or the growth of an existing crystal. Nanocrystal formation requires a set of operating parameters (e.g. bath composition, pH, temperature, current density, current on and off times during pulse plating, agitation, etc.) which promote massive nucleation throughout the entire electrodeposition process. What must be avoided are conditions that would result in a transition with increasing deposit thickness from initially fine grained structure to coarse columnar structure often observed in conventional electrodeposits [e.g. 12].

Electrodeposition processes have been developed for the synthesis of nanocrystalline deposits in many different shapes and forms [5, 6]. These range from thin and thick corrosion and wear resistant coatings to electroformed sheet and plate products for structural, magnetic or electronic applications. This technology can be easily incorporated with little extra costs in conventional electroplating facilities using a variety of different plating approached including rack plating, reel-to-reel plating, barrel plating, brush plating or continuous strip/foil plating.

As a result of their small grain size monolithic electrodeposits show significant improvements in many properties compared to their conventional counterparts. These include considerable increases in hardness, tensile strength, wear resistance and corrosion resistance all of which are well understood in terms of the underlying physical and chemical principles of nanomaterials [13]. The earliest applications of this type of nanocrystalline deposits was the in-situ electrosleeve nuclear reactor steam generator tubing repair technology developed in Canada since the early 1990’s for both Canadian and US nuclear reactors [14]. In this process, steam generator tubes (e.g. Alloys 600 or 400) whose structural integrity was compromised by localized degradation phenomena (e.g. by intergranular corrosion or pitting) were repaired by electroplating their insides with a 1 mm thick nanocrystalline Ni-P alloy to restore a complete pressure boundary. In order to give the required combination of strength, ductility, corrosion resistance and long term stability at temperatures in the 280-350^{0}C range, the grain size of the electrosleeve was adjusted in the 50-100 nm range. It should be noted that, in 1994, this electrodeposited nanostructure was the first large scale industrial application of any structural nanomaterial in the world. It saved the Ontario utilities alone several hundred million dollars.

3) Structurally Graded Nanometals

Monolithic nanometals with narrow grain size distributions exhibit remarkable mechanical properties in terms of hardness, tensile strength and wear resistance. However, their ductility is usually compromised, regardless of the processing route [15]. This is mainly the result of restricted dislocation activity at such small grain sizes. In recent years it has been recognized that considerable ductility can be restored in the materials through broader or bi-modal grain size distributions [15]. In view of this we have developed electroplating conditions for a variety of structurally graded nanomaterials [Fig. 3]. These include bi-modal distributions [Fig. 3a], alternate layers of large and small grain sizes [Fig. 3b] and grain size gradient deposits [Fig. 3c]. In such structures the small gain size regions provide the outstanding strength while the larger grains allow for sufficient dislocation activity to result in reasonable ductility values.

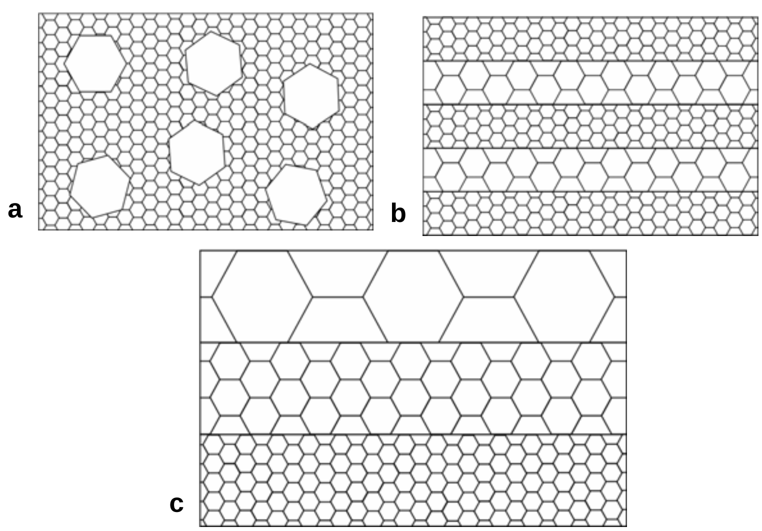

Figure 3: *Schematic diagrams showing various types of structurally graded nano-materials: a) bimodal grain size distribution; b) alternate layers with different grain sizes and c) grain size gradient structure.*

4) Nanocomposites

Composite coatings consisting of conventional polycrystalline metal electrodeposits with second phase particles co-deposited during electroplating have been in use for many years for applications such as increased wear resistance or reduced surface friction coatings [12]. Over the past several years this concept has been extended to nanocrystalline materials [6, 13, 16]. Figure 4 shows several examples of submicrocrystalline / nanocrystalline second phase particles or fibres embedded in a nanocrystalline metal matrix. Examples of second phase particles/fibres include Al_2O_3, TiO_2, SiC or B_4C for improved wear resistance applications, carbon nanotubes for increased strength or Teflon and MoS_2 for low friction coating applications. An alternative route to particle co-deposition is to first produce an alloy deposit as a supersaturated solid solution. Subsequent heat treating of such heat-treatable coatings produce the second phase particles by a precipitation reaction [5].

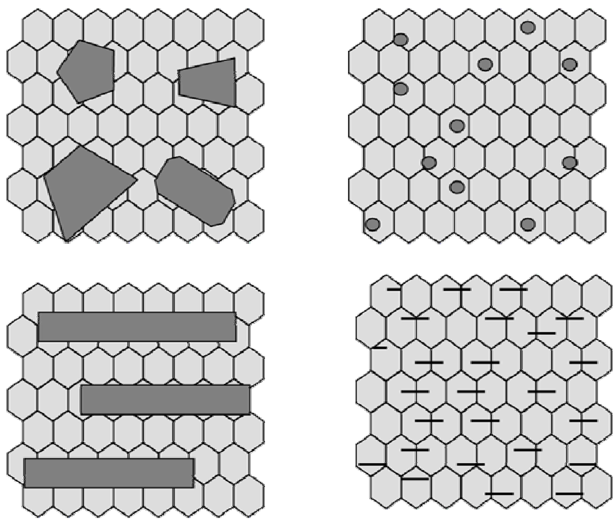

Figure 4: *Examples of nano-composite electrodeposits.*

5) Compositionally Modulated Alloy (CMA) Nanostructures

Compositionally modulated nanostructures consist of alternating layers of deposits with different chemical composition as schematically shown for Ni-Cu multilayers in Fig. 5. The critical nano-dimension in this case is the thickness of the individual layers. Because of their unusual microstructure these materials exhibit unexpected properties such as increased strength, elastic constants and tribological properties, as well as outstanding electromagnetic properties. In fact, one of the most advanced applications of CMA's are alternating layers of ferromagnetic and non-magnetic layers to produce the giant magnetoresistance effect which has already resulted in widespread industrial applications in the recording head industry [17]. CMA's can be produced by many different methods including physical vapor deposition, chemical vapor deposition and electrodeposition. Electrodeposition approaches include rotating substrate methods and potential-stepping methods. In the rotating substrate method two physically separated baths are used and the cathode is rotated between the two baths. In the potential stepping methods, ions of the two metallic species are contained in the same plating bath. By periodically stepping the potential between predetermined values, the relative deposition rates of the two species creates the required concentration changes in the multilayers. Using these approaches, many CMA structures have been produced by electrodeposition such as Ag-Pd, Cu-Ni, Cu-Pb and Ni-P with moduclation wavelengths down to few nm [18, 21]. Even nanomodulated ceramic structures have been produced by this technique [22].

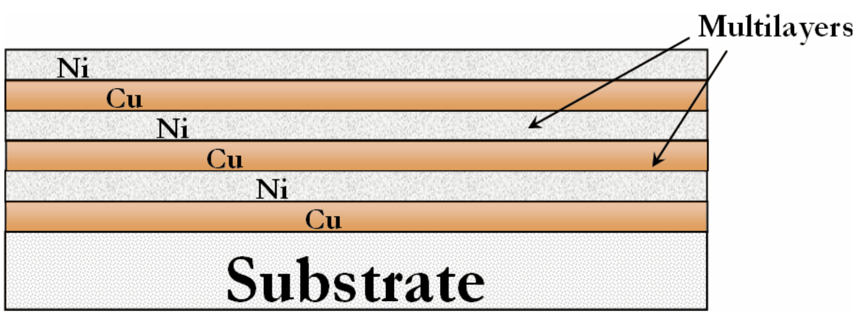

Figure 5: *Schematic diagram showing a compositionally modulated alloy deposit.*

6) Template Nanotechnology by Anodizing

Anodizing of aluminum is a widely used finishing process to improve the surface characteristics of aluminum parts [23-25]. This process involves the artificial build up of the natural protective aluminum oxide layer from a few nanometers thickness to tens or even hundreds of micrometers by making the aluminum part the anode in a suitable electrolyte. Under anodizing conditions a porous oxide layer with regular or irregular arrangements of hexagonal columns with pores extending from the free surface down to the initial barrier layer is produced (see top and side views in Fig. 6a, b). For requirements such as scratch or corrosion resistance the porous aluminum oxide is sealed, for example by boiling in water which hydrates and expands the oxide to effectively close the pores. In color anodizing (for example for architectural applications) the pores are impregnated with dyeing compounds or mineral pigments of different color, prior to sealing (Fig. 6c).

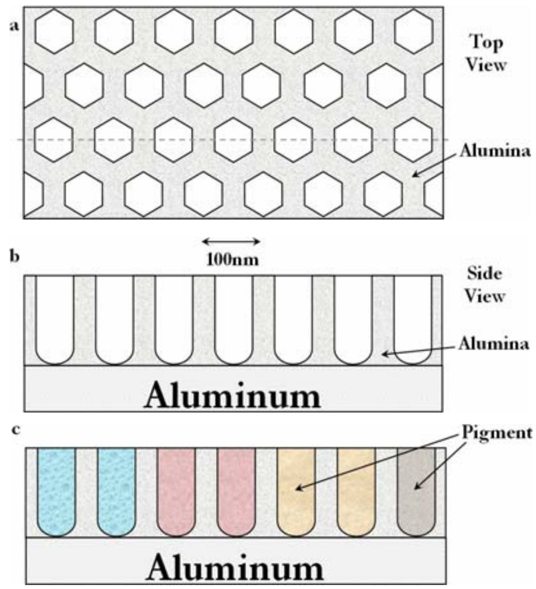

Figure 6: *Nanoporous aluminum oxide produced by anodizing:* ***a)*** *top view showing hexagonal pore structure;* ***b)*** *cross-sectional view and* ***c)*** *coloring by pigment addition.*

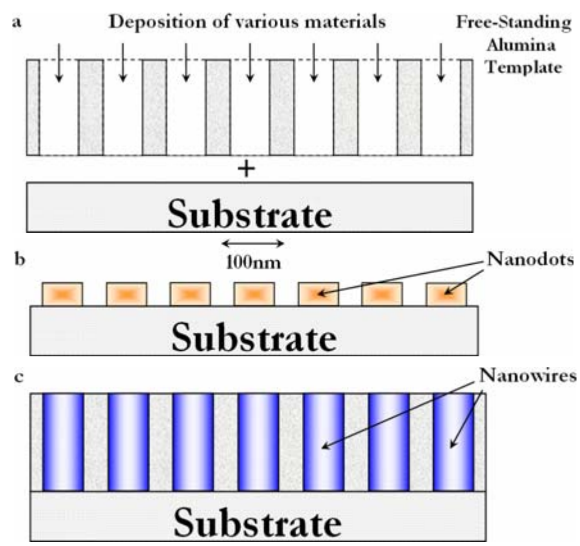

Figure 7: *Application of nanoporous alumina template in nanodot and nanowire synthesis*

Over the past 10 years the basic anodizing approach has been further developed to produce highly ordered nanoporous honeycomb oxide structures for use in nanostructure synthesis by the template approach [26]. In this process the porous alumina film is extracted by dissolution of the aluminum substrate and used as a free-standing mask to produce, by vapor deposition, structures such as nanodots or nanowires of various materials, in particular semiconductors (Fig. 7). For example regular arrays of so-called quantum dots produced by this method have very interesting electrical properties resulting from electron state confinement in crystals with very small external sizes.

7) Microsystem Technology

Microsystems can be described as intelligent miniaturized systems that combine sensing and/or actuating functions with processing functions. Such systems are typically multifunctional, combining two or more electrical, mechanical, optical, chemical, biological or magnetic properties such as in

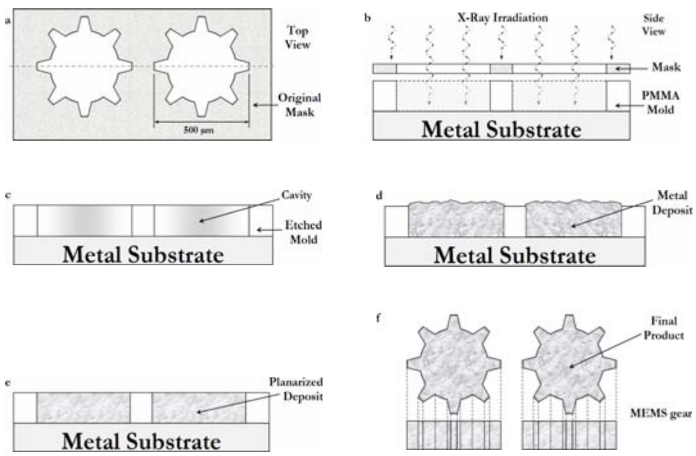

Figure 8: *Various steps in the production of a MEMS gear by electrodeposition*

Microelectromechanical Systems (MEMS). Many microsystems are produced by various micromachining methods on a single substrate in form of a monolithic system (for example an all Si device). However, other designs require metallic components which, in most cases, are produced by electrodeposition methods (e.g. the so called LIGA process) [e.g. 27]. Figure 7 shows a series of schematic diagrams of the various process steps involved in making a microgear by the LIGA process. The first steps are preparation of mask and mold into which the metal is to be deposited. Traditional LIGA parts have a columnar grain structure with very high grain shape anisotropy. As the size of the microsystem parts are getting smaller and smaller this structure becomes unacceptable because it leads to loss in overall strength, non-uniform properties and unreliable system performance [28]. We have recently shown that these problems can be alleviated by adopting nanostructured electrodeposits for microsystem components [29, 30]. By using equiaxed nanocrystalline Ni, Co or Ni-Fe deposits, property variations due to grain size/shape anisotropies have been eliminated and the overall performance of the components in terms of specific strength, elastic energy storage capability, thermal shock resistance and reduced eddy current losses were improved enormously.

8) Summary

Nanotechnology is one of the fastest growing areas in science, engineering, biology and medicine and is expected to have a tremendous impact on society over the next few decades. In view of the expected returns on investment many countries have established their own nanotechnology platforms with substantial government funding. Many industries have already formulated their plans for strategic positioning in this very broad field. Electroplating and surface finishing industries have a lot to offer in this area in particular when it comes to meeting the challenges in providing new nanostructured materials of improved performance or manufacturing capabilities to produce structures, devices and systems on a micro/nanoscale.

9) Acknowledgments

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SESSION P - NANOMATERIALS - I

Wednesday, June 30, 2004

Advancing Microsystem Technologies Through Electroplated Nanostructures

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Abstract

Factors affecting reliability and performance are the main concerns when dealing with microsystem components / devices with continuously shrinking external dimensions. In particular, microstructural non-uniformities leading to materials property variations across the microcomponent have presented major challenges. However, recent developments in the field of electroplated nanocrystalline materials can offer an avenue to address many of these technical difficulties.

In this paper, the deficiencies of metallic microsystem components currently in use are addressed, followed by a comparison which shows how nano-electroplated microcomponents can alleviate these problems. Materials properties enhancements that are achievable as a result of having nanostructured microcomponents will be discussed. The effects of grain size reduction on several specific performance indicators such as elastic energy storage capacity and wear resistance will be examined.

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Introduction

Although metallic components for microelectromechanical systems (MEMS) have been available since the 1980s, the microstructures of these microcomponents are still typically the same as for macrostructures produced by bulk processing. With the ever-decreasing size of the components and devices to less than 1000µm, the tolerances for defects and non-uniformities in the materials and finished products are proportionally reduced. For example, the same defect density that would normally be acceptable in a gear 1cm in diameter can become detrimental in a MEMS gear having a diameter of only 1mm, thus greatly increasing the probability of catastrophic failures and significantly reducing the reliability of such a component. Today, most metallic MEMS components are fabricated using conventional electroplating techniques with little consideration regarding the structure-property relationships of the plated structure with respect to dimensional scaling [1].

LIGA (German acronym for LIthographic [lithography], Galvanoformung [electroforming] and Abformung [molding]) is the most widely used process to fabricate materials and components for MEMS, in which individual microcomponents are made by specialized electroplating techniques. Figure 1 shows schematically the various steps involved in a typical LIGA process.

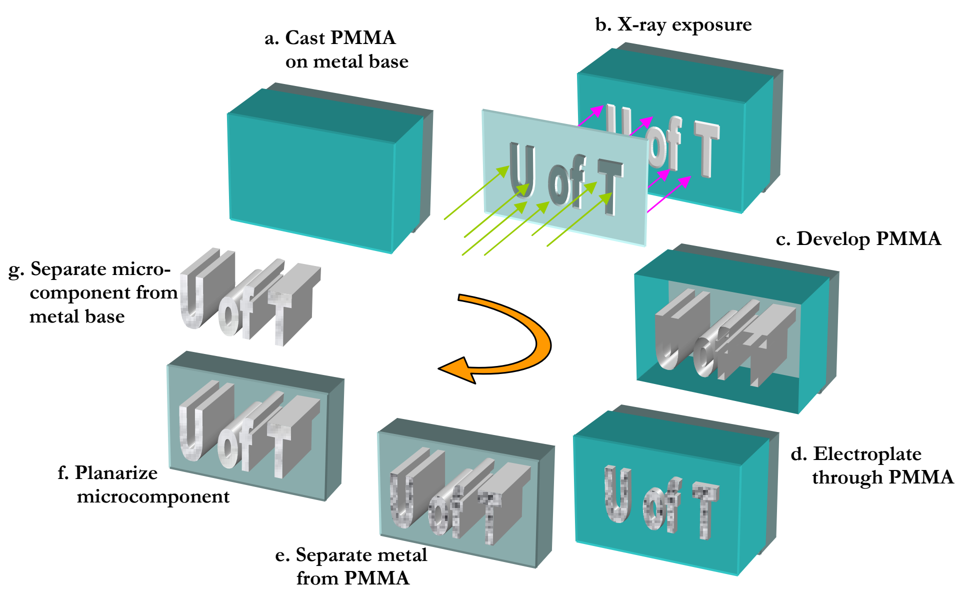


Figure 1 Schematic diagrams showing the various steps in a typical LIGA process; (a) PMMA cast on metal substrate , (b) X-ray exposure, (c) PMMA development, (d) electroplating through PMMA mold, (e) separating PMMA from plated component and substrate, (f) planarize microcomponent and (g) final product separates from substrate.

The process requires a polymer mold (e.g., PMMA) which is made by microlithography techniques (e.g., using synchrotron X-ray or UV irradiation). The developed mold then acts as a mask in the electroplating step, allowing only the exposed area(s) to be electroplated. The electroplated structure, when removed from the mold is the finished MEMS microcomponent. The advantage of LIGA is that structures can be made of almost any material that can be electroplated at relatively low stress levels. These include nickel (Ni), copper (Co), gold (Au), silver (Ag), cobalt (Co) as well as nickel alloys (typically Ni-Co and Ni-Fe), with nickel being the most commonly LIGA-processed material [2].

The development of LIGA processes for specific applications is not without challenges. Because the most important step in LIGA is based on electrodeposition, it is subjected to the same processing issues normally associated with electroplating practices. That is to say, the effect of processing parameters (such as bath composition and pH, operating temperature and current density, etc.) on the quality of the deposits directly translates to the degree of success of a specific LIGA process. However, hydrodynamic conditions in a mold cavity are quite different and much more difficult to control than for a conventional electroplating system.

In this paper, the microstructural deficiencies of currently available LIGA products are addressed, followed by an overview of what advantages nanocrystalline electrodeposits can offer to advance microsystem technologies. More specifically, materials property enhancements that are achievable as a result of having nanostructured MEMS components will be discussed along with the importance of property uniformity / microstructural integrity across the components. It should be noted that the results presented in this paper are from studies on electroplated nickel. Directionally similar results are expected for other metals used in MEMS, as already demonstrated for Co deposits [3].

Microstructural and Property Variations in Conventional Electrodeposits

Technical challenges with LIGA processes are numerous, and many of the performance / reliability problems can be attributed to the incommensurate scaling of microstructural features (i.e., grain size, grain shape, grain orientation) with the external dimensions of the components. It has been shown that many of the reliability and durability issues in electroplated microcomponents can be traced back to the microstructural evolution stages during the deposition process, leading to local property variations that point to a non-uniform structure within the material.

Figure 2 shows a cross-section of a nickel microcomponent prepared by conventional nickel electroplating technology. The grain structure changes from equiaxed fine grains to columnar having a high aspect ratio with the long axis in the growth direction. In other words, strong grain shape and size anisotropies exist within the deposit. This type of microstructure is one of the main drawbacks of LIGA products made by using conventional electroplating techniques, in particular when dealing with component and device sizes that are comparable to the size of the anisotropic (non-uniform) grains in the final product. Materials properties that are sensitive to grain orientation (e.g., elastic constants, thermal expansion, magnetostriction) would change from quasi-isotropic in the initial fine-grained deposit layer to being strongly anisotropic with increasing deposit thickness. Similarly, properties that depend strongly on grain size (e.g., hardness, strength, ductility, coercivity) will show considerable changes in a direction perpendicular to the substrate.

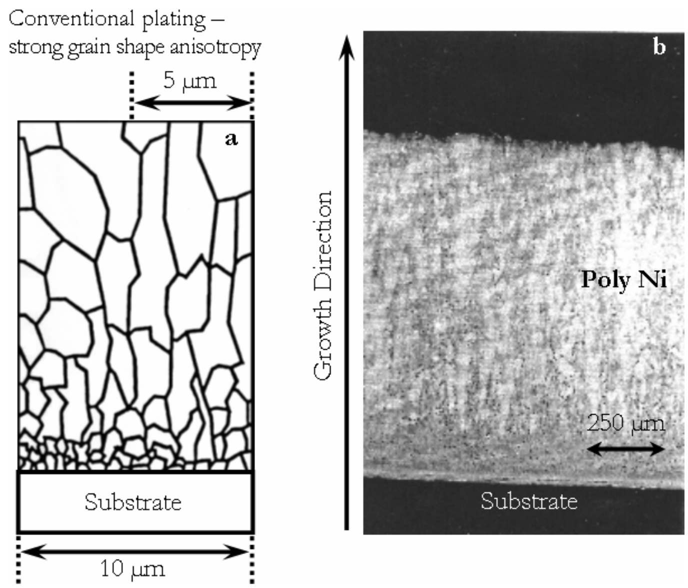
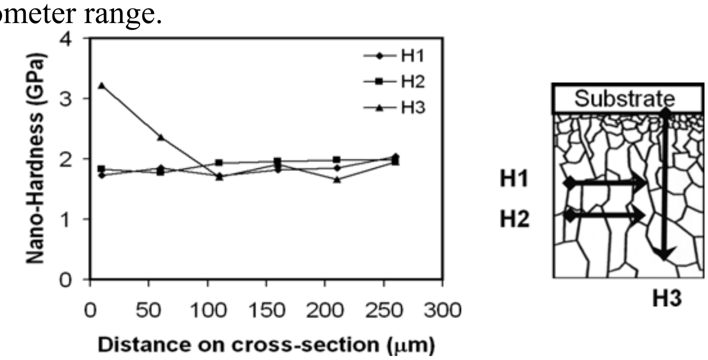


Figure 2 A microcomponent made of electroplated polycrystalline nickel produced by conventional electrodeposition: a) schematic cross-section of the columnar grain structure; b) actual cross-section [adopted from ref.4].

Figure 3 shows the results of nanoindentation measurements (nano-hardness and Young's modulus) performed on the cross-section of an electroplated nickel microcomponent produced by conventional means [4]. The results presented in this figure clearly show the inadequacy of such a microstructure. The properties depend on the location of the measurements and can show quite large variations. The hardness ranged from over 3GPa in the fine-grained region to less than 2GPa in the columnar grain section. The Young's modulus varied by a factor of more than 2 between the lowest and highest values (275GPa vs. 130GPa) depending on the local crystal orientation [3]. These observed non-uniformities present a serious issue in terms of device performance that must be addressed for the next generation of MEMS technology dealing with components in the micrometer range.



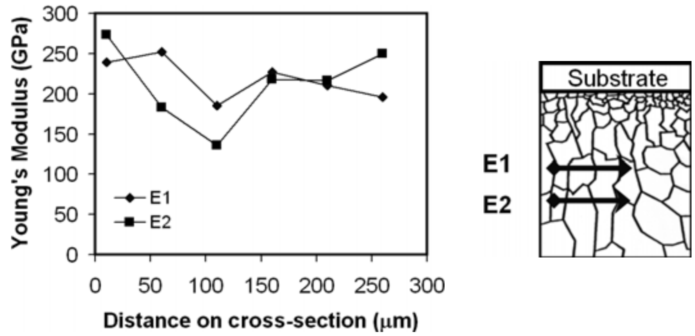


Figure 3 Cross-sectional hardness and Young's modulus for a nickel microcomponent produced by conventional electrodeposition showing non-uniformity across the component [adopted from ref.4].

Although efforts have been made to address and alleviate these concerns, primarily recognizing the importance of crystallographic texture and developing remedies such as post-deposition recrystallization annealing and crystallographic texture modifications during plating [5], success using these approaches has been rather limited.

Microstructure and Properties of Nanostructured Electrodeposits

The importance of average grain size and grain size distribution in the final LIGA products has not yet been fully recognized and addressed. This is the main focus of our research efforts in terms of advancing MEMS technology. In this approach, the problem of non-uniform grain size and shape is alleviated by reducing the grain size of the electrodeposit to the nanometer range – by means of a nano-electroplating process [6,7]. By this approach, fully dense nanostructured deposits can be produced with only minor modifications to existing electroplating processes. Figure 4 illustrates this principle. Figure 4a is a schematic diagram representing the nanometer-sized grains grown on a substrate with a very uniform grain size and shape distribution; Figure 4b is a cross-sectional transmission electron micrograph of an actual nano-electroplated nickel component. The nanostructure in the electrodeposit is established at the interface with the substrate and maintained throughout the entire thickness of the component.

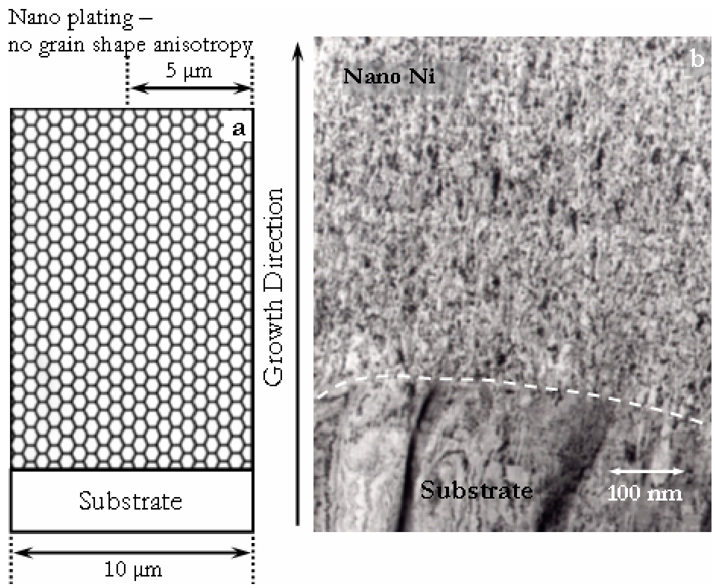


Figure 4 A microcomponent made of nanocrystalline nickel deposited onto polycrystalline phosphor bronze substrate by nano-electroplating: a) schematic cross-section showing uniform grain size and shape; b) actual cross-section [adopted from ref.4].

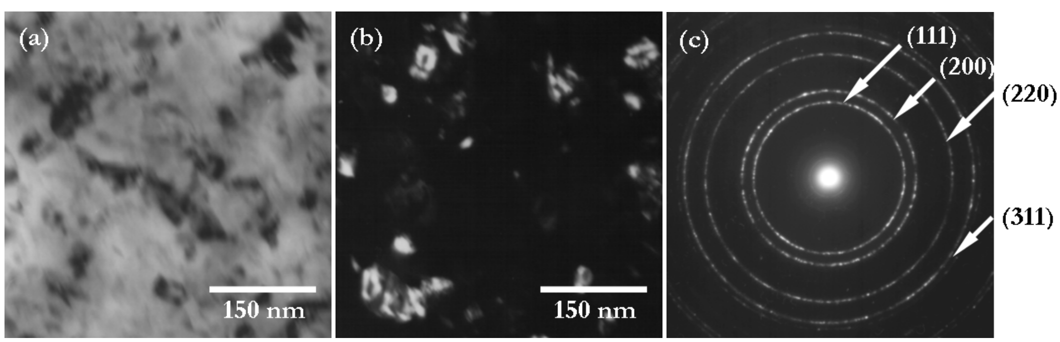


Figure 5 Electron micrographs: (a) brightfield; b) darkfield) and electron diffraction pattern of an electroplated nanocrystalline pure nickel (25nm grain size).

Figure 5 shows the brightfield (BF) and darkfield (DF) transmission electron micrographs as well as an electron diffraction pattern (DP) of the electroplated nanocrystalline pure nickel sample in planar cross-section parallel to the substrate. It can be seen from the BF and DF micrographs (Figures 5a and 5b) that the plated material exhibits an equiaxed microstructure also in planar cross-section. The continuous rings seen in the electron DP (Figure 5c) show clearly that this deposit has a true nanocrystalline structure, with individual grains being separated by large angle grain boundaries.

The same cross-sectional mechanical properties (i.e., nano-hardness and Young's modulus) of nano-electroplated microcomponent materials have also been assessed (see Figure 6). When examining these properties, two major improvements can be observed for nano-electroplated nickel. First, the local variations of hardness and Young's modulus seen in Figure 3 for conventional nickel are notably absent. There is no gradient in hardness in a direction perpendicular to the substrate, and the Young's modulus is relatively constant at a level of about 200GPa, the value for bulk nickel report in the literature [8]. Second, the overall hardness of the nano-plated component is considerably higher (> 6GPa) compared with the hardness of the conventional nickel (2 to 3GPa, depending on location in Figure 3). It is very encouraging to confirm that the uniform structure of nanocrystalline deposits indeed results in uniform and enhanced mechanical properties throughout the entire cross-section of the component. For the end user, nano-plating of MEMS components therefore minimizes the uncertainty regarding property variations in the final product.

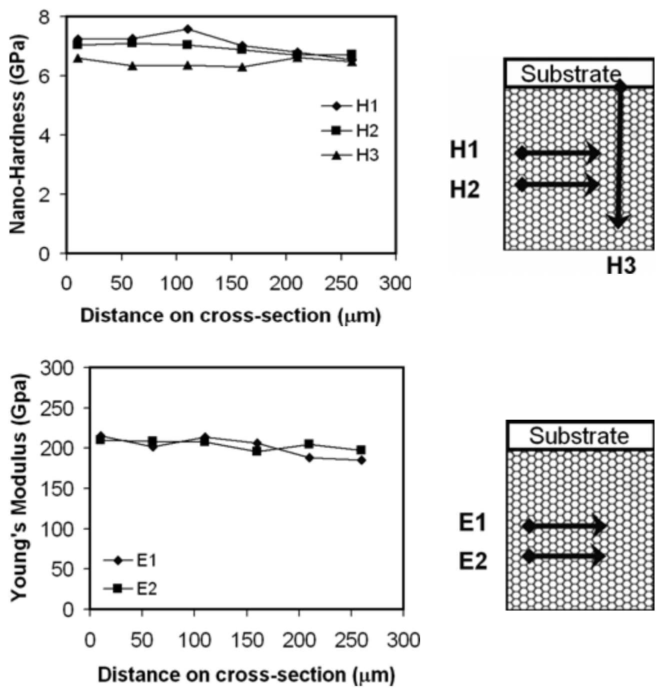


Figure 6 Cross-sectional nano-hardness and Young's modulus for a nickel microcomponent produced by nano-electroplating. Properties are relatively constant throughout the entire component [adopted from ref.4].

Effect of Grain Size on Properties of Nickel Electrodeposits

With the major issue of microstructural and property uniformity of nano-plated nickel addressed in the previous section, it is of interest to examine some of the other properties of nanocrystalline nickel that could be beneficial to applications in MEMS technology.

Properties Affected by Grain Size

Many properties have been shown to be strongly affected by the crystallite size of the material. For example, yield strength (σ_y), tensile strength (σ_{UTS}), hardness (H_V), tensile elongation (ε_f), wear rate (W) and coefficient of friction (□), coercivity (H_C) and corrosion potential (E_{CORR}) have all been shown to display very different property values for nanocrystalline materials as compared to conventional polycrystals [9]. When considering materials properties important to MEMS applications, these grain size effects can offer additional advantages. The following discussion will focus on some of the more important property enhancements achieved in electroplated nanostructures.

Figure 7 shows the microhardness (H_V) of electroplated nickel of various grain sizes (from 10µm down to 10nm). At a grain size of 10µm, the microhardness of conventional nickel is less than 200VHN. However, as grain size decreases, the hardness of the material increases as per the Hall-Patch relationship [10,11], reaching a hardness value that is over 300% that of the conventional material at a grain size of about 10nm.

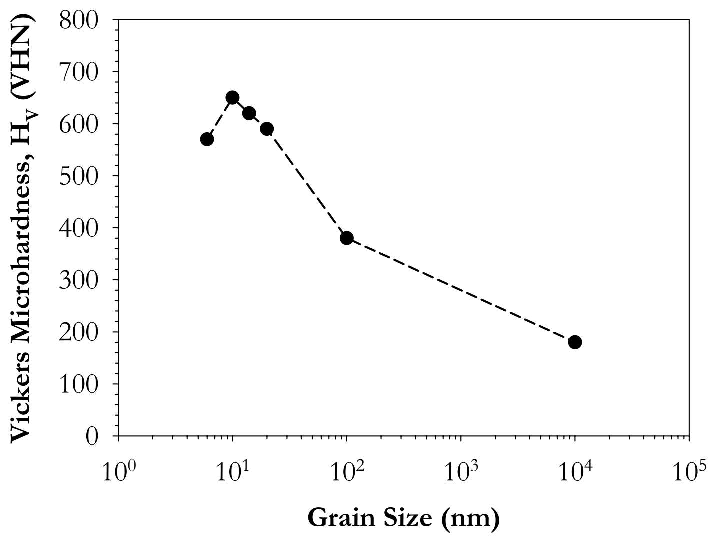


Figure 7 Vickers microhardness of electroplated nickel as a function of grain size showing a three-fold increase when grain size is reduced from 10µm to about 10 nm [9].

It should be pointed out that there is a deviation from the regular Hall-Patch relationship at the smallest grain sizes (< 10nm) for nano-electroplated nickel. The reasons for this deviation which is also observed in some nanocrystalline materials produced by other synthesis methods are still not completely understood. While various theories and models have been proposed, a detailed discussion of this effect is beyond the scope of this paper.

Figure 8 shows a similar grain-size dependence for the yield strength of nickel. The yield strength of conventional nickel, at a grain size of 10µm, is about 180MPa. It increases with decreasing grain size reaching a maximum value of > 900MPa at 10nm.

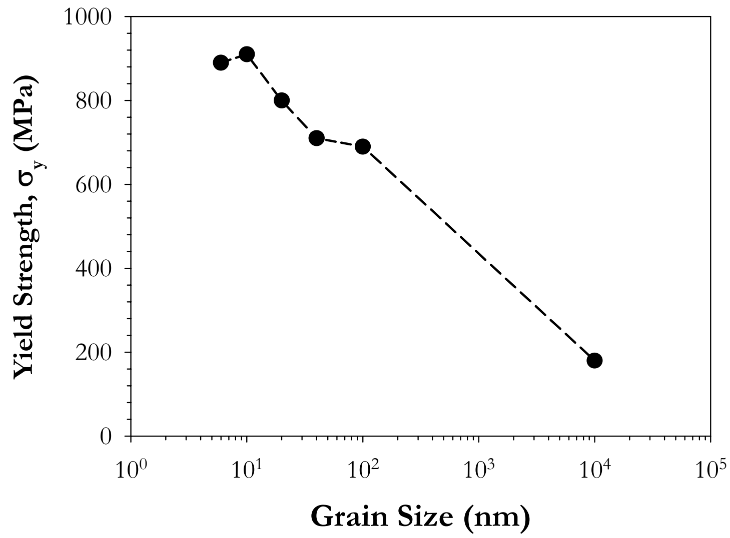


Figure 8 Yield strength of electroplated nickel as a function of grain size showing a five-fold increase when grain size is reduced from 10µm to about 10nm [9].

While hardness and yield strength are static mechanical properties, wear can be considered a kinetic property of particular importance for MEMS structures involving moving parts. In Figure 9, the sliding wear rate of nickel is presented as a function of grain size. As grain size decreases, the wear rate dropped substantially. The wear rate for a 10nm nano-electroplated nickel is less than 1% that for the conventional material at 10µm grain size.

Since grain boundaries and triple junctions contribute to the scattering of electrons, a nanostructured material is expected to have a much higher electrical resistivity simply because of the high population of these intercrystalline defects in the structure. For example, at a grain size of 10nm, and assuming a grain boundary width of 1nm as proposed in a recent geometrical model [12], the fraction of atoms that are located either at the grain boundaries or triple junction is over 30%. In other words, about one-third of the entire material consists of interfacial defects.

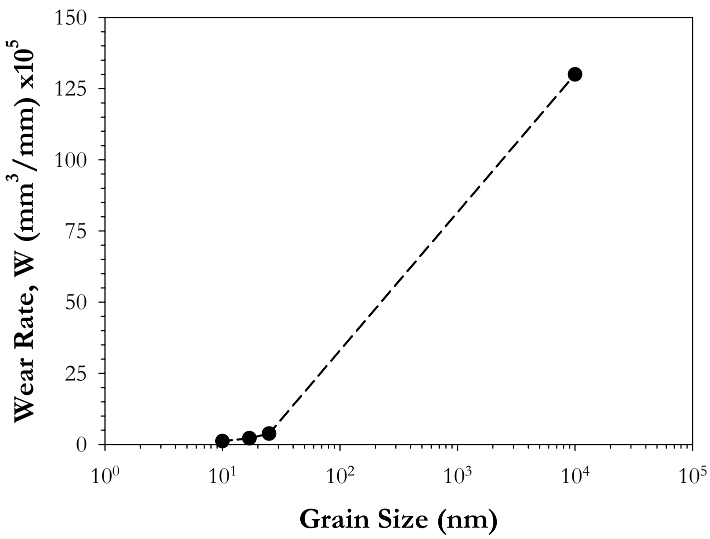


Figure 9 Sliding wear rate of electroplated nickel as a function of grain size; 10nm nano-electroplated nickel showing less than 1% of the wear rate of 10µm conventional nickel [9].

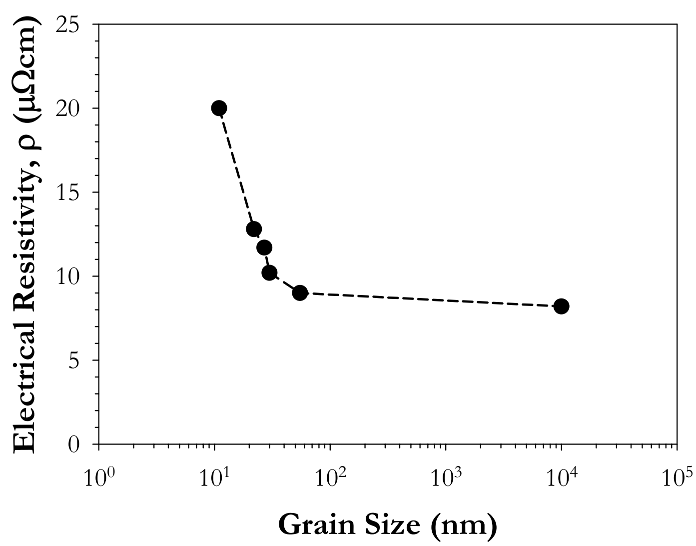


Figure 10 Room temperature electrical resistivity of nickel as a function of grain size, showing strong grain size dependence below 100nm [9].

Electrical resistivity measurements were performed on electrodeposited nickel with various grain sizes. As seen in Figure 10 for nano-electroplated nickel, the room temperature electrical resistivity is increased by about 250% for a material having a grain size of 10nm ($\rho \approx 20\mu\Omega cm$) when compared with conventional nickel with a grain size of about 10µm ($\rho \approx 8\mu\Omega cm$).

Grain Size Independent Properties

There are several properties of electroplated nickel that are not or very little affected by grain size including heat capacity (C_P), saturation magnetization (M_S), thermal expansion coefficient (α) and Young's modulus (E) [9]. The following discussion will be limited to the most important properties considered in the material selection for MEMS applications.

The published value of Young's modulus (E) for pure polycrystalline nickel is about 207GPa [8]. In Figure 11, Young's modulus measurements for electrodeposited nickel are plotted as a function of grain size from 10µm to less than 10nm. The value for the large-grained sample agrees very well with the published value. The graph shows that Young's modulus is essentially independent of grain size.

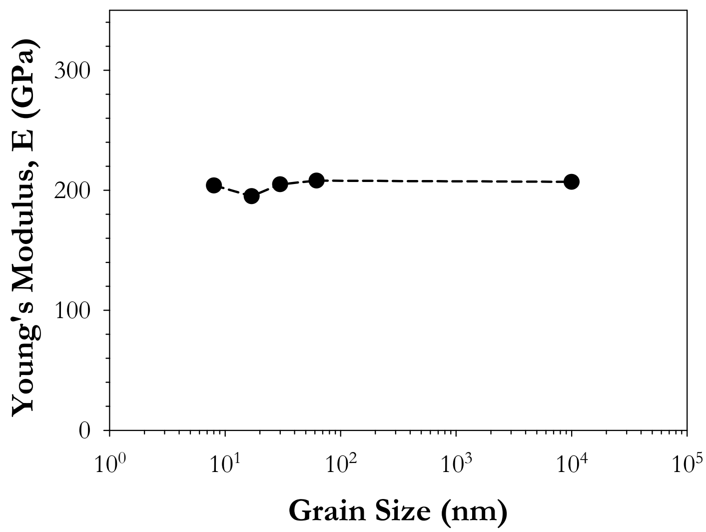


Figure 11 *Young's modulus of nickel as a function of grain size* [9].

Another property that is not strongly affected by an ultra-fine grain structure is the thermal expansion coefficient, α. Figure 12 shows that, compared with the thermal expansion coefficient of nickel at 10µm grain size, nickel with a 10nm grain size shows only a few percent (≈ 3.5%) reduction.

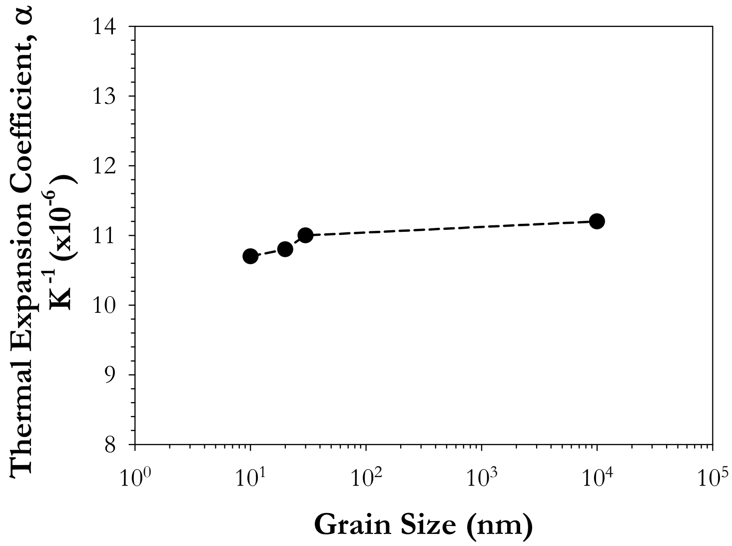


Figure 12 *Weak grain size dependence for the thermal expansion coefficient of nickel* [9].

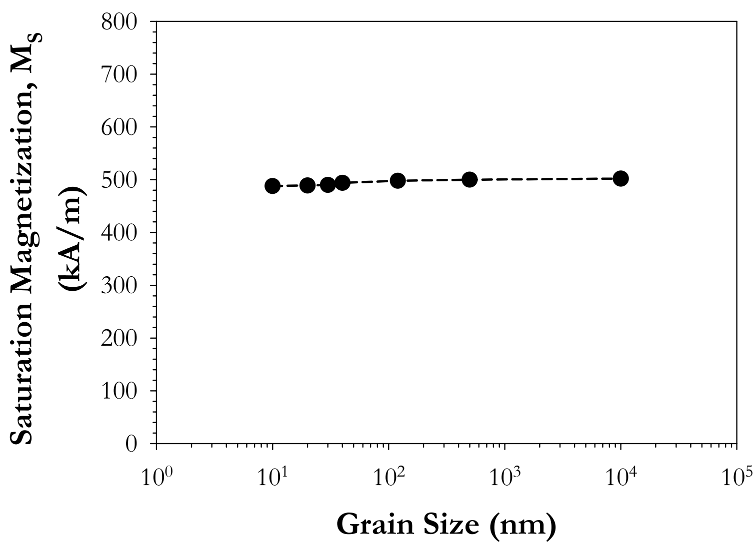


Figure 13 *Saturation magnetization of electrodeposited nickel showing no significant grain size dependence*[9].

One of the earliest studies on the saturation magnetization (M_S) of nanocrystalline nickel (< 20nm grain size) prepared by the inert gas condensation technique found a 40% reduction in M_S compared to conventional nickel [13]. This unfavourable result initially caused some concerns in terms of full functionality of nanocrystalline materials in magnetic applications. However, this drastic decrease in saturation magnetization was later attributed to residual porosity resulting from this particular processing method. When fully-dense nano-electroplated nickel was examined, it was found that the saturation magnetization is not strongly affected by grain size [14]. Figure 13 shows this result; the saturation magnetization for pure nickel remained the same throughout the entire grain size range examined (from 10µm to about 10nm). For MEMS components requiring soft magnetic materials, this result is of significant importance.

Performance Enhancement by Grain Size Reduction

In addition to offering a fundamental solution to eliminate unacceptable property variations in MEMS components, electroplated nanostructures exhibit inherent property enhancements that are beneficial in the final application of MEMS devices. Given the information available on property enhancements for nano-electroplated nickel presented above, one can assess performance improvements that can be expected from nanostructured MEMS components. In this section, some important performance indicators for microcomponents will be explored using an Ashby-type approach [15].

With the ever-shrinking dimensions of MEMS structures, the strength of miniature components becomes increasingly important. As seen in Figure 8, the yield strength of nanostructured nickel (at a grain size of 10nm) was increased by a factor of 5 over that of a large-grained nickel material (10µm). This structurally superior material is able to withstand much more stringent loading conditions than what can be tolerated with conventional materials. From a deformation mechanism point of view, the advantage of nanostructured materials is enormous when considering components with very small external dimensions as indicated in Figures 3 and 4, for example, for a hypothetical component with a width of 5µm. For such as small component, the width approaches the grain size of conventional nickel (see Figure 3). Therefore, there are very few grain boundaries in the cross-section of such a component which could prevent dislocation motion, resulting in a rapid loss of strength. On the other hand, for a nanocrystalline component with the same external size (see Figure 4), there are still hundreds of grain boundaries in cross-section to maintain the strength level of the system.

Other materials properties that are dependent on the yield strength will also benefit from this substantial increase in the yield strength. For example, resilience, R (or elastic energy storage capacity), is one of the properties that depend on both yield strength and Young's modulus: $R = \sigma_y^2/2E$. It is one of the most important properties in components such as micro-springs and levers. With the improved yield strength, nano-nickel can store much more elastic energy than conventional materials. Figure 14 shows the resilience of nickel as a function of grain size, normalized with respect to the value obtained for a 10µm nickel material. Simply by reducing the grain size to 10nm and keeping all other factors constant, the resilience of nickel is enhanced by a factor of 25 over that of conventional material.

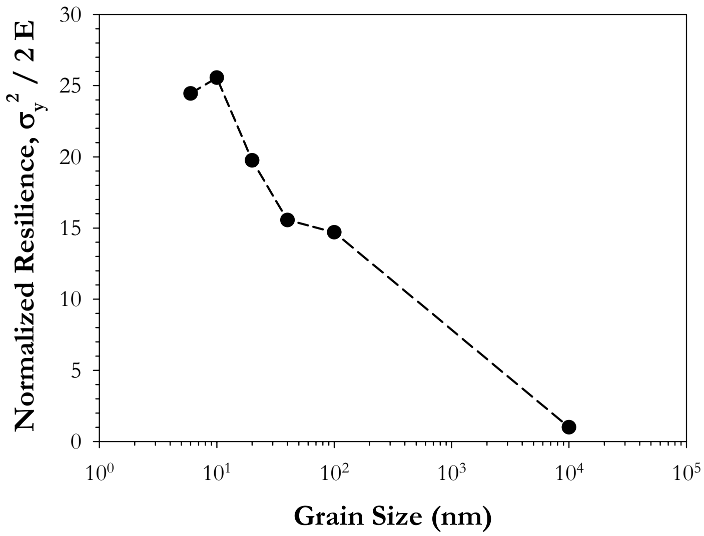


Figure 14 Resilience of nickel as a function of grain size (normalized to value at 10µm grain size).

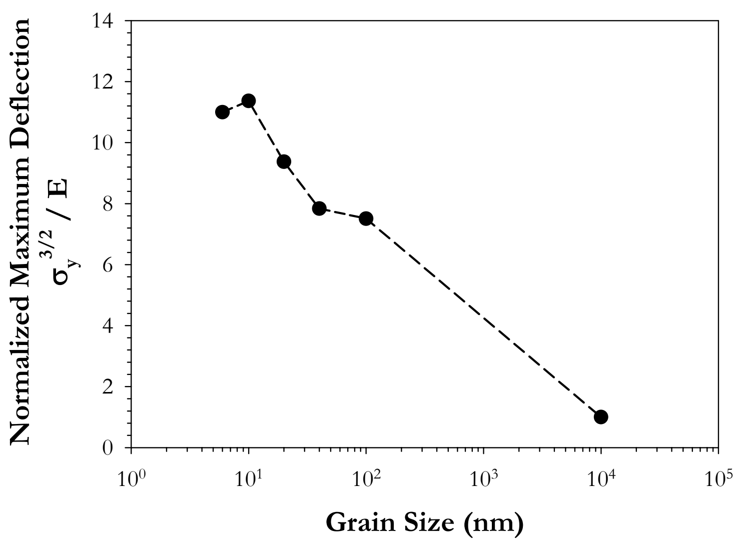


Figure 15 Flexural Strength of nickel as a function of grain size (normalized to value at 10µm grain size).

Similarly, for diaphragm or membrane type applications, the maximum deflection under a specific pressure before fracture occurs also depends on yield strength and Young's modulus. In this case, the performance indicator of importance is $M = \sigma_y^{3/2}/E$, with maximum deflection being proportional to M. Figure 15 shows M of nickel as a function of grain size. As seen in this figure, the maximum deflection attainable for a nano-electroplated nickel is almost 12 times higher than for conventional nickel material.

From the performance enhancement seen in hardness, resilience and maximum deflection for a specific pressure, microcomponents such as micro-springs, levers or diaphragms can operate at a higher load levels and more demanding conditions without failure. Conversely, when designing a MEMS device using nano-electroplated nickel, the same specifications can be met with a smaller component, which would create more real estate for other components / devices on a platform where space is a premium.

Another enhancement that has been observed for nano-electroplated nickel is the sliding wear characteristics, with sliding wear resistance being the reciprocal of sliding wear (1/W). The sliding wear resistance of nickel is plotted as a function of grain size, normalized to the value obtained for the 10µm material (see Figure 16). For nano-electroplated nickel at 10nm grain size, the sliding wear resistance increases by more than 100 times. With this magnitude of improvement, the life of the microcomponents will be considerably prolonged. In other words, dimensional degradation due to wear of the already small microcomponents will be greatly reduced.

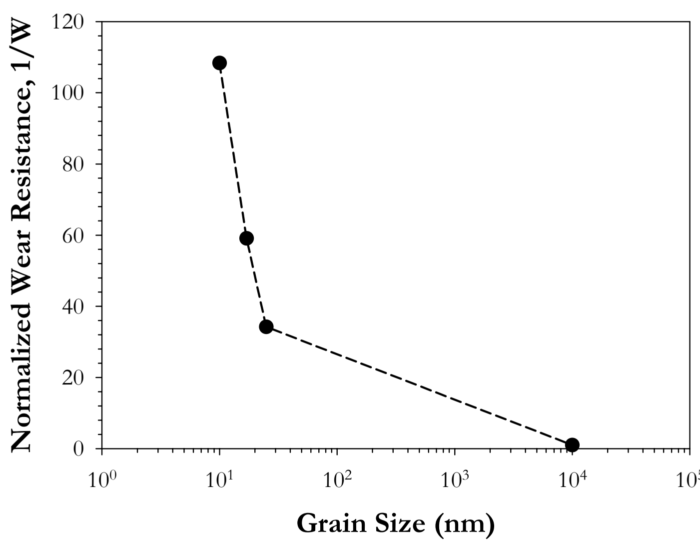


Figure 16 Sliding wear resistance of nickel as a function of grain size (normalized to the value at 10µm grain size).

Energy losses due to eddy currents can lead to diminished efficiency of an electromagnetic component / device. A material having a higher electrical resistivity (ρ) reduces eddy current losses (which are proportional to $1/\rho^2$) and improves overall energy conversion efficiency. This property is particularly important in high frequency applications. In conventional materials, higher resistivities are usually achieved by incorporating solute elements into the material by design. However, magnetic properties that are sensitive to solute additions (e.g., saturation magnetization, magnetostriction and coercivity) are often compromised in this approach. In light of this, the ideal solution would be to have a material with an inherently higher electrical resistivity without the need for changing its composition. From the enhanced electrical resisitivity seen for nano-electroplated nickel (see Figure 10), nominal energy losses can be estimated. Figure 17 is the energy loss through eddy currents as a function of grain size for nickel, normalized with respect to conventional nickel with 10μm grain size. The nano-electroplated nickel exhibits a loss that is less than 20% of that of the conventional material. This provides for more efficient devices and the amount of work that can be expected from a device will be improved compared with those made of conventional materials. Furthermore, as the energy loss translates to heat, the size of heat sinks can be reduced and requirements in thermal conditioning and device environmental control can be relaxed considerably.

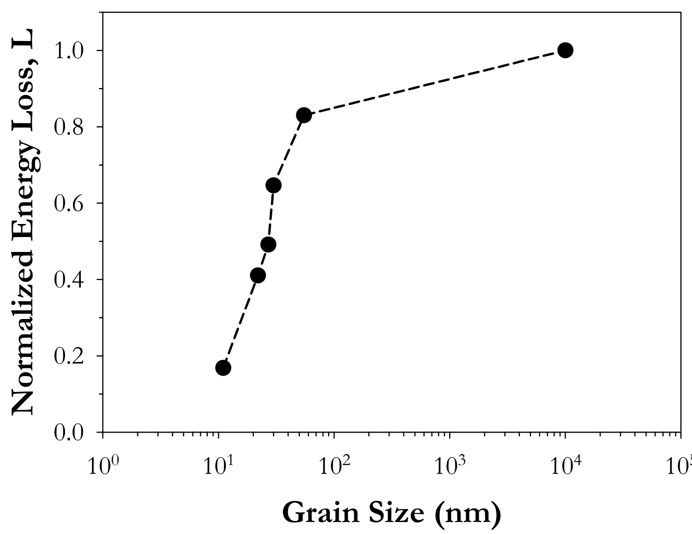


Figure 17 Energy loss due to eddy currents as a function of grain size (normalized to value at 10μm grain size).

Summary

Although MEMS technology has greatly advanced in recent years, there are still several technical problems associated with LIGA-processed materials. The non-uniformities in microstructure observed across conventional LIGA microcomponents result in considerable local property variations that must be addressed, as they become intolerable with the ever-decreasing size and dimensions of the microcomponents.

We have presented a new approach to electroplating-based MEMS technology by which proper microstructure scaling is taken into consideration to ensure materials property stability and microstructural integrity throughout the microcomponents. By nano-electroplating, no point-to-point property variations in cross-sections of nickel microcomponents were eliminated. Through nano-electroplating, many materials properties are significantly improved, including hardness, yield strength and wear resistance. Moreover, when compared to conventionally prepared materials, nano-electroplated nickel is over 25 times more resilient, 12 times higher in maximum deflection, over 100 times more wear resisitant and exhibits 80% less energy loss due to eddy currents. From this nanostructured materials platform, the next generation of performance enhanced MEMS components and devices can be developed.

Acknowledgements

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Development of Stable Baths for Electroplating

CoFe and CoFeNi Soft Magnetic Thin Films

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Conventional low pH (2.3-3.5) baths, for the electrodeposition of CoFe and CoFeNi thin films, suffer from stability problems. In addition, voids can form in the deposits due to the electroplating of hydrogen. New, more stable baths with relatively high pH levels have been developed by introducing a stabilizer. The effects of stabilizer dosage, bath Co/Fe concentration ratios and plating temperature on the deposition of CoFe and CoFeNi thin films have been investigated. CoFe and CoFeNi thin films with good magnetic properties have been plated out from the newly developed plating baths.

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CHAPTER 10.

SUMMARY.

Having listened to all the speakers, and read some relevant literature, here is a summary. And an attempt to answer some of the questions raised at the start of the programme.

1. History.

Dr. Richard Feynman, a Nobel Prize winner, challenged the scientific community with his talk ***There's Plenty of Room at the Bottom*** given at a meeting of the American Physical Society at CALTEC in December 1959. He pointed out that miniaturization had made it possible to write the Lord's Prayer on the head of a pin. But if you arranged atoms like the dots of a dot-matrix printer then the whole of the Encyclopedia Britannica could be placed on the head of a pin. And biologists know that it only needs about 50 atoms in a DNA molecule to store all the information about a cell. So it should be possible to store enormous amounts of data at the atomic level.

Feynman said that he was not afraid to consider that we can arrange atoms. Ultimately we should be able to arrange atoms to form the molecules we want. He saw the prospect of developing mechanisms out of atoms. These mechanisms could in turn be formed into small factories.

He also saw the prospect of increasing the speed and reducing the size of computers. His paper is available in book form as well as on the Internet, and is well worth reading nearly half a century latter (1).

In the 1980's Eric Drexler took up Feynmann's challenge. Based on his doctorate from MIT he published a book ***Nanosystems; molecular machinery, manufacture and computation*** in 1992. His work brought the word **nanotechnology** into general use, although Tokyo Prof. Norio Tanigushi had coined the word in 1974.

Drexler promotes the concept that nanoassemblers can produce material by assembling it atom-by-atom. Factories of assemblers could produce material endlessly – and even replicate themselves. This led to the idea of 'grey-goo'. A concept that latter started to scare people, and resulted in him having to explain that 'grey-goo' is unlikely to ever exist. Dr. Drexler founded the *Foresight Institute* (2), which promotes nanotechnology and molecular manufacturing.

Key to the development of nanoscience and nanotechnology is the development of microscopes – giving the ability to observe, and work at the nanoscale. Ernst Ruska and Max Knoll at the Technical College, Berlin developed the first electron microscope in 1931. Based on work on the topografiner at the US National Bureau of Standards in the late 1960's, Gerd Binning and Heinrich Rohrer developed the Scanning Tunneling Microscope (STM) in IBM's Zurich labs in 1981. In 1986, IBM researchers Gerd Binning, Calvin Quate and Christoph Gerber invented the Atomic Force Microscope (AFM). In the same year Ruska, Binning and Rohrer were awarded the Nobel Prize for their work. This development of microscopes moved from optical microscopes that just looked at the surface, to electron microscopes which in some types scanned, or felt their way to map the molecular surface. And some can also position atoms, one at a time. Utilising piezoelectric effects achieves measurements and accurate positioning. A measurable electric field across a crystal can create a controlled movement in the nanometric range.

A Nobel Prize has also been awarded to Sir Harold Kroto (University of Sussex), Robert Curl and Richard Smalley (Rice University) for the invention of ***buckyballs*** in 1985 (3). The US National Science Foundation called buckyballs the ***biggest chemical discovery since benzene in 1825.***

Sumio Iijima first created ***nanotubes*** at NEC in 1991 (4).

2. Nanoscience and nanotechnology defined.

Most of our lecturers have tabled their definition of nanoscience and nanotechnology. Most had several parts to the definition, with the one common theme being that of length between around 100 nanometre (nm) down to a fraction of 1nm. Dr. Sagman pointed out that there is a whole world smaller than nano – the pico-metric size. In fact one can go even smaller. The nucleus of a carbon atom is only a millionth of a nanometre, and that is formed of protons and neutrons. And even they are formed of quarks – so far the smallest item know to scientists.

Rather than stumble over a defined size, many are opting for a definition along the lines – ***Working at the molecular level to create and use material, structures and systems having novel properties.*** It sounds fine but begs the question 'What is novel?'

At the nanoscale Brownian motion, van de Waals attraction and quantum mechanics can dominate; rather than traditional Newtonian mechanics. This difference is probably the most significant, and differentiates nanotechnology from traditional engineering as we know it today.

3. Is nanoscience new?

Soot, whether from candles or diesel engines has been around for a long time and is in the nanometric size range. The ancient Chinese and Egyptians found a way of keeping nanosized soot in suspension by adding a natural polymer, gum arabic to form Indian ink. (16)

Medieval artisans found that adding some forms of gold and silver powders to melting glass could create brilliant stained glass in a variety of colours like green, orange, yellow and blue. What they were doing was creating a finely dispersed array of quantum dots of the precious metals in the cooling process of the viscous glass.

Chemists have been dealing at the molecular and atomic level for over a century. Kodak has been using nanosized particles in colour film since the 1920's.

DNA at the nanoscale has been studied for half a century in the biological and medical field. And nuclear physicists have been working with nanoscale atoms and sub-nanoscale particles for decades. Computer chipmakers have been producing at the nanoscale for some years.

Probably the largest field of nanoscience is cell biology. All living things, including us, starts at the nanometric level. Living cells contain molecules, proteins and DNA – all at the nanometric scale.

Those in the polymer chemistry field, film industry and the computer chip makers are unlikely to rename themselves as being in the nanoindustry – no more than we are going to say we are 'nanobodies'!

4. What is the nanoindustry?

A comparison with the 'computer industry' will help answer this question. The computer industry can be considered the sum of the chipmakers like Intel, the hardware suppliers like IBM and DELL, and the software companies like Microsoft and Adobe. But there is another huge section of industry that is involved with computers – the aerospace industry is dependent on computer technology, as is medical equipment, and even the traditional auto industry puts computers in every car. And we all have our PC's. Similarly the nanoindustry has makers of nanomaterials and nanoinstrumentation. But there is already a large section of traditional business that is heavily into nanotechnology. They are unlikely to rename themselves. Nanotechnology, like computers, is an enabling technology that crosses traditional definitions - as well as being used by existing industries.

5. Where will nanoindustry locate?

Once again the comparison with the computer industry helps. Will the nanoindustry have its 'Silicon Valley', and will all the manufacturing be in Asia? The industry is at too early a stage to make predictions. But every government of developed and developing countries is keen to fund nanotechnology R&D so that it will not to be left behind.

6. What is being spent on nano R&D?

The highest funding for nanoscience and technology is in the USA, followed by Japan and Europe – with China and other Asian countries not far behind. President Clinton announced the National Nanotechnology

Initiative (NNI) in 2000. In 2003 President Bush signed a Nanotechnology R&D Act. For 2004, the funding for these two initiatives was $847M for NNI and $645M from the R&D Act – giving a total Federal funding of nearly $1¼B. Of this funding $597M is to be spent by the National Science Foundation, $394M by the Department of Energy, $222 by the Department of Defense and $62M by NASA. In addition, around $¼B has been committed by various State Governments. Industry funding numbers are difficult to obtain, but are thought to be similar to government funding. Venture capital funding is a very small percentage of the total at this stage.

Europe and Japan have each committed around $1B, some of which covers several years work.

Canada has established a $120M National Institute of Nanotechnology (NINT) in Edmonton as a joint venture between NRC and the University of Alberta (5). Most large Canadian Universities have some nanoscience or nanotechnology activity.

In total about $8B per year is now being spent around the World on nanoscience and nanotechnology. In general the justification for this funding is the expectation of solid commercial returns in the not too distant future. So some signs of commercialization will be necessary to keep the R&D funding flowing.

7. The debate on direction – Drexler vs Smalley.

Eric Drexler argues that the NNI, and most other worldwide nanoinitiatives have lost direction – they are not funding work on nanomachinery and nanoassemblers. He claims that Richard Smalley has had too much influence over the direction of national R&D spending. Smalley argues that nanoassemblers are not possible, as forces at the nano level will prevent man from being able to assemble atoms as he wants. The ***you can/you can't*** debate has been going on for some time (6). Producing neat computer renderings of nanomechanisms does not resolve the debate. What is needed are some solid research results. Maybe some indication is coming from work by David Leigh and his team at Edinburgh University. They have created a 'molecular motor' consisting of a small chemical ring locked onto a larger ring. Depending on the chemical reaction, the direction in which the small ring drives around the large ring can be changed (7). Despite this remarkable development, the direction of nanotechnology research seems to be focused on more immediate commercial applications. It should be pointed out that the Edinburgh researchers did not assemble their motor by mechanically placing atoms one at a time.

But nanomachinery is very appealing for mechanical engineers. The idea of building machinery from the atom up, rather than the traditional method of carving away large quantities of material, is attractive.

Miniaturization to date has been limited by the ability to manufacture accurately at small scale. The idea of assembling atom-by-atom removes this problem. A gear with 100 atoms for teeth is accurate – you can count whether there are 100 teeth and not 99 or 101. But liking the concept does not solve the problem of manipulating atoms in the world of quantum forces and Brownian motion.

8. The problems engineers can face in the 'nano world'.

Richard Jones has captured the problems for engineers with a simple analogy - trying to assemble a nano bicycle. First the larger components such as frame and wheels, if made of chains of single atoms will have little stiffness and be floppy. Then Brownian motion will hamper the task of assembly. Everything will be jostled. It will be like trying to thread a needle while standing in a crowded bus while it is going along a bumpy road. Then all the other components like the nuts and bolts, having a large surface area to volume will be attracted to each other by electrostatic forces – van de Waals attraction. This will make them coagulate into a sticky mass.

This analogy might make it sound as though nanoassembly will not be possible. Prof. Jones cautions against jumping to this conclusion. He sees it as an opportunity to learn how to handle another set of forces and condition outside our usual realm.

9. What is the potential of nanotechnology?

This is the $T question. Are the predictions for a $1T nanomarket by 2015 all hype? Is it the technology of the 21st century? Is it still years away? The comparison with the computer revolution is once again useful. Remember the early predictions that only a few computers would be needed! And the question ***Why do we need to continually push for faster chips and higher density chips?***

Investment gurus are trying to persuade clients to look for the embryonic equivalent of Microsoft within emerging nanocompanies.

Our lecturers have given us some clues on the future potential – all are optimistic about a large future for nanotechnology. It seems probable that nanotechnology can be as dramatic as the computer revolution. But there is still a lot of hype – hype on some ideas that will never get to market. The market will only support products that either are cheaper and better than current products, or have some new feature that customers are prepared to buy. This later reason is so difficult to predict. Just look at past developments – did we know we needed laptops that we can use anywhere, and cell phones with photographic capability?

The US National Science Foundation has predicted a $1T world market for nanotechnology by 2015 with a possible spread from $½T to $2T. They predict the $1T market will be 31% materials, 28% electronics, 17%

pharmaceuticals, 9% chemical manufacturing, 6% aerospace and 9% others. Lots of questions on the potential for nanotechnology are raised and answered in a slide show by Sean Murdock of Atomworks in 2002 (8).

A recent report ***Nanotubes for the Energy Market*** (9) says that carbon nanofibres are already in 50% of all lithium batteries, because they double their energy capacity. Multiwalled nanotubes can enable a 10-fold improvement in fuel cells. As prices drop over the next 5 years, they will be used in 70% of all fuel cells – and will probably be the technological development that will really start the fuel cell industry (after years of plodding progress). CNT prices will decrease by a factor of 10 to 100 in the next 5 years. Production will shift from the US and Japan to other parts of Asia. Korea will probably be the major supplier of nanotubes by 2010.

It is tempting to list all the interesting products based on nanotechnology, but there are many excellent summaries by others. Also our speakers already listed many promising developments. A summary of nanotechnology produced for the European Commission (10) covers the whole waterfront – with a certain degree of hype (it is on this CD). The German Association of Engineers produced it, so it has pedigree! Another extensive and more sober summary is in the report ***Nanoscience and nanotechnologies: opportunities and uncertainties*** (11) produced jointly by the Royal Society and Royal Academy of Engineering.

Some reports tend to say that nanotechnology has yet to show its promise, and may be years away. Clearly the authors have not been seeing how much nanotechnology is already in the marketplace – in sunscreen creams, car parts, and clothing in every department store. Others say that the big developments will be in medical applications. Yes – Chapter 7 introduced us to the big advances probable in that field, but nanotechnology is almost certain to affect many applications. Whilst a lot has been said about advances in monitoring and measurement in the medical field, it is likely that similar changes can enter the engineering field, which could be transformed by better monitoring and instrumentation.

10. The Science Fiction side of nanotechnology.

We mentioned ‘Grey-goo’ in section 1, and in chapter 7 Dr. Marcotte explained how ‘nanobots’ are the science fiction side of nanomedicine. But it is such an intriguing subject that it attracts science fiction writers. Michael Crichton, the author of ***Jurassic Park,*** has written another science fiction novel ***Prey*** based on the idea that a self-reproducing swarm of nanoparticles escaped from a laboratory. While he acknowledges that the book is science fiction, in the introduction he questions how this new technology should be controlled. He points out that its reckless pursuit could produce dire consequences. One of the problems with science fiction writers is that so many of their fictional ideas have eventually become reality. Just re-read Jules Verne! So it is not surprising that the public might believe in science fiction – and be concerned.

11. Concerns – Royal and otherwise.

Separating science fiction from probable reality is difficult for the general public – and for many in the science and engineering communities. As a result it is easy to start emotional fear. An Ottawa based social advocacy foundation, ETC produced an 84 page report early in 2003 called ***The Big Down.*** (12) They comment, *the realm of nanoscience is utterly unimaginable to most of us.* Nevertheless they say that there are so many concerns with nanoscience that there should be a moratorium on all nanoscience work. They show their colours when they say that history suggests that *in recent decades we have witnessed the privatization of science and a staggering concentration of power in the hands of giant multinational companies. In more distant past, industrial revolutions have, at least initially, increased poverty.* Should we heed such concerns? It is too easy to quickly dismiss their work – recall the issues with DDT, irradiated foods and genetically modified (GM) foods.

In 2003 Prince Charles added to the concern he has with genetically modified foods by worrying whether nanotechnology will be used wisely. It is said that he or his staff had read ***The Big Down***. He asked the Royal Society to help weigh the risks.

In a similar vein the Astronomer Royal, Sir Martin Rees, has written a book ***Our Final Century*** in which he sees that the risks from uncontrolled virus, environmental disaster and 'grey-goo' could reduce the chance of civilization surviving the 21^{st} century to 50:50.

Whilst only the ETC report is mentioned, a quick Internet survey will show a lot of people expressing concern over nanotechnology development. A common question is ***Are nanotubes as hazardous as asbestos?*** A summary of papers expressing concern is in reference (13). Interestingly, risk issues were hardly raised at any of our lectures - although it was raised briefly at the end of Prof. Uwe Erb's summary lecture. It appears that those for nanotechnology, and those against, are already well polarised – and there seems to be little dialogue between the two cultures.

Many asking for caution subscribe to the ***precautionary principle*** – to not advance without knowing the risk. At face value it is an attractive concept – but scientific advances are by nature explorations into the unknown and therefore it is not easy to quantify the risks. What is required is a prudent plan of development that is coupled with work to establish the potential hazards.

A well described prudent plan was outlined to the US House of Representatives in April 2003 by Ray Kurzweil, an eminent computer scientist and futurist from MIT. Kurzweil is seen by some as controversial, because of his predictions on Artificial Intelligence and the ability of computers to overtake human thinking. Despite the controversy he has a good track record with his predictions. His views on the social implications of nanotechnology (14) are well worth reading and have been included on this CD.

Another good paper ***"Nanotechnologies: Risks and Rewards"*** (15) a Cientifica White Paper by Tim Harper and Andrew Dunn discusses the societal and business issues involved in the technology (In fact this paper has more general relevance as it effectively reviews the risk facing any business working in a new technology.)

12. The UK Government asks for the views from RS and RAEng

In June 2003 the UK Government asked the Royal Society together with the Royal Academy of Engineering to ***carry out an independent study of likely developments and whether nanotechnology raises or is likely to raise new ethical, health and safety or social issues not covered by current regulation.*** An extensive and informative web site (11) includes submissions from over 80 interested parties as well as the final report. Some of the key issues they debated were:-

- *Is there a lack of public input into new technology and therefore a lack of control?*
- *Should technical change slow down to keep pace with public determination?*
- *Should technology be imposed on the public?*
- *Should the power of new technology be with private enterprise?*
- *Should control be with Government or the private sector?*
- *Should there be an international convention for evaluating new technologies?*
- *How important is the media in determining public attitude?*
- *Does polarisation lead to a lack of rational debate?*

They reported that it is difficult to predict the direction a technology will take. Predicting what will trigger social and ethical concerns is even more difficult. And these days public attitude can play a crucial role in realising, or not, the potential of new technological advances.

Their final report was published in July 2004 and has 21 recommendations. These can be summarised as recommending prudent controls and regulations but with no draconian laws imposed, nor any halt to R&D or application of the technology. The Government should monitor the industry and ensure adequate funding for health and safety research that will keep pace with other developments. One recommendation was for ongoing dialogue with the general public. This was also one of the reasons for setting up our nano lecture programme. The better informed the engineering community is, then the more likely that members will feel comfortable with entering the public debate and help avoid polarization. And in turn this will reduce the chance of fear dominating decisions – and fear delaying decisions that could benefit society.

13. Sources for further study and useful links.

The lectures were all interesting and informative. However a full understanding needs a broader background in science than is typical in an engineer's education, particularly in chemistry, biology and quantum physics. A good start is a book written in layman's language by Richard Jones called ***Soft Machines: nanotechnology and life.*** (16)

We had support from the Canadian NanoBusiness Alliance in organizing the lectures. Their web site (17) has a lot of information, including links to Canadian organizations working in nanotechnology.

ASME has established a Nanotechnology Institute (18) where they list current nanotechnology meetings. They have introduced an interesting concept – a ***nanotechnology boot camp***, where you can get a 4 day intensive introduction to nanotechnology.

IBM has been very prominent in the development of nanoscience, particularly with their work on microscopes. Some of their work is displayed on the IBM research web site (19).

We did not get any reference to the impact of nanotechnology on the civil engineering and construction industry during our lectures. However a UK organization - New Construction Research and Innovation Strategy Panel (nCRISP) has an interesting report (20) ***The Emperor's New Coating; new dimensions for the built environment, the nanotechnology revolution.*** This paper lists the potential impact of nanotechnology on the Civil Engineering field. Major impact might be in special concrete and new surface coatings.

The UK plans for nanotechnology are explained in a Government DTI report (21) ***New Dimensions for Manufacturing: A UK Strategy for Nanotechnology.***

A lot of information is on the web site of the US National Nanotechnology Initiative (22).

The NRC web site has information on nanotechnology (23).

A summary of work on the environmental aspects of nanotechnology is on the US EPA web site (24).

The 2005 BBC Reith Lectures (25) are given by Lord Broers on ***The Triumph of Technology.*** Lecture 4 of the 5 lecture series is on ***Nanoscience and Nanotechnology.***

We hope that you will want to continue to keep in touch with the developments in nanotechnology. Many web sites have regular updates but the most extensive is the free weekly newsletter from Cientifica – ***The Trends in Nanotechnology – TNT.*** (26). This newsletter is very readable and seems to be unique in covering both the developments within nanotechnology as well as reporting on the views of those with concerns about the technology. However they are very thorough, the weekly newsletter can have over 100 Internet links for more details on the topics they report. So it is a full time job following them all!

14. Summary.

The lecture series has been a great learning experience for us and we believe for all who attended the talks. We started the programme thinking that nanotechnology might be a promising technology for the future. Now we find that new shirts and pants based on this technology are already in the department store, and it is in sunscreen and components of new cars. Despite this, nanotechnology is still in its infancy. The real test will be whether the technology can be successfully commercialised. As Ray Kurzweil points out, any serious study of the history of technology shows an exponential pattern (or more precisely a series of ***S*** shaped curves.). He predicts that most of technology will be nanotechnology by the 2020's. Even if his prediction is only slightly out, it is wise for all involved in science and engineering to follow developments in this field.

Back to our comparison of nanotechnological development with computers. For the computer revolution some got a head start by learning as the products emerged, and even got involved in programming. Others waited until experts provided the systems. Whichever route was taken the end result is that we are all involved with computers in every facet of our lives. Nanoscience and technology would appear to be following a similar path.

Yes – there is a lot of hype, but also a lot of solid progress. It has been reported that ***nanotech is a growth industry – at least for journalists!*** To support this comment there have been more than 2600 references to nanotechnology in the popular press in the first two months of 2005. No doubt there will be plenty more to read!

However, despite the hype, there is a strong incentive for all engineers to keep in touch with developments in this fascinating new technology – and not be left behind!

Don Lawson, Aug. 2005.

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KurzweilAI.net

Testimony of Ray Kurzweil on the Societal Implications of Nanotechnology
by Ray Kurzweil

Despite calls to relinquish research in nanotechnology, we will have no choice but to confront the challenge of guiding nanotechnology in a constructive direction. Advances in nanotechnology and related advanced technologies are inevitable. Any broad attempt to relinquish nanotechnology will only push it underground, which would interfere with the benefits while actually making the dangers worse.

Testimony presented April 9, 2003 at the Committee on Science, U.S. House of Representatives Hearing to examine the societal implications of nanotechnology and consider H.R. 766, The Nanotechnology Research and Development Act of 2003.

Summary of Testimony:

The size of technology is itself inexorably shrinking. According to my models, both electronic and mechanical technologies are shrinking at a rate of 5.6 per linear dimension per decade. At this rate, most of technology will be "nanotechnology" by the 2020s.

We are immeasurably better off as a result of technology, but there is still a lot of suffering in the world to overcome. We have a moral imperative, therefore, to continue the pursuit of knowledge and advanced technologies, such as nanotechnology, that can continue to overcome human affliction. There is also an economic imperative to continue due to the pervasive acceleration of technology, including miniaturization, in the competitive economy.

Nanotechnology is not a separate field of study that we can simply relinquish. We will have no choice but to confront the challenge of guiding nanotechnology in a constructive direction. There are strategies we can deploy, but there will need to be continual development of defensive strategies.

We can take some level of comfort from our relative success in dealing with one new form of fully non-biological, self-replicating pathogen: the software virus.

The most immediate danger is not self-replicating nanotechnology, but rather self-replicating biotechnology. We need to place a much higher priority on developing vitally needed defensive technologies such as antiviral medications. Keep in mind that a bioterrorist does not need to put his "innovations" through the FDA.

Any broad attempt to relinquish nanotechnology will only push it underground, which would interfere with the benefits while actually making the dangers worse.

Existing regulations on the safety of foods, drugs, and other materials in the environment are sufficient to deal with the near-term applications of nanotechnology, such as nanoparticles.

Full Verbal Testimony:

Chairman Boehlert, distinguished members of the U.S. House of Representatives Committee on Science, and other distinguished guests, I appreciate this opportunity to respond to your questions and concerns on the vital issue of the societal implications of nanotechnology. Our rapidly growing ability to manipulate matter and energy at ever smaller scales promises to transform virtually every sector of society, including health and medicine, manufacturing, electronics and computers, energy, travel, and defense. There will be increasing overlap between nanotechnology and other technologies of increasing influence, such as biotechnology and artificial intelligence. As with any other technological transformation, we will be faced with deeply intertwined promise and peril.

In my brief verbal remarks, I only have time to summarize my conclusions on this complex subject, and I am providing the Committee with an expanded written response that attempts to explain the reasoning behind my views.

Eric Drexler's 1986 thesis developed the concept of building molecule-scale devices using molecular assemblers that would precisely guide chemical reactions. Without going through the history of the controversy surrounding feasibility, it is fair to say that the consensus today is that nano-assembly is indeed feasible, although the most dramatic capabilities are still a couple of decades away.

The concept of nanotechnology today has been expanded to include essentially any technology where the key features are measured in a modest number of nanometers (under 100 by some definitions). By this standard, contemporary electronics has already passed this threshold.

For the past two decades, I have studied technology trends, along with a team of researchers who have assisted me in gathering critical measures of technology in different areas, and I have been developing mathematical models of how technology evolves. Several conclusions from this study have a direct bearing on the issues before this hearing. Technologies, particularly those related to information, develop at an exponential pace, generally doubling in capability and price-performance every year. This observation includes the power of computation, communication – both wired and wireless, DNA sequencing, brain scanning, brain reverse engineering, and the size and scope of human knowledge in general. Of particular relevance to this hearing, the size of technology is itself inexorably shrinking. According to my models, both electronic and mechanical technologies are shrinking at a rate of 5.6 per linear dimension per decade. At this rate, most of technology will be "nanotechnology" by the 2020s.

The golden age of nanotechnology is, therefore, a couple of decades away. This era will bring us the ability to essentially convert software, i.e., information, directly into physical products. We will be able to produce virtually any product for pennies per pound. Computers will have greater computational capacity than the human brain, and we will be completing the reverse engineering of the human brain to reveal the software design of human intelligence. We are already placing devices with narrow intelligence in our bodies for diagnostic and therapeutic purposes. With the advent of nanotechnology, we will be able to keep our bodies and brains in a healthy, optimal state indefinitely. We will have technologies to reverse environmental pollution. Nanotechnology and related advanced technologies of the 2020s will bring us the opportunity to overcome age-old problems, including pollution, poverty, disease, and aging.

We hear increasingly strident voices that object to the intermingling of the so-called natural world with the products of our technology. The increasing intimacy of our human lives with our technology is not a new story, and I would remind the committee that had it not been for the technological advances of the past two centuries, most of us here today would not be here today. Human life expectancy was 37 years in 1800. Most humans at that time lived lives dominated by poverty, intense labor, disease, and misfortune. We are immeasurably better off as a result of technology, but there is still a lot of suffering in the world to overcome. We have a moral imperative, therefore, to continue the pursuit of knowledge and of advanced technologies that can continue to overcome human affliction.

There is also an economic imperative to continue. Nanotechnology is not a single field of study that we can simply relinquish, as suggested by Bill Joy's essay, "Why the Future Doesn't Need Us." Nanotechnology is advancing on hundreds of fronts, and is an extremely diverse activity. We cannot relinquish its pursuit without essentially relinquishing all of technology, which would require a Brave New World totalitarian scenario, which is inconsistent with the values of our society.

Technology has always been a double-edged sword, and that is certainly true of nanotechnology. The same technology that promises to advance human health and wealth also has the potential for destructive applications. We can see that duality today in biotechnology. The same techniques that could save millions of lives from cancer and disease may also empower a bioterrorist to create a bioengineered pathogen.

A lot of attention has been paid to the problem of self-replicating nanotechnology entities that could essentially form a nonbiological cancer that would threaten the planet. I discuss in my written testimony steps we can take now and in the future to ameliorate these dangers. However, the primary point I would like to make is that we will have no choice but to confront the challenge of guiding nanotechnology in a constructive direction. Any broad attempt to relinquish nanotechnology will only push it underground, which would interfere with the benefits while actually making the dangers worse.

As a test case, we can take a small measure of comfort from how we have dealt with one recent technological challenge. There exists today a new form of fully nonbiological self-replicating entity that didn't exist just a few decades ago: the computer virus. When this form of destructive intruder first appeared, strong concerns were voiced that as they became more sophisticated, software pathogens had the potential to destroy the computer network medium they live in. Yet the "immune system" that has evolved in response to this challenge has been largely effective. Although destructive self-replicating software entities do cause damage from time to time, the injury is but a small fraction of the benefit we receive from the computers and communication links that harbor them. No one would suggest we do away with computers, local area networks, and the Internet because of software viruses.

One might counter that computer viruses do not have the lethal potential of biological viruses or of destructive nanotechnology. This is not always the case: we rely on software to monitor patients in critical care units, to fly and land airplanes, to guide intelligent weapons in our current campaign in Iraq, and other "mission critical" tasks. To the extent that this is true, however, this observation only strengthens my argument. The fact that computer viruses are not usually deadly to humans only means that more people are willing to create and release them. It also means that our response to the danger is that much less intense. Conversely, when it comes to self-replicating entities that are potentially lethal on a large scale, our response on all levels will be vastly more serious, as we have seen since 9-11.

I would describe our response to software pathogens as effective and successful. Although they remain (and always will remain) a concern, the danger remains at a nuisance level. Keep in mind that this success is in an industry in which there is no regulation, and no certification for practitioners. This largely unregulated industry is also enormously productive. One could argue that it has contributed more to our technological and economic progress than any other enterprise in human history.

Some of the concerns that have been raised, such as Bill Joy's article, are effective because they paint a picture of future dangers as if they were released on today's unprepared world. The reality is that the sophistication and power of our defensive technologies and knowledge will grow along with the dangers.

The challenge most immediately in front of us is not self-replicating nanotechnology, but rather self-replicating biotechnology. The next two decades will be the golden age of biotechnology, whereas the comparable era for nanotechnology will follow in the 2020s and beyond. We are now in the early stages of a transforming technology based on the intersection of biology and information science. We are learning the "software" methods of life and disease processes. By reprogramming the information processes that lead to and encourage disease and aging, we will have the ability to overcome these afflictions. However, the same knowledge can also empower a terrorist to create a bioengineered pathogen.

As we compare the success we have had in controlling engineered software viruses to the coming challenge of controlling engineered biological viruses, we are struck with one salient difference. As I noted, the software industry is almost completely unregulated. The same is obviously not the case for biotechnology. A bioterrorist does not need to put his "innovations" through the FDA. However, we do require the scientists developing the defensive technologies to follow the existing regulations, which slow down the innovation process at every step. Moreover, it is impossible, under existing regulations and ethical standards, to test defenses to bioterrorist agents on humans. There is already extensive discussion to modify these regulations to allow for animal models and simulations to replace infeasible human trials. This will be necessary, but I believe we will need to go beyond these steps to accelerate the development of vitally needed defensive technologies.

With the human genome project, 3 to 5 percent of the budgets were devoted to the ethical, legal, and social implications (ELSI) of the technology. A similar commitment for nanotechnology would be appropriate and constructive.

Near-term applications of nanotechnology are far more limited in their benefits as well as more benign in their potential dangers. These include developments in the materials area involving the addition of particles with multi-nanometer features to plastics, textiles, and other products. These have perhaps the greatest potential in the area of pharmaceutical development by allowing new strategies for highly targeted drugs that perform their intended function and reach the appropriate tissues, while minimizing side effects. This development is not qualitatively different than what we have been doing for decades in that many new materials involve constituent particles that are novel and of a similar physical scale. The emerging nanoparticle technology provides more precise control, but the idea of introducing new nonbiological materials into the environment is hardly a new phenomenon. We cannot say a priori that all nanoengineered particles are safe, nor would it be appropriate to deem them necessarily unsafe. Environmental tests thus far have not shown reasons for undue concern, and it is my view that existing regulations on the safety of foods, drugs, and other materials in the environment are sufficient to deal with these near-term applications.

The voices that are expressing concern about nanotechnology are the same voices that have expressed undue levels of concern about genetically modified organisms. As with nanoparticles, GMO's are neither inherently safe nor unsafe, and reasonable levels of regulation for safety are appropriate. However, none of the dire warnings about GMO's have come to pass. Already, African nations, such as Zambia and Zimbabwe, have rejected vitally needed food aid under pressure from European anti-GMO activists. The reflexive anti-technology stance that has been reflected in the GMO controversy will not be helpful in balancing the benefits and risks of nanoparticle technology.

In summary, I believe that existing regulatory mechanisms are sufficient to handle near-term applications of nanotechnology. As for the long term, we need to appreciate that a myriad of nanoscale technologies are inevitable. The current examinations and dialogues on achieving the promise while ameliorating the peril are appropriate and will deserve sharply increased attention as we get closer to realizing these revolutionary technologies.

Written Testimony

I am pleased to provide a more detailed written response to the issues raised by the committee. In this written portion of my response, I address the following issues:

- **Models of Technology Trends**: A discussion of why nanotechnology and related advanced technologies are inevitable. The underlying technologies are deeply integrated into our society and are advancing on many diverse fronts.

- **A Small Sample of Examples of True Nanotechnology**: a few of the implications of nanotechnology two to three decades from now.
- **The Economic Imperatives of the Law of Accelerating Returns**: the exponential advance of technology, including the accelerating miniaturization of technology, is driven by economic imperative, and, in turn, has a pervasive impact on the economy.
- **The Deeply Intertwined Promise and Peril of Nanotechnology and Related Advanced Technologies**: Technology is inherently a doubled-edged sword, and we will need to adopt strategies to encourage the benefits while ameliorating the risks. Relinquishing broad areas of technology, as has been proposed, is not feasible and attempts to do so will only drive technology development underground, which will exacerbate the dangers.

Models of Technology Trends

A diverse technology such as nanotechnology progresses on many fronts and is comprised of hundreds of small steps forward, each benign in itself. An examination of these trends shows that technology in which the key features are measured in a small number of nanometers is inevitable. I hereby provide some examples of my study of technology trends.

The motivation for this study came from my interest in inventing. As an inventor in the 1970s, I came to realize that my inventions needed to make sense in terms of the enabling technologies and market forces that would exist when the invention was introduced, which would represent a very different world than when it was conceived. I began to develop models of how distinct technologies – electronics, communications, computer processors, memory, magnetic storage, and the size of technology – developed and how these changes rippled through markets and ultimately our social institutions. I realized that most inventions fail not because they never work, but because their timing is wrong. Inventing is a lot like surfing, you have to anticipate and catch the wave at just the right moment.

In the 1980s, my interest in technology trends and implications took on a life of its own, and I began to use my models of technology trends to project and anticipate the technologies of future times, such as the year 2000, 2010, 2020, and beyond. This enabled me to invent with the capabilities of the future. In the late 1980s, I wrote my first book, *The Age of Intelligent Machines*, which ended with the specter of machine intelligence becoming indistinguishable from its human progenitors. This book included hundreds of predictions about the 1990s and early 2000 years, and my track record of prediction has held up well.

During the 1990s I gathered empirical data on the apparent acceleration of all information-related technologies and sought to refine the mathematical models underlying these observations. In *The Age of Spiritual Machines* (ASM), which I wrote in 1998, I introduced refined models of technology, and a theory I called "the law of accelerating returns," which explained why technology evolves in an exponential fashion.

The Intuitive Linear View versus the Historical Exponential View

The future is widely misunderstood. Our forebears expected the future to be pretty much like their present, which had been pretty much like their past. Although exponential trends did exist a thousand years ago, they were at that very early stage where an exponential trend is so flat and so slow that it looks like no trend at all. So their lack of expectations was largely fulfilled. Today, in accordance with the common wisdom, everyone expects continuous technological progress and the social repercussions that follow. But the future will nonetheless be far more surprising than most observers realize because few have truly internalized the implications of the fact that the rate of change itself is accelerating.

Most long-range forecasts of technical feasibility in future time periods dramatically underestimate the power of future developments because they are based on what I call the "intuitive linear" view of history rather than the "historical exponential view." To express this another way, it is not the case that we will experience a hundred years of progress in the twenty-first century; rather we will witness on the order of twenty thousand years of progress (at *today's* rate of progress, that is).

When people think of a future period, they intuitively assume that the current rate of progress will continue for future periods. Even for those who have been around long enough to experience how the pace increases over time, an unexamined intuition nonetheless provides the impression that progress changes at the rate that we have experienced recently. From the mathematician's perspective, a primary reason for this is that an exponential curve approximates a straight line when viewed for a brief duration. It is typical, therefore, that even sophisticated commentators, when considering the future, extrapolate the current pace of change over the next 10 years or 100 years to determine their expectations. This is why I call this way of looking at the future the "intuitive linear" view.

But a serious assessment of the history of technology shows that technological change is exponential. In exponential growth, we find that a key measurement such as computational power is multiplied by a constant factor for each unit of time (e.g., doubling every year) rather than just being added to incrementally. Exponential growth is a feature of any evolutionary process, of which technology is a primary example. One can examine the data in different ways, on different time scales, and for a wide variety of technologies ranging from electronic to biological, as well as social implications ranging from the size of the economy to human life span, and the acceleration of progress and growth applies. Indeed, we find not just simple exponential growth, but "double" exponential growth, meaning that the rate of exponential growth is itself growing exponentially. These observations do not rely merely on an assumption of the continuation of Moore's law (i.e., the exponential shrinking of transistor sizes on an integrated circuit), but is based on a rich model of diverse technological processes. What it clearly shows is that technology, particularly the pace of technological change, advances (at least) exponentially, not linearly, and has been doing so since the advent of technology, indeed since the advent of evolution on Earth.

Many scientists and engineers have what my colleague Lucas Hendrich calls "engineer's pessimism." Often an engineer or scientist who is so immersed in the difficulties and intricate details of a contemporary challenge fails to appreciate the ultimate long-term implications of their own work, and, in particular, the larger field of work that they operate in. Consider the biochemists in 1985 who were skeptical of the announcement of the goal of transcribing the entire genome in a mere 15 years. These scientists had just spent an entire year transcribing a mere one ten-thousandth of the genome, so even with reasonable anticipated advances, it seemed to them like it would be hundreds of years, if not longer, before the entire genome could be sequenced. Or consider the skepticism expressed in the mid 1980s that the Internet would ever be a significant phenomenon, given that it included only tens of thousands of nodes. The fact that the number of nodes was doubling every year and there were, therefore, likely to be tens of millions of nodes ten years later was not appreciated by those who struggled with "state of the art" technology in 1985, which permitted adding only a few thousand nodes throughout the world in a year.

I emphasize this point because it is the most important failure that would-be prognosticators make in considering future trends. The vast majority of technology forecasts and forecasters ignore altogether this "historical exponential view" of technological progress. Indeed, almost everyone I meet has a linear view of the future. That is why people tend to overestimate what can be achieved in the short term (because we tend to leave out necessary details), but underestimate what can be achieved in the long term (because the exponential growth is ignored).

The Law of Accelerating Returns

The ongoing acceleration of technology is the implication and inevitable result of what I call the "law of accelerating returns," which describes the acceleration of the pace and the exponential growth of the products of an evolutionary process. This includes technology, particularly information-bearing technologies, such as computation. More specifically, the law of accelerating returns states the following:

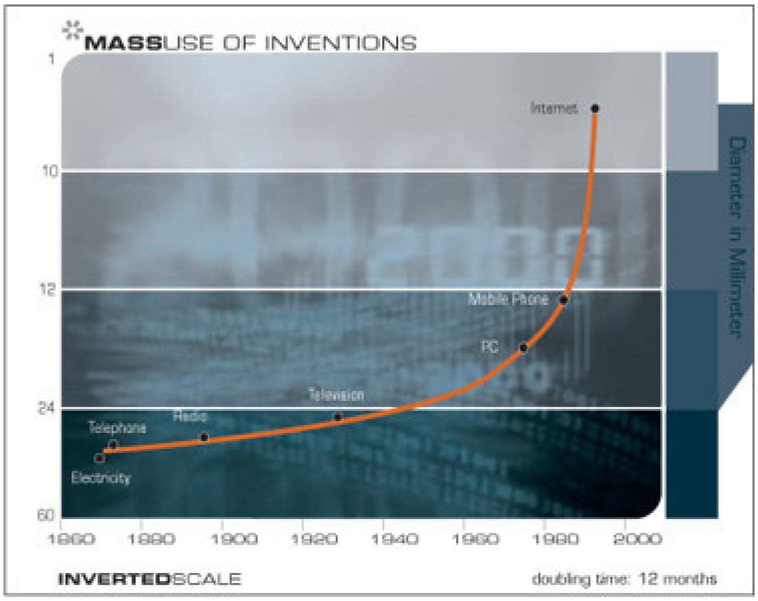
- Evolution applies positive feedback in that the more capable methods resulting from one stage of evolutionary progress are used to create the next stage. As a result, the rate of progress of an evolutionary process increases exponentially over time. Over time, the "order" of the information embedded in the evolutionary process (i.e., the measure of how well the information fits a purpose, which in evolution is survival) increases.
- A correlate of the above observation is that the "returns" of an evolutionary process (e.g., the speed, cost-effectiveness, or overall "power" of a process) increase exponentially over time.
- In another positive feedback loop, as a particular evolutionary process (e.g., computation) becomes more effective (e.g., cost effective), greater resources are deployed towards the further progress of that process. This results in a second level of exponential growth (i.e., the rate of exponential growth itself grows exponentially).
- Biological evolution is one such evolutionary process.
- Technological evolution is another such evolutionary process. Indeed, the emergence of the first technology-creating species resulted in the new evolutionary process of technology. Therefore, technological evolution is an outgrowth of – and a continuation of – biological evolution.
- A specific paradigm (a method or approach to solving a problem, e.g., shrinking transistors on an integrated circuit as an approach to making more powerful computers) provides exponential growth until the method exhausts its potential. When this happens, a paradigm shift (a fundamental change in the approach) occurs, which enables exponential growth to continue.
- Each paradigm follows an "S-curve," which consists of slow growth (the early phase of exponential growth), followed by rapid growth (the late, explosive phase of exponential growth), followed by a leveling off as the particular paradigm matures.
- During this third or maturing phase in the life cycle of a paradigm, pressure builds for the next paradigm shift.
- When the paradigm shift occurs, the process begins a new S-curve.
- Thus the acceleration of the overall evolutionary process proceeds as a sequence of S-curves, and the overall exponential growth consists of this cascade of S-curves.

- The resources underlying the exponential growth of an evolutionary process are relatively unbounded.
- One resource is the (ever-growing) order of the evolutionary process itself. Each stage of evolution provides more powerful tools for the next. In biological evolution, the advent of DNA allowed more powerful and faster evolutionary "experiments." Later, setting the "designs" of animal body plans during the Cambrian explosion allowed rapid evolutionary development of other body organs, such as the brain. Or to take a more recent example, the advent of computer-assisted design tools allows rapid development of the next generation of computers.
- The other required resource is the "chaos" of the environment in which the evolutionary process takes place and which provides the options for further diversity. In biological evolution, diversity enters the process in the form of mutations and ever- changing environmental conditions, including cosmological disasters (e.g., asteroids hitting the Earth). In technological evolution, human ingenuity combined with ever-changing market conditions keep the process of innovation going.

If we apply these principles at the highest level of evolution on Earth, the first step, the creation of cells, introduced the paradigm of biology. The subsequent emergence of DNA provided a digital method to record the results of evolutionary experiments. Then, the evolution of a species that combined rational thought with an opposable appendage (the thumb) caused a fundamental paradigm shift from biology to technology. The upcoming primary paradigm shift will be from biological thinking to a hybrid combining biological and nonbiological thinking. This hybrid will include "biologically inspired" processes resulting from the reverse engineering of biological brains.

If we examine the timing of these steps, we see that the process has continuously accelerated. The evolution of life forms required billions of years for the first steps (e.g., primitive cells); later on progress accelerated. During the Cambrian explosion, major paradigm shifts took only tens of millions of years. Later on, Humanoids developed over a period of millions of years, and Homo sapiens over a period of only hundreds of thousands of years.

With the advent of a technology-creating species, the exponential pace became too fast for evolution through DNA-guided protein synthesis and moved on to human-created technology. Technology goes beyond mere tool making; it is a process of creating ever more powerful technology using the tools from the previous round of innovation, and is, thereby, an evolutionary process. The first technological steps -- sharp edges, fire, the wheel – took tens of thousands of years. For people living in this era, there was little noticeable technological change in even a thousand years. By 1000 AD, progress was much faster and a paradigm shift required only a century or two. In the nineteenth century, we saw more technological change than in the nine centuries preceding it. Then in the first twenty years of the twentieth century, we saw more advancement than in all of the nineteenth century. Now, paradigm shifts occur in only a few years time. The World Wide Web did not exist in anything like its present form just a few years ago; it didn't exist at all a decade ago.



The paradigm shift rate (i.e., the overall rate of technical progress) is currently doubling (approximately) every decade; that is, paradigm shift times are halving every decade (and the rate of acceleration is itself growing exponentially). So, the technological progress in the twenty-first century will be equivalent to what would require (in the linear view) on the order of 200 centuries. In contrast, the twentieth century saw only about 20 years of progress (again at today's rate of progress) since we have been speeding up to current rates. So the twenty-first century will see about a thousand times greater technological change than its predecessor.

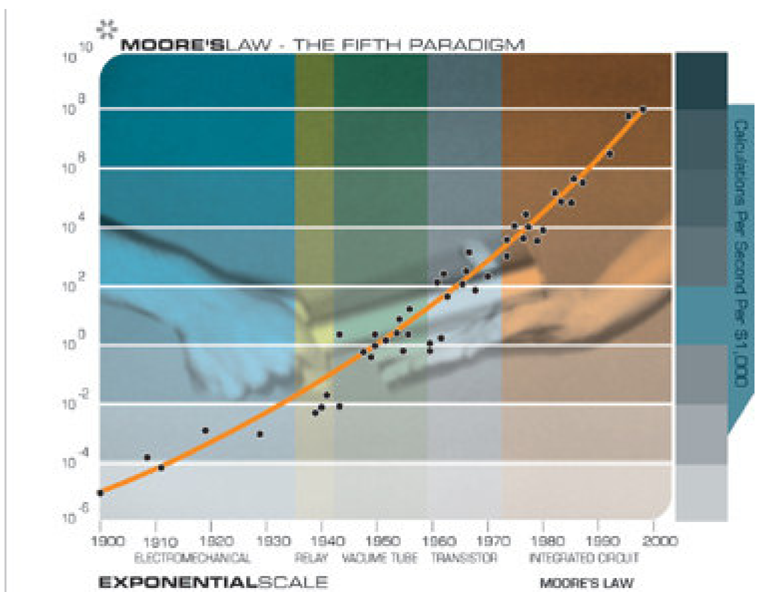
Moore's Law and Beyond

There is a wide range of technologies that are subject to the law of accelerating returns. The exponential trend that has gained the greatest public recognition has become known as "Moore's Law." Gordon Moore, one of the inventors of integrated circuits, and then Chairman of Intel, noted in the mid-1970s that we could squeeze twice as many transistors on an integrated circuit every 24 months. Given that the electrons have less distance to travel, the circuits also run twice as fast, providing an overall quadrupling of computational power.

However, the exponential growth of computing is much broader than Moore's Law.

If we plot the speed (in instructions per second) per $1000 (in constant dollars) of 49 famous calculators and computers spanning the entire twentieth century, we note that there were four completely different paradigms that provided exponential growth in the price-performance of computing before the integrated circuits were invented. Therefore, Moore's Law was not the first, but the fifth paradigm to exponentially grow the power of computation. And it won't be the last. When Moore's Law reaches the end of its S-Curve, now expected before 2020, the exponential growth will continue with three-dimensional molecular computing, a prime example of the application of nanotechnology, which will constitute the sixth paradigm.

When I suggested in my book *The Age of Spiritual Machines*, published in 1999, that three-dimensional molecular computing, particularly an approach based on using carbon nanotubes, would become the dominant computing hardware technology in the teen years of this century, that was considered a radical notion. There has been so much progress in the past four years, with literally dozens of major milestones having been achieved, that this expectation is now a mainstream view.



Moore's Law Was Not the First, but the Fifth Paradigm to Provide Exponential Growth of Computing. Each time one paradigm runs out of steam, another picks up the pace

The exponential growth of computing is a marvelous quantitative example of the exponentially growing returns from an evolutionary process. We can express the exponential growth of computing in terms of an accelerating pace: it took 90 years to achieve the first MIPS (million instructions per second) per thousand dollars; now we add one MIPS per thousand dollars every day.

Moore's Law narrowly refers to the number of transistors on an integrated circuit of fixed size, and sometimes has been expressed even more narrowly in terms of transistor feature size. But rather than feature size (which is only one contributing factor), or even number of transistors, I think the most appropriate measure to track is computational speed per unit cost. This takes into account many levels of "cleverness" (i.e., innovation, which is to say, technological evolution). In addition to all of the innovation in integrated circuits, there are multiple layers of innovation in computer design, e.g., pipelining, parallel processing, instruction look-ahead, instruction and memory caching, and many others.

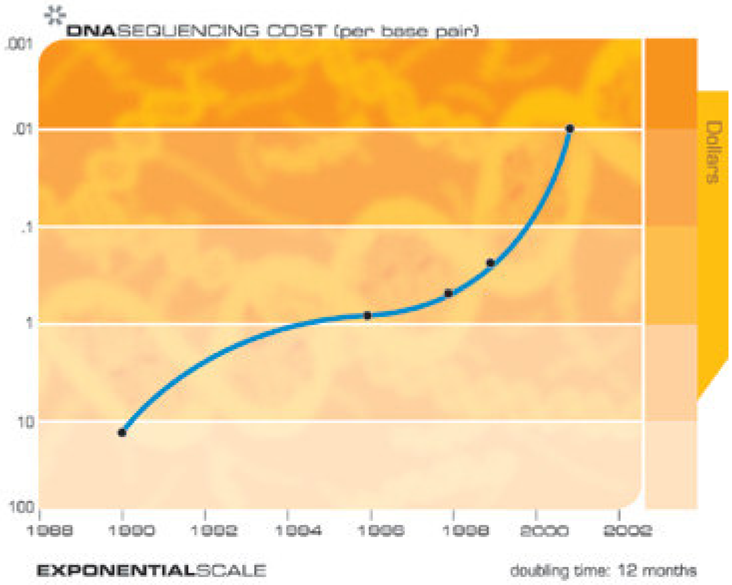
The human brain uses a very inefficient electrochemical digital-controlled analog computational process. The bulk of the calculations are done in the interneuronal connections at a speed of only about 200 calculations per second (in each connection), which is about ten million times slower than contemporary electronic circuits. But the brain gains its prodigious powers from its extremely parallel organization *in three dimensions*. There are many technologies in the wings that build circuitry in three dimensions. Nanotubes, an example of nanotechnology, which is already working in laboratories, build circuits from pentagonal arrays of carbon atoms. One cubic inch of nanotube circuitry would be a million times more powerful than the human brain. There are more than enough new computing technologies now being researched, including three-dimensional silicon chips, optical and silicon spin computing, crystalline computing, DNA computing, and quantum computing, to keep the law of accelerating returns as applied to computation going for a long time.

As I discussed above, it is important to distinguish between the "S" curve (an "S" stretched to the right, comprising very slow, virtually unnoticeable growth – followed by very rapid growth – followed by a flattening out as the process approaches an asymptote) that is characteristic of any specific technological paradigm and the continuing exponential growth that is characteristic of the ongoing evolutionary process of technology. Specific paradigms, such as Moore's Law, do ultimately reach levels at which exponential growth is no longer feasible. That is why Moore's Law is an S curve. But the growth of computation is an ongoing exponential (at least until we "saturate" the Universe with the intelligence of our human-machine civilization, but that will not be a limit in this coming century). In accordance with the law of accelerating returns, paradigm shift, also called innovation, turns the S curve of any specific paradigm into a continuing exponential. A new paradigm (e.g., three-dimensional circuits) takes over when the old paradigm approaches its natural limit, which has already happened at least four times in the history of computation. This difference also distinguishes the tool making of non-human species, in which the mastery of a tool-making (or using) skill by each animal is characterized by an abruptly ending S shaped learning curve, versus human-created technology, which has followed an exponential pattern of growth and acceleration since its inception.

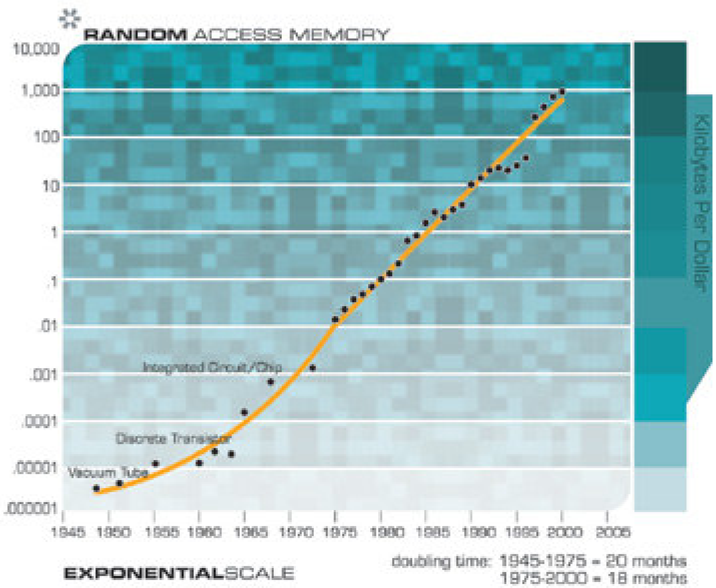
DNA Sequencing, Memory, Communications, the Internet, and Miniaturization

This "law of accelerating returns" applies to all of technology, indeed to any true evolutionary process, and can be measured with remarkable precision in information-based technologies. There are a great many examples of the exponential growth implied by the law of accelerating returns in technologies, as varied as DNA sequencing, communication speeds, brain scanning, electronics of all kinds, and even in the rapidly shrinking size of technology, which is directly relevant to the discussion at this hearing. The future nanotechnology age results not from the exponential explosion of computation alone, but rather from the interplay and myriad synergies that will result from manifold intertwined technological revolutions. Also, keep in mind that every point on the exponential growth curves underlying these panoply of technologies (see the graphs below) represents an intense human drama of innovation and competition. It is remarkable therefore that these chaotic processes result in such smooth and predictable exponential trends.

As I noted above, when the human genome scan started fourteen years ago, critics pointed out that given the speed with which the genome could then be scanned, it would take thousands of years to finish the project. Yet the fifteen year project was nonetheless completed slightly ahead of schedule.

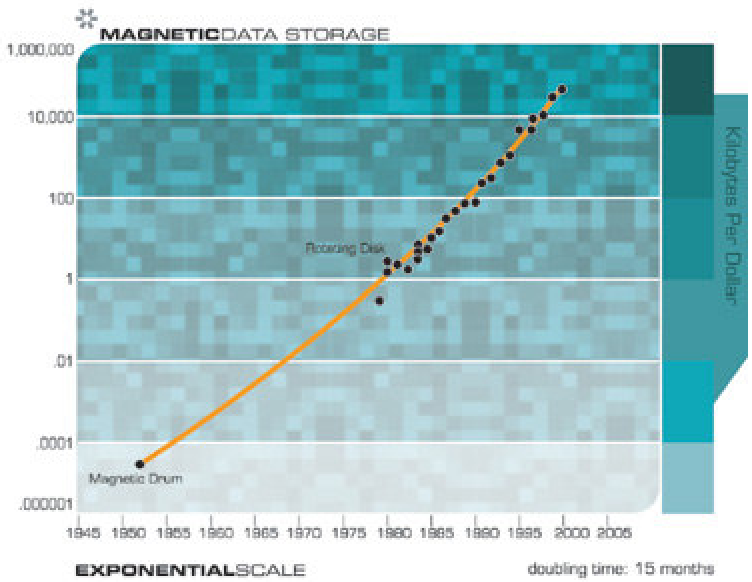


Of course, we expect to see exponential growth in electronic memories such as RAM.

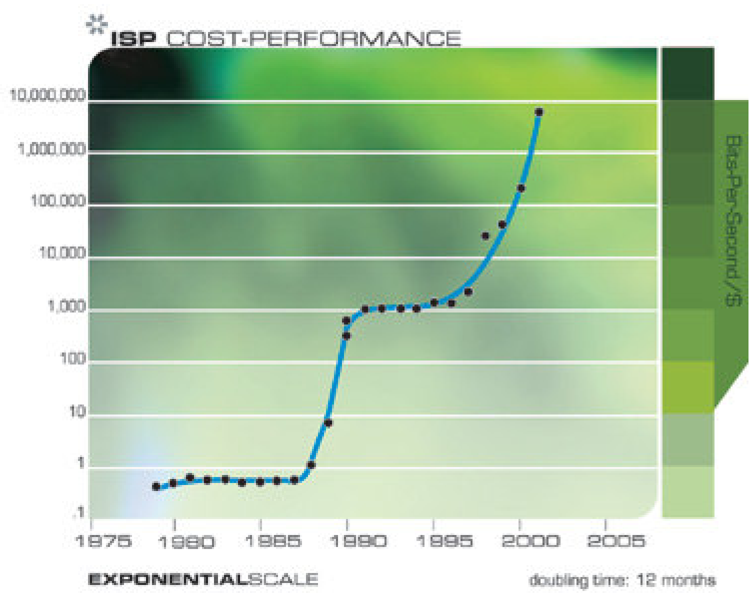


Notice How Exponential Growth Continued through Paradigm Shifts from Vacuum Tubes to Discrete Transistors to Integrated Circuits

However, growth in magnetic memory is not primarily a matter of Moore's law, but includes advances in mechanical and electromagnetic systems.



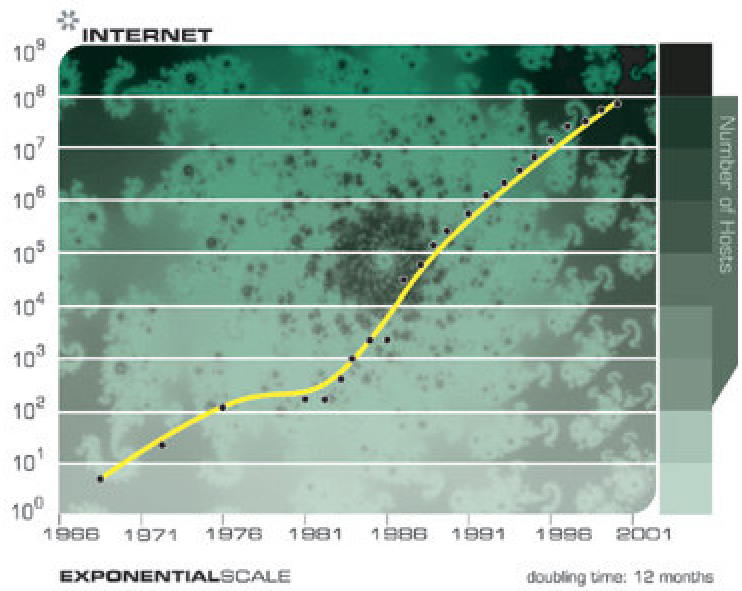
Exponential growth in communications technology has been even more explosive than in computation and is no less significant in its implications. Again, this progression involves far more than just shrinking transistors on an integrated circuit, but includes accelerating advances in fiber optics, optical switching, electromagnetic technologies, and others.

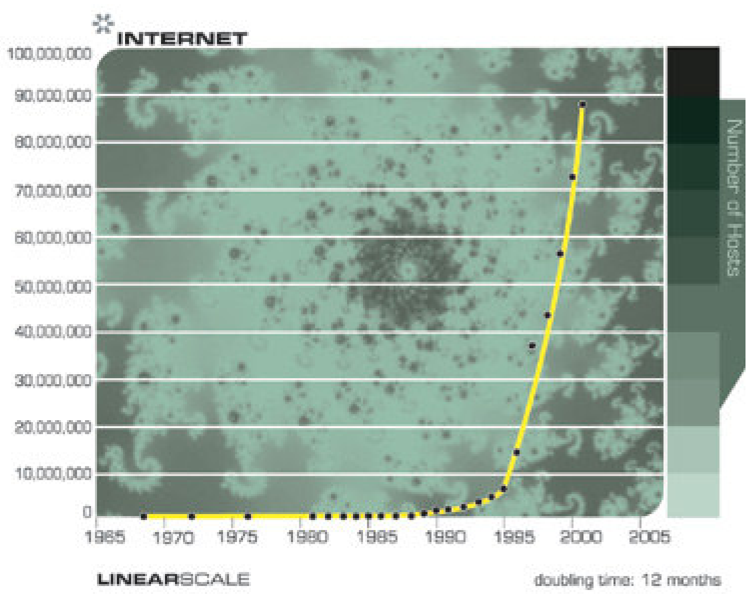


Notice Cascade of "S" Curves

Note that in the above chart we can actually see the progression of "S" curves: the acceleration fostered by a new paradigm, followed by a leveling off as the paradigm runs out of steam, followed by renewed acceleration through paradigm shift.

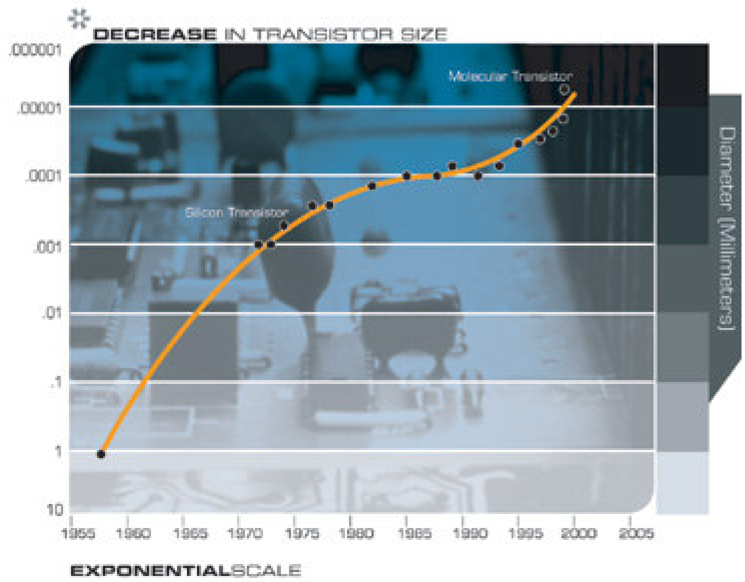
The following two charts show the overall growth of the Internet based on the number of hosts (server computers). These two charts plot the same data, but one is on an exponential axis and the other is linear. As I pointed out earlier, whereas technology progresses in the exponential domain, we experience it in the linear domain. So from the perspective of most observers, nothing was happening until the mid 1990s when seemingly out of nowhere, the World Wide Web and email exploded into view. But the emergence of the Internet into a worldwide phenomenon was readily predictable much earlier by examining the exponential trend data.

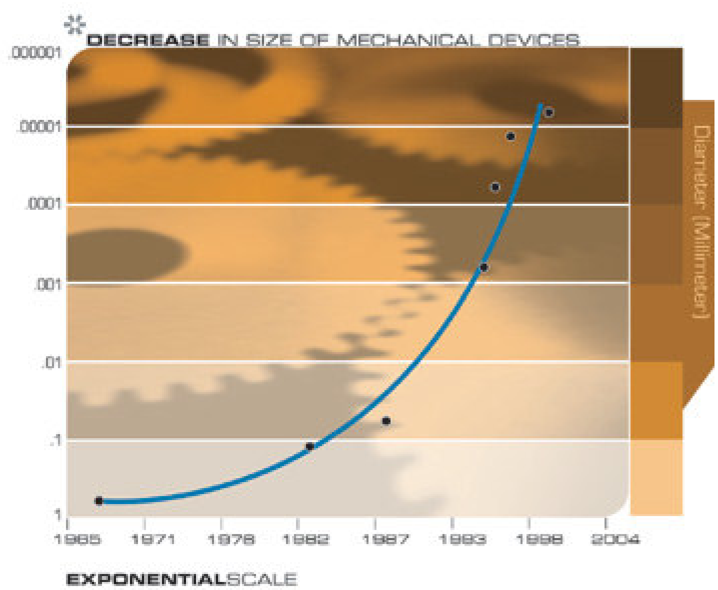




Notice how the explosion of the Internet appears to be a surprise from the Linear Chart, but was perfectly predictable from the Exponential Chart

The most relevant trend to this hearing, and one that will have profound implications for the twenty-first century is the pervasive trend towards making things smaller, i.e., miniaturization. The salient implementation sizes of a broad range of technologies, both electronic and mechanical, are shrinking, also at a double-exponential rate. At present, we are shrinking technology by a factor of approximately 5.6 per linear dimension per decade.





A Small Sample of Examples of True Nanotechnology

Ubiquitous nanotechnology is two to three decades away. A prime example of its application will be to deploy billions of "nanobots": small robots the size of human blood cells that can travel inside the human bloodstream. This notion is not as futuristic as it may sound in that there have already been successful animal experiments using this concept . There are already four major conferences on "BioMEMS" (Biological Micro Electronic Mechanical Systems) covering devices in the human blood stream.

Consider several examples of nanobot technology, which, based on miniaturization and cost reduction trends, will be feasible within 30 years. In addition to scanning the human brain to facilitate human brain reverse engineering, these nanobots will be able to perform a broad variety of diagnostic and therapeutic functions inside the bloodstream and human body. Robert Freitas, for example, has designed robotic replacements for human blood cells that perform hundreds or thousands of times more effectively than their biological counterparts. With Freitas' "respirocytes," (robotic red blood cells), you could do an Olympic sprint for 15 minutes without taking a breath. His robotic macrophages will be far more effective than our white blood cells at combating pathogens. His DNA repair robot would be able to repair DNA transcription errors, and even implement needed DNA changes. Although Freitas' conceptual designs are two or three decades away, there has already been substantial progress on bloodstream-based devices. For example, one scientist has cured type I Diabetes in rats with a nanoengineered device that incorporates pancreatic Islet cells. The device has seven- nanometer pores that let insulin out, but block the antibodies which destroy these cells. There are many innovative projects of this type already under way.

Clearly, nanobot technology has profound military applications, and any expectation that such uses will be "relinquished" are highly unrealistic. Already, DOD is developing "smart dust," which are tiny robots the size of insects or even smaller. Although not quite nanotechnology, millions of these devices can be dropped into enemy territory to provide highly detailed surveillance. The potential application for even smaller, nanotechnology-based devices is even greater. Want to find Saddam Hussein or Osama bin Laden? Need to locate hidden weapons of mass destruction? Billions of essentially invisible spies could monitor every square inch of enemy territory, identify every person and every weapon, and even carry out missions to destroy enemy targets. The only way for an enemy to counteract such a force is, of course, with their own nanotechnology. The point is that nanotechnology-based weapons will obsolete weapons of larger size.

In addition, nanobots will also be able to expand our experiences and our capabilities. Nanobot technology will provide fully immersive, totally convincing virtual reality in the following way. The nanobots take up positions in close physical proximity to every interneuronal connection coming from all of our senses (e.g., eyes, ears, skin). We already have the technology for electronic devices to communicate with neurons in both directions that requires no direct physical contact with the neurons. For example, scientists at the Max Planck Institute have developed "neuron transistors" that can detect the firing of a nearby neuron, or alternatively, can cause a nearby neuron to fire, or suppress it from firing. This amounts to two-way communication between neurons and the electronic-based neuron transistors. The Institute scientists demonstrated their invention by controlling the movement of a living leech from their computer. Again, the primary aspect of nanobot-based virtual reality that is not yet feasible is size and cost.

When we want to experience real reality, the nanobots just stay in position (in the capillaries) and do nothing. If we want to enter virtual reality, they suppress all of the inputs coming from the real senses, and replace them with the signals that would be appropriate for the virtual environment. You (i.e., your brain) could decide to cause your muscles and limbs to move as you normally would, but the nanobots again intercept these interneuronal signals, suppress your real limbs from moving, and instead cause your virtual limbs to move and provide the appropriate movement and reorientation in the virtual environment.

The Web will provide a panoply of virtual environments to explore. Some will be recreations of real places, others will be fanciful environments that have no "real" counterpart. Some indeed would be impossible in the physical world (perhaps, because they violate the laws of physics). We will be able to "go" to these virtual environments by ourselves, or we will meet other people there, both real people and simulated people. Of course, ultimately there won't be a clear distinction between the two.

By 2030, going to a web site will mean entering a full-immersion virtual-reality environment. In addition to encompassing all of the senses, these shared environments can include emotional overlays as the nanobots will be capable of triggering the neurological correlates of emotions, sexual pleasure, and other derivatives of our sensory experience and mental reactions.

In the same way that people today beam their lives from web cams in their bedrooms, "experience beamers" circa 2030 will beam their entire flow of sensory experiences, and if so desired, their emotions and other secondary reactions. We'll be able to plug in (by going to the appropriate web site) and experience other people's lives as in the plot concept of 'Being John Malkovich.' Particularly interesting experiences can be archived and relived at any time.

We won't need to wait until 2030 to experience shared virtual-reality environments, at least for the visual and auditory senses. Full-immersion visual-auditory environments will be available by the end of this decade, with images written directly onto our retinas by our eyeglasses and contact lenses. All of the electronics for the computation, image reconstruction, and very high bandwidth wireless connection to the Internet will be embedded in our glasses and woven into our clothing, so computers as distinct objects will disappear.

In my view, the most significant implication of the development of nanotechnology and related advanced technologies of the 21^{st} century will be the merger of biological and nonbiological intelligence. First, it is important to point out that well before the end of the twenty-first century, thinking on nonbiological substrates will dominate. Biological thinking is stuck at 10^{26} calculations per second (for all biological human brains), and that figure will not appreciably change, even with bioengineering changes to our genome. Nonbiological intelligence, on the other hand, is growing at a double-exponential rate and will vastly exceed biological intelligence well before the middle of this century. However, in my view, this nonbiological intelligence should still be considered human as it is fully derivative of the human-machine civilization. The merger of these two worlds of intelligence is not merely a merger of biological and nonbiological thinking mediums, but more importantly one of method and organization of thinking.

One of the key ways in which the two worlds can interact will be through nanobots. Nanobot technology will be able to expand our minds in virtually any imaginable way. Our brains today are relatively fixed in design. Although we do add patterns of interneuronal connections and neurotransmitter concentrations as a normal part of the learning process, the current overall capacity of the human brain is highly constrained, restricted to a mere hundred trillion connections. Brain implants based on massively distributed intelligent nanobots will ultimately expand our memories a trillion fold, and otherwise vastly improve all of our sensory, pattern recognition, and cognitive abilities. Since the nanobots are communicating with each other over a wireless local area network, they can create any set of new neural connections, can break existing connections (by suppressing neural firing), can create new hybrid biological-nonbiological networks, as well as add vast new nonbiological networks.

Using nanobots as brain extenders is a significant improvement over the idea of surgically installed neural implants, which are beginning to be used today (e.g., ventral posterior nucleus, subthalmic nucleus, and ventral lateral thalamus neural implants to counteract Parkinson's Disease and tremors from other neurological disorders, cochlear implants, and others.) Nanobots will be introduced without surgery, essentially just by injecting or even swallowing them. They can all be directed to leave, so the process is easily reversible. They are programmable, in that they can provide virtual reality one minute, and a variety of brain extensions the next. They can change their configuration, and clearly can alter their software. Perhaps most importantly, they are massively distributed and therefore can take up billions or trillions of positions throughout the brain, whereas a surgically introduced neural implant can only be placed in one or at most a few locations.

The Economic Imperatives of the Law of Accelerating Returns

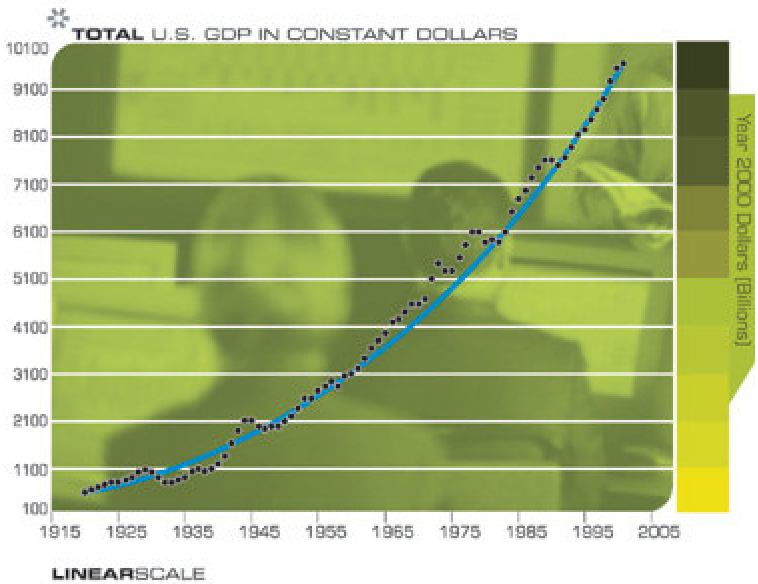
It is the economic imperative of a competitive marketplace that is driving technology forward and fueling the law of accelerating returns. In turn, the law of accelerating returns is transforming economic relationships.

The primary force driving technology is economic imperative. We are moving towards nanoscale machines, as well as more intelligent machines, as the result of a myriad of small advances, each with their own particular economic justification.

To use one small example of many from my own experience at one of my companies (Kurzweil Applied Intelligence), whenever we came up with a slightly more intelligent version of speech recognition, the new version invariably had greater value than the earlier generation and, as a result, sales increased. It is interesting to note that in the example of speech recognition software, the three primary surviving competitors stayed very close to each other in the intelligence of their software. A few other companies that failed to do so (e.g., Speech Systems) went out of business. At any point in time, we would be able to sell the version prior to the latest version for perhaps a quarter of the price of the current version. As for versions of our technology that were two generations old, we couldn't even give those away.

There is a vital economic imperative to create smaller and more intelligent technology. Machines that can more precisely carry out their missions have enormous value. That is why they are being built. There are tens of thousands of projects that are advancing the various aspects of the law of accelerating returns in diverse incremental ways. Regardless of near-term business cycles, the support for "high tech" in the business community, and in particular for software advancement, has grown enormously. When I started my optical character recognition (OCR) and speech synthesis company (Kurzweil Computer Products, Inc.) in 1974, high-tech venture deals totaled approximately $10 million. Even during today's high tech recession, the figure is 100 times greater. We would have to repeal capitalism and every visage of economic competition to stop this progression.

The economy (viewed either in total or per capita) has been growing exponentially throughout this century:

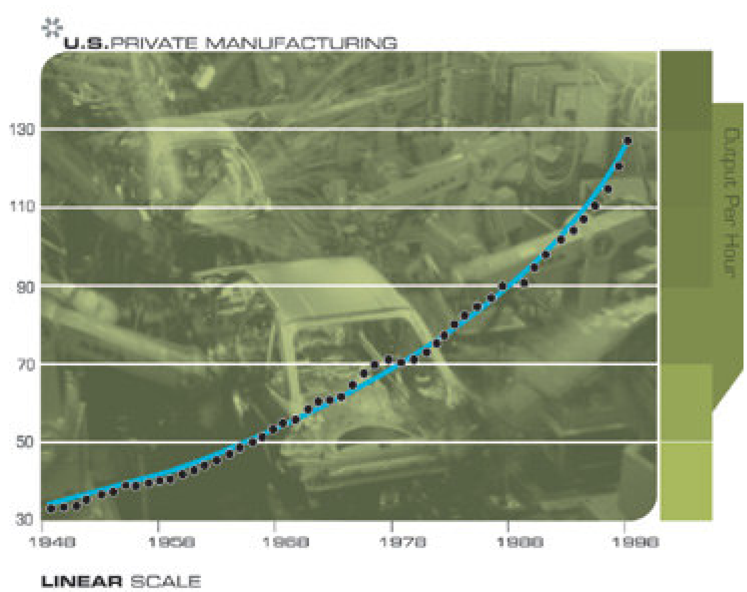


Note that the underlying exponential growth in the economy is a far more powerful force than periodic recessions. Even the "Great Depression" represents only a minor blip compared to the underlying pattern of growth. Most importantly, recessions, including the depression, represent only temporary deviations from the underlying curve. In each case, the economy ends up exactly where it would have been had the recession/depression never occurred.

Productivity (economic output per worker) has also been growing exponentially. Even these statistics are greatly understated because they do not fully reflect significant improvements in the quality and features of products and services. It is not the case that "a car is a car;" there have been significant improvements in safety, reliability, and features. Certainly, $1000 of computation today is immeasurably more powerful than $1000 of computation ten years ago (by a factor of more than1000). There are a myriad of such examples. Pharmaceutical drugs are increasingly effective. Products ordered in five minutes on the web and delivered to your door are worth more than products that you have to fetch yourself. Clothes custom-manufactured for your unique body scan are worth more than clothes you happen to find left on a store rack. These sorts of improvements are true for most product categories, and none of them are reflected in the productivity statistics.

The statistical methods underlying the productivity measurements tend to factor out gains by essentially concluding that we still only get one dollar of products and services for a dollar despite the fact that we get much more for a dollar (e.g., compare a $1,000 computer today to one ten years ago). University of Chicago Professor Pete Klenow and University of Rochester Professor Mark Bils estimate that the value of existing goods has been increasing at 1.5% per year for the past 20 years because of qualitative improvements. This still does not account for the introduction of entirely new products and product categories (e.g., cell phones, pagers, pocket computers). The Bureau of Labor Statistics, which is responsible for the inflation statistics, uses a model that incorporates an estimate of quality growth at only 0.5% per year, reflecting a systematic underestimate of quality improvement and a resulting overestimate of inflation by at least 1 percent per year.

Despite these weaknesses in the productivity statistical methods, the gains in productivity are now reaching the steep part of the exponential curve. Labor productivity grew at 1.6% per year until 1994, then rose at 2.4% per year, and is now growing even more rapidly. In the quarter ending July 30, 2000, labor productivity grew at 5.3%. Manufacturing productivity grew at 4.4% annually from 1995 to 1999, durables manufacturing at 6.5% per year.



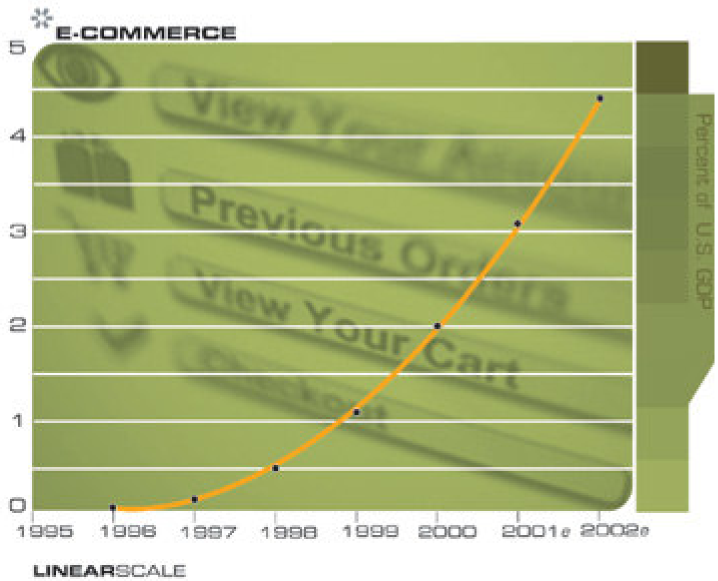
The 1990s have seen the most powerful deflationary forces in history. This is why we are not seeing inflation. Yes, it's true that low unemployment, high asset values, economic growth, and other such factors are inflationary, but these factors are offset by the double-exponential trends in the price-performance of all information-based technologies: computation, memory, communications, biotechnology, miniaturization, and even the overall rate of technical progress. These technologies deeply affect all industries. We are also undergoing massive disintermediation in the channels of distribution through the Web and other new communication technologies, as well as escalating efficiencies in operations and administration.

All of the technology trend charts above represent massive deflation. There are many examples of the impact of these escalating efficiencies. BP Amoco's cost for finding oil is now less than $1 per barrel, down from nearly $10 in 1991. Processing an Internet transaction costs a bank one penny, compared to over $1 using a teller ten years ago. A Roland Berger/Deutsche Bank study estimates a cost savings of $1200 per North American car over the next five years. A more optimistic Morgan Stanley study estimates that Internet-based procurement will save Ford, GM, and DaimlerChrysler about $2700 per vehicle.

It is important to point out that a key implication of nanotechnology is that it will bring the economics of software to hardware, i.e., to physical products. Software prices are deflating even more quickly than hardware.

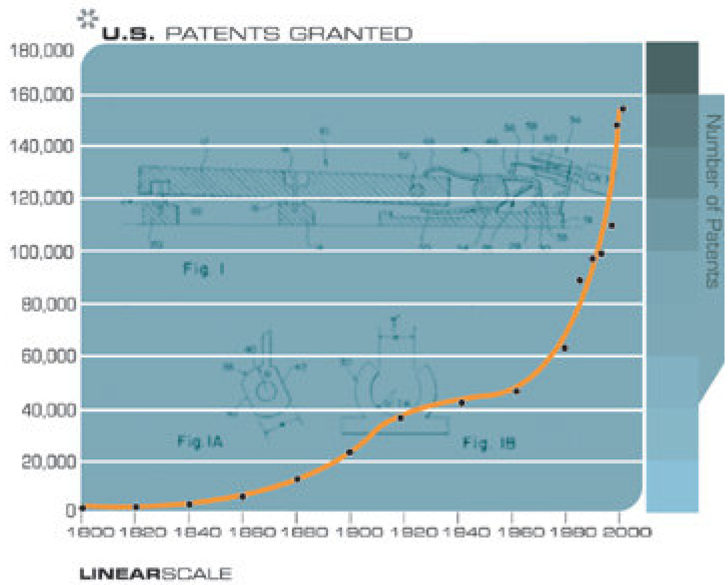
Software Price-Performance Has Also Improved at an Exponential Rate (Example: Automatic Speech Recognition Software)

	1985	**1995**	**2000**
Price	$5,000	$500	$50
Vocabulary Size (# words)	1,000	10,000	100,000
Continuous Speech?	No	No	Yes
User Training Required (Minutes)	180	60	5
Accuracy	Poor	Fair	Good



Current economic policy is based on outdated models that include energy prices, commodity prices, and capital investment in plant and equipment as key driving factors, but do not adequately model the size of technology, bandwidth, MIPs, megabytes, intellectual property, knowledge, and other increasingly vital (and increasingly increasing) constituents that are driving the economy.

Another indication of the law of accelerating returns in the exponential growth of human knowledge, including intellectual property. If we look at the development of intellectual property within the nanotechnology field, we see even more rapid growth.

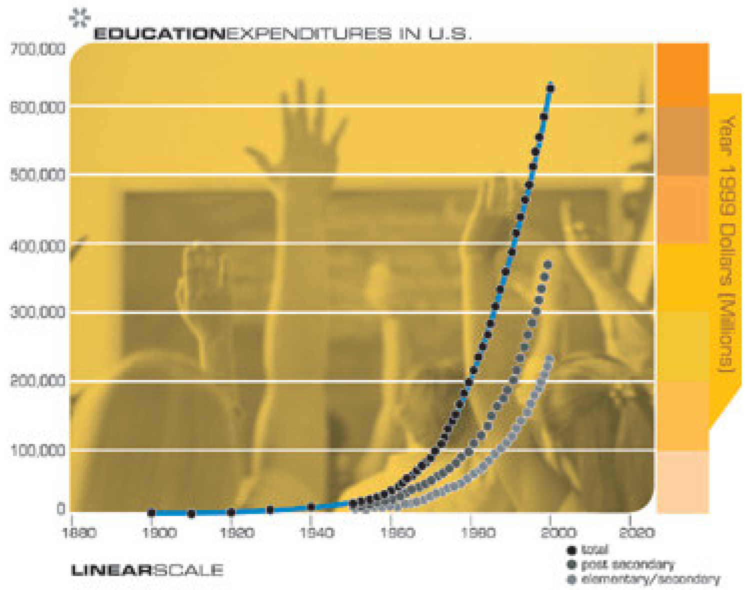


None of this means that cycles of recession will disappear immediately. Indeed there is a current economic slowdown and a technology-sector recession. The economy still has some of the underlying dynamics that historically have caused cycles of recession, specifically excessive commitments such as over-investment, excessive capital intensive projects and the overstocking of inventories. However, the rapid dissemination of information, sophisticated forms of online procurement, and increasingly transparent markets in all industries have diminished the impact of this cycle. So "recessions" are likely to have less direct impact on our standard of living. The underlying long-term growth rate will continue at a double exponential rate.

Moreover, innovation and the rate of paradigm shift are not noticeably affected by the minor deviations caused by economic cycles. All of the technologies exhibiting exponential growth shown in the above charts are continuing without losing a beat through this economic slowdown.

The overall growth of the economy reflects completely new forms and layers of wealth and value that did not previously exist, or least that did not previously constitute a significant portion of the economy (but do now): new forms of nanoparticle-based materials, genetic information, intellectual property, communication portals, web sites, bandwidth, software, data bases, and many other new technology-based categories.

Another implication of the law of accelerating returns is exponential growth in education and learning. Over the past 120 years, we have increased our investment in K-12 education (per student and in constant dollars) by a factor of ten. We have a one hundred fold increase in the number of college students. Automation started by amplifying the power of our muscles, and in recent times has been amplifying the power of our minds. Thus, for the past two centuries, automation has been eliminating jobs at the bottom of the skill ladder while creating new (and better paying) jobs at the top of the skill ladder. So the ladder has been moving up, and thus we have been exponentially increasing investments in education at all levels.



The Deeply Intertwined Promise and Peril of Nanotechnology and Related Advanced Technologies

Technology has always been a double-edged sword, bringing us longer and healthier life spans, freedom from physical and mental drudgery, and many new creative possibilities on the one hand, while introducing new and salient dangers on the other. Technology empowers both our creative and destructive natures. Stalin's tanks and Hitler's trains used technology. We still live today with sufficient nuclear weapons (not all of which appear to be well accounted for) to end all mammalian life on the planet. Bioengineering is in the early stages of enormous strides in reversing disease and aging processes. However, the means and knowledge will soon exist in a routine college bioengineering lab (and already exists in more sophisticated labs) to create unfriendly pathogens more dangerous than nuclear weapons. As technology accelerates towards the full realization of biotechnology, nanotechnology and "strong" AI (artificial intelligence at human levels and beyond), we will see the same intertwined potentials: a feast of creativity resulting from human intelligence expanded many-fold combined with many grave new dangers.

Consider unrestrained nanobot replication. Nanobot technology requires billions or trillions of such intelligent devices to be useful. The most cost-effective way to scale up to such levels is through self-replication, essentially the same approach used in the biological world. And in the same way that biological self-replication gone awry (i.e., cancer) results in biological destruction, a defect in the mechanism curtailing nanobot self-replication would endanger all physical entities, biological or otherwise. I address below steps we can take to address this grave risk, but we cannot have complete assurance in any strategy that we devise today.

Other primary concerns include "who is controlling the nanobots?" and "who are the nanobots talking to?" Organizations (e.g., governments, extremist groups) or just a clever individual could put trillions of undetectable nanobots in the water or food supply of an individual or of an entire population. These "spy" nanobots could then monitor, influence, and even control our thoughts and actions. In addition to introducing physical spy nanobots, existing nanobots could be influenced through software viruses and other software "hacking" techniques. When there is software running in our brains, issues of privacy and security will take on a new urgency.

My own expectation is that the creative and constructive applications of this technology will dominate, as I believe they do today. However, I believe we need to invest more heavily in developing specific defensive technologies. As I address further below, we are at this stage today for biotechnology, and will reach the stage where we need to directly implement defensive technologies for nanotechnology during the late teen years of this century.

If we imagine describing the dangers that exist today to people who lived a couple of hundred years ago, they would think it mad to take such risks. On the other hand, how many people in the year 2000 would really want to go back to the short, brutish, disease-filled, poverty-stricken, disaster-prone lives that 99 percent of the human race struggled through a couple of centuries ago? We may romanticize the past, but up until fairly recently, most of humanity lived extremely fragile lives where one all-too-common misfortune could spell disaster. Substantial portions of our species still live in this precarious way, which is at least one reason to continue technological progress and the economic enhancement that accompanies it.

People often go through three stages in examining the impact of future technology: awe and wonderment at its potential to overcome age old problems; then a sense of dread at a new set of grave dangers that accompany these new technologies; followed, finally and hopefully, by the realization that the only viable and responsible path is to set a careful course that can realize the promise while managing the peril.

This congressional hearing was party inspired by Bill Joy's cover story for Wired magazine, *Why The Future Doesn't Need* Us. Bill Joy, cofounder of Sun Microsystems and principal developer of the Java programming language, has recently taken up a personal mission to warn us of the impending dangers from the emergence of self-replicating technologies in the fields of genetics, nanotechnology, and robotics, which he aggregates under the label "GNR." Although his warnings are not entirely new, they have attracted considerable attention because of Joy's credibility as one of our leading technologists. It is reminiscent of the attention that George Soros, the currency arbitrager and arch capitalist, received when he made vaguely critical comments about the excesses of unrestrained capitalism .

Joy's concerns include genetically altered designer pathogens, followed by self-replicating entities created through nanotechnology. And if we manage to survive these first two perils, we will encounter robots whose intelligence will rival and ultimately exceed our own. Such robots may make great assistants, but who's to say that we can count on them to remain reliably friendly to mere humans?

Although I am often cast as the technology optimist who counters Joy's pessimism, I do share his concerns regarding self-replicating technologies; indeed, I played a role in bringing these dangers to Bill's attention. In many of the dialogues and forums in which I have participated on this subject, I end up defending Joy's position with regard to the feasibility of these technologies and scenarios when they come under attack by commentators who I believe are being quite shortsighted in their skepticism. Even so, I do find fault with Joy's prescription: halting the advance of technology and the pursuit of knowledge in broad fields such as nanotechnology.

In his essay, Bill Joy eloquently described the plagues of centuries past and how new self-replicating technologies, such as mutant bioengineered pathogens and "nanobots" run amok, may bring back long-forgotten pestilence. Indeed these are real dangers. It is also the case, which Joy acknowledges, that it has been technological advances, such as antibiotics and improved sanitation, which have freed us from the prevalence of such plagues. Suffering in the world continues and demands our steadfast attention. Should we tell the millions of people afflicted with cancer and other devastating conditions that we are canceling the development of all bioengineered treatments because there is a risk that these same technologies may someday be used for malevolent purposes? Having asked the rhetorical question, I realize that there is a movement to do exactly that, but I think most people would agree that such broad-based relinquishment is not the answer.

The continued opportunity to alleviate human distress is one important motivation for continuing technological advancement. Also compelling are the already apparent economic gains I discussed above that will continue to hasten in the decades ahead. The continued acceleration of many intertwined technologies are roads paved with gold (I use the plural here because technology is clearly not a single path). In a competitive environment, it is an economic imperative to go down these roads. Relinquishing technological advancement would be economic suicide for individuals, companies, and nations.

The Relinquishment Issue

This brings us to the issue of relinquishment, which is Bill Joy's most controversial recommendation and personal commitment. I do feel that relinquishment at the right level is part of a responsible and constructive response to these genuine perils. The issue, however, is exactly this: at what level are we to relinquish technology?

Ted Kaczynski would have us renounce all of it. This, in my view, is neither desirable nor feasible, and the futility of such a position is only underscored by the senselessness of Kaczynski's deplorable tactics. There are other voices, less reckless than Kaczynski, who are nonetheless arguing for broad-based relinquishment of technology. Bill McKibben, the environmentalist who was one of the first to warn against global warming, takes the position that "environmentalists must now grapple squarely with the idea of a world that has enough wealth and enough technological capability, and should not pursue more." In my view, this position ignores the extensive suffering that remains in the human world, which we will be in a position to alleviate through continued technological progress.

Another level would be to forego certain fields -- nanotechnology, for example -- that might be regarded as too dangerous. But such sweeping strokes of relinquishment are equally untenable. As I pointed out above, nanotechnology is simply the inevitable end result of the persistent trend towards miniaturization that pervades all of technology. It is far from a single centralized effort, but is being pursued by a myriad of projects with many diverse goals.

One observer wrote:

"A further reason why industrial society cannot be reformed. . . is that modern technology is a unified system in which all parts are dependent on one another. You can't get rid of the "bad" parts of technology and retain only the "good" parts. Take modern medicine, for example. Progress in medical science depends on progress in chemistry, physics, biology, computer science and other fields. Advanced medical treatments require expensive, high-tech equipment that can be made available only by a technologically progressive, economically rich society. Clearly you can't have much progress in medicine without the whole technological system and everything that goes with it."

The observer I am quoting is, again, Ted Kaczynski. Although one will properly resist Kaczynski as an authority, I believe he is correct on the deeply entangled nature of the benefits and risks. However, Kaczynski and I clearly part company on our overall assessment on the relative balance between the two. Bill Joy and I have dialogued on this issue both publicly and privately, and we both believe that technology will and should progress, and that we need to be actively concerned with the dark side. If Bill and I disagree, it's on the granularity of relinquishment that is both feasible and desirable.

Abandonment of broad areas of technology will only push them underground where development would continue unimpeded by ethics and regulation. In such a situation, it would be the less-stable, less-responsible practitioners (e.g., terrorists) who would have all the expertise.

I do think that relinquishment at the right level needs to be part of our ethical response to the dangers of 21st century technologies. One constructive example of this is the proposed ethical guideline by the Foresight Institute, founded by nanotechnology pioneer Eric Drexler, that nanotechnologists agree to relinquish the development of physical entities that can self-replicate in a natural environment. Another is a ban on self-replicating physical entities that contain their own codes for self-replication. In what nanotechnologist Ralph Merkle calls the "broadcast architecture," such entities would have to obtain such codes from a centralized secure server, which would guard against undesirable replication. I discuss these guidelines further below.

The broadcast architecture is impossible in the biological world, which represents at least one way in which nanotechnology can be made safer than biotechnology. In other ways, nanotech is potentially more dangerous because nanobots can be physically stronger than protein-based entities and more intelligent. It will eventually be possible to combine the two by having nanotechnology provide the codes within biological entities (replacing DNA), in which case biological entities can use the much safer broadcast architecture. I comment further on the strengths and weaknesses of the broadcast architecture below.

As responsible technologies, our ethics should include such "fine-grained" relinquishment, among other professional ethical guidelines. Other protections will need to include oversight by regulatory bodies, the development of technology-specific "immune" responses, as well as computer assisted surveillance by law enforcement organizations. Many people are not aware that our intelligence agencies already use advanced technologies such as automated word spotting to monitor a substantial flow of telephone conversations. As we go forward, balancing our cherished rights of privacy with our need to be protected from the malicious use of powerful 21st century technologies will be one of many profound challenges. This is one reason that such issues as an encryption "trap door" (in which law enforcement authorities would have access to otherwise secure information) and the FBI "Carnivore" email-snooping system have been controversial, although these controversies have abated since 9-11-2001.

As a test case, we can take a small measure of comfort from how we have dealt with one recent technological challenge. There exists today a new form of fully nonbiological self replicating entity that didn't exist just a few decades ago: the computer virus. When this form of destructive intruder first appeared, strong concerns were voiced that as they became more sophisticated, software pathogens had the potential to destroy the computer network medium they live in. Yet the "immune system" that has evolved in response to this challenge has been largely effective. Although destructive self-replicating software entities do cause damage from time to time, the injury is but a small fraction of the benefit we receive from the computers and communication links that harbor them. No one would suggest we do away with computers, local area networks, and the Internet because of software viruses.

One might counter that computer viruses do not have the lethal potential of biological viruses or of destructive nanotechnology. This is not always the case; we rely on software to monitor patients in critical care units, to fly and land airplanes, to guide intelligent weapons in our current campaign in Iraq, and other "mission-critical" tasks. To the extent that this is true, however, this observation only strengthens my argument. The fact that computer viruses are not usually deadly to humans only means that more people are willing to create and release them. It also means that our response to the danger is that much less intense. Conversely, when it comes to self-replicating entities that are potentially lethal on a large scale, our response on all levels will be vastly more serious, as we have seen since 9-11.

I would describe our response to software pathogens as effective and successful. Although they remain (and always will remain) a concern, the danger remains at a nuisance level. Keep in mind that this success is in an industry in which there is no regulation, and no certification for practitioners. This largely unregulated industry is also enormously productive. One could argue that it has contributed more to our technological and economic progress than any other enterprise in human history. I discuss the issue of regulation further below.

Development of Defensive Technologies and the Impact of Regulation

Joy's treatise is effective because he paints a picture of future dangers as if they were released on today's unprepared world. The reality is that the sophistication and power of our defensive technologies and knowledge will grow along with the dangers. When we have "gray goo" (unrestrained nanobot replication), we will also have "blue goo" ("police" nanobots that combat the "bad" nanobots). The story of the 21st century has not yet been written, so we cannot say with assurance that we will successfully avoid all misuse. But the surest way to prevent the development of the defensive technologies would be to relinquish the pursuit of knowledge in broad areas. We have been able to largely control harmful software virus replication because the requisite knowledge is widely available to responsible practitioners. Attempts to restrict this knowledge would have created a far less stable situation. Responses to new challenges would have been far slower, and it is likely that the balance would have shifted towards the more destructive applications (e.g., software viruses).

The challenge most immediately in front of us is not self-replicating nanotechnology, but rather self-replicating biotechnology. The next two decades will be the golden age of biotechnology, whereas the comparable era for nanotechnology will follow in the 2020s and beyond. We are now in the early stages of a transforming technology based on the intersection of biology and information science. We are learning the "software" methods of life and disease processes. By reprogramming the information processes that lead to and encourage disease and aging, we will have the ability to overcome these afflictions. However, the same knowledge can also empower a terrorist to create a bioengineered pathogen.

As we compare the success we have had in controlling engineered software viruses to the coming challenge of controlling engineered biological viruses, we are struck with one salient difference. As I noted above, the software industry is almost completely unregulated. The same is obviously not the case for biotechnology. A bioterrorist does not need to put his "innovations" through the FDA. However, we do require the scientists developing the defensive technologies to follow the existing regulations, which slow down the innovation process at every step. Moreover, it is impossible, under existing regulations and ethical standards, to test defenses to bioterrorist agents. There is already extensive discussion to modify these regulations to allow for animal models and simulations to replace infeasible human trials. This will be necessary, but I believe we will need to go beyond these steps to accelerate the development of vitally needed defensive technologies.

For reasons I have articulated above, stopping these technologies is not feasible, and pursuit of such broad forms of relinquishment will only distract us from the vital task in front of us. In terms of public policy, the task at hand is to rapidly develop the defensive steps needed, which include ethical standards, legal standards, and defensive technologies. It is quite clearly a race. As I noted, in the software field, the defensive technologies have remained a step ahead of the offensive ones. With the extensive regulation in the medical field slowing down innovation at each stage, we cannot have the same confidence with regard to the abuse of biotechnology.

In the current environment, when one person dies in gene therapy trials, there are congressional investigations and all gene therapy research comes to a temporary halt. There is a legitimate need to make biomedical research as safe as possible, but our balancing of risks is completely off. The millions of people who desperately need the advances to be made available by gene therapy and other breakthrough biotechnology advances appear to carry little political weight against a handful of well-publicized casualties from the inevitable risks of progress.

This equation will become even more stark when we consider the emerging dangers of bioengineered pathogens. What is needed is a change in public attitude in terms of tolerance for needed risk.

Hastening defensive technologies is absolutely vital to our security. We need to streamline regulatory procedures to achieve this. However, we also need to greatly increase our investment explicitly in the defensive technologies. In the biotechnology field, this means the rapid development of antiviral medications. We will not have time to develop specific countermeasures for each new challenge that comes along. We are close to developing more generalized antiviral technologies, and these need to be accelerated.

I have addressed here the issue of biotechnology because that is the threshold and challenge that we now face. The comparable situation will exist for nanotechnology once replication of nano-engineered entities has been achieved. As that threshold comes closer, we will then need to invest specifically in the development of defensive technologies, including the creation of a nanotechnology-based immune system. Bill Joy and other observers have pointed out that such an immune system would itself be a danger because of the potential of "autoimmune" reactions (i.e., the immune system using its powers to attack the world it is supposed to be defending).

However, this observation is not a compelling reason to avoid the creation of an immune system. No one would argue that humans would be better off without an immune system because of the possibility of auto immune diseases. Although the immune system can itself be a danger, humans would not last more than a few weeks (barring extraordinary efforts at isolation) without one. The development of a technological immune system for nanotechnology will happen even without explicit efforts to create one. We have effectively done this with regard to software viruses. We created a software virus immune system not through a formal grand design project, but rather through our incremental responses to each new challenge. We can expect the same thing will happen as challenges from nanotechnology based dangers emerge. The point for public policy will be to specifically invest in these defensive technologies.

It is premature today to develop specific defensive nanotechnologies since we can only have a general idea of what we are trying to defend against. It would be similar to the engineering world creating defenses against software viruses before the first one had been created. However, there is already fruitful dialogue and discussion on anticipating this issue, and significantly expanded investment in these efforts is to be encouraged.

As I mentioned above, the Foresight Institute, for example, has devised a set of ethical standards and strategies for assuring the development of safe nanotechnology. These guidelines include:

- "Artificial replicators must not be capable of replication in a natural, uncontrolled environment."
- "Evolution within the context of a self-replicating manufacturing system is discouraged."
- "MNT (molecular nanotechnology) designs should specifically limit proliferation and provide traceability of any replicating systems."
- "Distribution of molecular manufacturing development capability should be restricted whenever possible, to responsible actors that have agreed to the guidelines. No such restriction need apply to end products of the development process."

Other strategies that the Foresight Institute has proposed include:

- Replication should require materials not found in the natural environment.
- Manufacturing (replication) should be separated from the functionality of end products. Manufacturing devices can create end products, but cannot replicate themselves, and end products should have no replication capabilities.
- Replication should require replication codes that are encrypted, and time limited. The broadcast architecture mentioned earlier is an example of this recommendation.

These guidelines and strategies are likely to be effective with regarding to preventing accidental release of dangerous self-replicating nanotechnology entities. The situation with regard to intentional design and release of such entities is more complex and more challenging. We can anticipate approaches that would have the potential to defeat each of these layers of protections by a sufficiently determined and destructive opponent.

Take, for example, the broadcast architecture. When properly designed, each entity is unable to replicate without first obtaining replication codes. These codes are not passed on from one replication generation to the next. However, a modification to such a design could bypass the destruction of the replication codes and thereby pass them on to the next generation. To overcome that possibility, it has been recommended that the memory for the replication codes be limited to only a subset of the full replication code so that there is insufficient memory to pass the codes along. However, this guideline could be defeated by expanding the size of the replication code memory to incorporate the entire code. Another protection that has been suggested is to encrypt the codes and to build in protections such as time expiration limitations in the decryption systems. However, we can see the ease with which protections against unauthorized replications of intellectual property such as music files has been defeated. Once replication codes and protective layers are stripped away, the information can be replicated without these restrictions.

My point is not that protection is impossible. Rather, we need to realize that any level of protection will only work to a certain level of sophistication. The "meta" lesson here is that we will need to continue to advance the defensive technologies, and keep them one or more steps ahead of the destructive technologies. We have seen analogies to this in many areas, including technologies for national defense, as well as our largely successful efforts to combat software viruses, that I alluded to above.

What we can do today with regard to the critical challenge of self-replication in nanotechnology is to continue the type of effective study that the Foresight Institute has initiated. With the human genome project, three to five percent of the budgets were devoted to the ethical, legal, and social implications (ELSI) of the technology. A similar commitment for nanotechnology would be appropriate and constructive.

Technology will remain a double-edged sword, and the story of the 21st century has not yet been written. It represents vast power to be used for all humankind's purposes. We have no choice but to work hard to apply these quickening technologies to advance our human values, despite what often appears to be a lack of consensus on what those values should be.

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Nanotechnology

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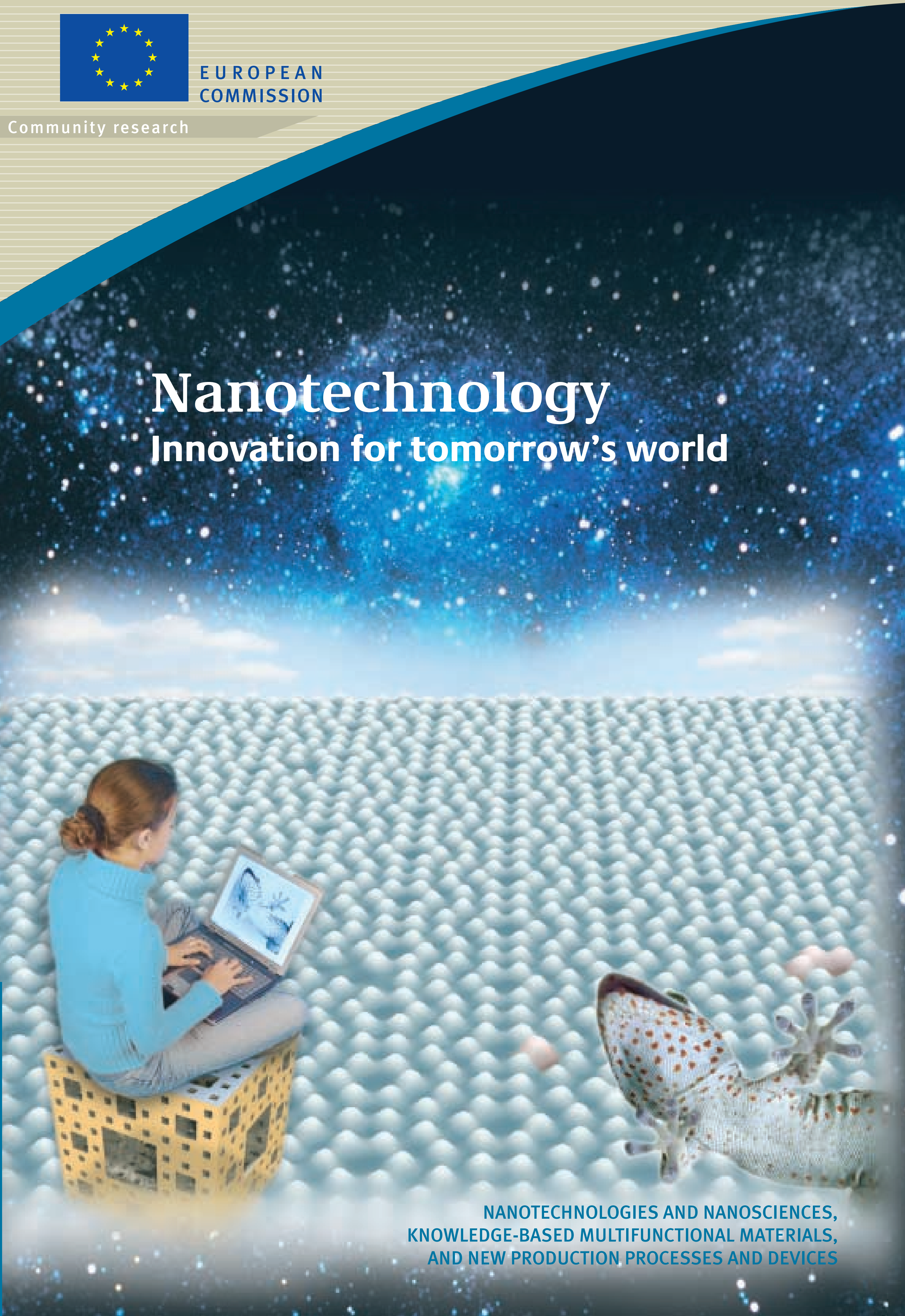

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EUROPEAN COMMISSION

Nanotechnology

Innovation for tomorrow's world

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Foreword

Nanotechnology is a new approach that refers to understanding and mastering the properties of matter at the nano-scale: one nano-meter (one billionth of meter) is the length of a small molecule. At this level, matter exhibits different and often amazing properties and the borders between established scientific and technical disciplines fade. Hence the strong interdisciplinary character that is associated with nanotechnology.

Nanotechnology is often described as having a “disruptive” or “revolutionary” potential in terms of its possible impact on industrial production routes. Nanotechnology offers possible solutions to many current problems by means of smaller, lighter, faster and better performing materials, components and systems. This opens up new opportunities for wealth creation and employment. Nanotechnology is also expected to make some essential contributions to solving global and environmental challenges by realising more specific-to-use products and processes, save resources and lower waste and emissions.

Currently, enormous progress is being made in the worldwide nanotechnological race. Europe invested early with many programmes in nanosciences starting during the mid- to late-1990’s. It has subsequently developed a strong knowledge-base and now needs to ensure that European industry and society can reap the benefits of this knowledge through the development of new products and processes.

Nanotechnology is the subject of a recent Commission communication (‘Towards a European strategy for nanotechnology’). In this Communication, it is not only proposed that research in nanosciences and nanotechnologies should be boosted, but that several other interdependent dynamics must be taken into account:

- Greater coordination of national research programmes and investment also to ensure that Europe has teams and infrastructures (“poles of excellence”) that can compete at international-level. In parallel, collaboration between research organisations in the public and private sector across Europe is essential for achieving sufficient critical mass.
- Other competitiveness factors should not be overlooked, such as adequate metrology, regulations and intellectual property rights so as to pave the way for industrial innovation to be carried out and lead to competitive advantages, both for large and small- and medium-sized companies.
- Activities related to education and training are of great importance; in particular, there is scope in Europe to improve the entrepreneurial character of researchers as well as the production engineers’ positive attitude to change. The realisation of true interdisciplinary research in nanotechnology may also require new approaches to education and training for research and industry.
- Social aspects (such as public information and communication, health and environmental issues, and risk assessment) are further key factors to ensure the responsible development of nanotechnology and that it meets people’s expectations. Public and investors’ confidence in nanotechnology will be crucial for its long-term development and fruitful application.

The aim of this brochure is to illustrate what nanotechnology is and what it can offer to the European citizens.

Ezio Andreta
Director “Industrial Technologies”
Research Directorate-general
European Commission

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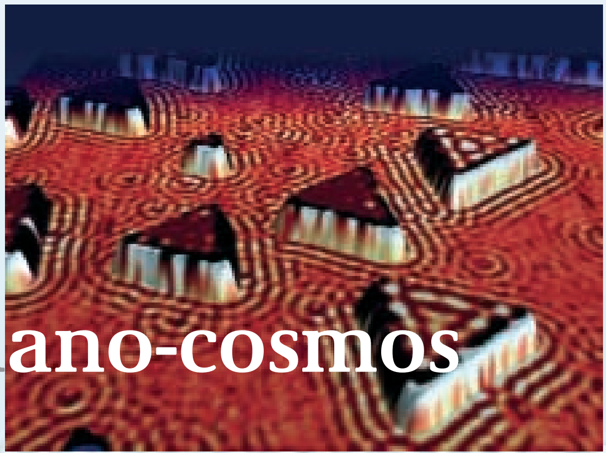
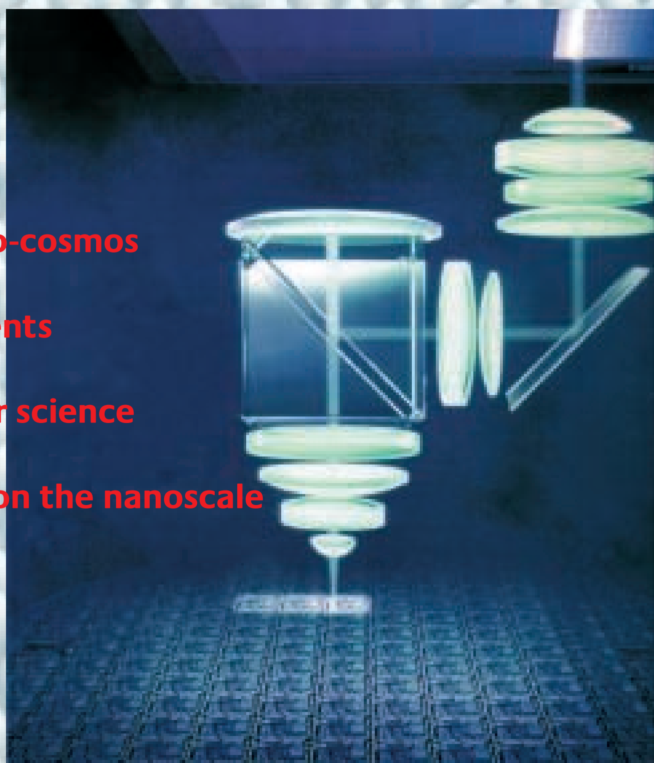
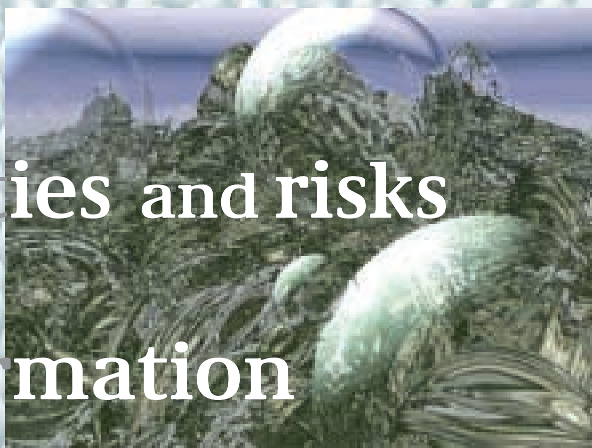


Journey into the nano-cosmos

Instruments and processes



Nanotechnology in society



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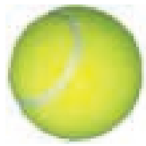
Journey into the nano-cosmos



The atom: old idea and the new reality

Amedeo Avogadro (1776-1856), a physics professor in Turin, the first man to analyse a raindrop.

Our material world is made up of atoms. This was the claim made over 2 400 years ago by the Greek philosopher Democratus. The modern Greeks expressed their thanks by stamping his effigy on their 10-Drachma coin. This was in wide circulation, although not in the same numbers as atoms. A single raindrop contains about 1 000 000 000 000 000 000 000 of them, for atoms are miniscule – only one tenth of a nanometre in size, and a nanometre measures a mere one-millionth of a millimetre.

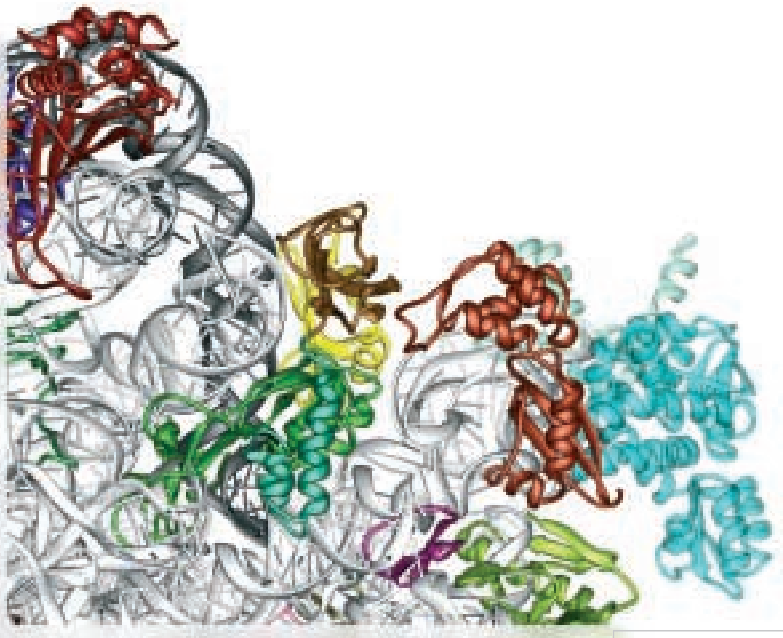
The ratio of the diameter of a magnesium atom to a tennis ball is the same as that of a tennis ball to the Earth. Just think of that when you next take a magnesium tablet!

The spirit of Democratus hangs over the nano-scene, a sea of infinite possibilities.

A few centuries later, Lucretius, a Roman writer, wrote a poem about atoms: *"The Universe consists of infinite space and an infinite number of irreducible particles, atoms, whose variety is equally infinite. … Atoms vary only in shape, size and weight; they are impenetrably hard, unchanging, the limit of physical divisibility …"*

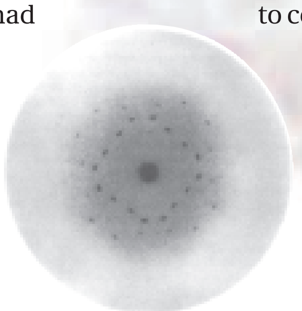
This was all very well, although it was at that point nothing more than pure speculation. For a long time, no more thought was given to such matters.

In the 17th century, Johannes Kepler, the famous astronomer, devoted thought to snowflakes, and published his ideas in 1611: the regular shape could only be due to simple, uniform building blocks. The idea of the atom again began to attract popularity.

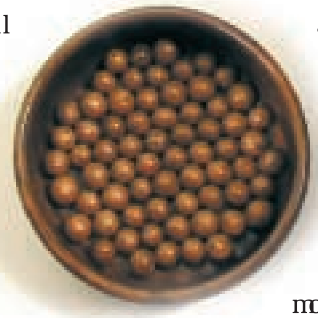


The structure of biological nanomachines like ribosomes are crystallographically determined by Ada Yonath, DESY, Hamburg.

Scientists who worked with minerals and crystals took the existence of atoms as granted. In 1912 however, direct proof was obtained at the University of Munich: a copper sulphate crystal split up x-ray light in the same way that the material of an umbrella splits up the light from a lantern – the crystal had to consist of atoms, arranged in an ordered structure, like the yarn in umbrella material, or a pile of oranges in a market.



The reason why the atoms in the crystal arrange themselves so regularly is simple. The matter makes itself as comfortable as possible, and the most comfortable way is a regular, ordered structure. Even nuts shaken in a bowl form regular patterns, and this process is even easier for atoms.

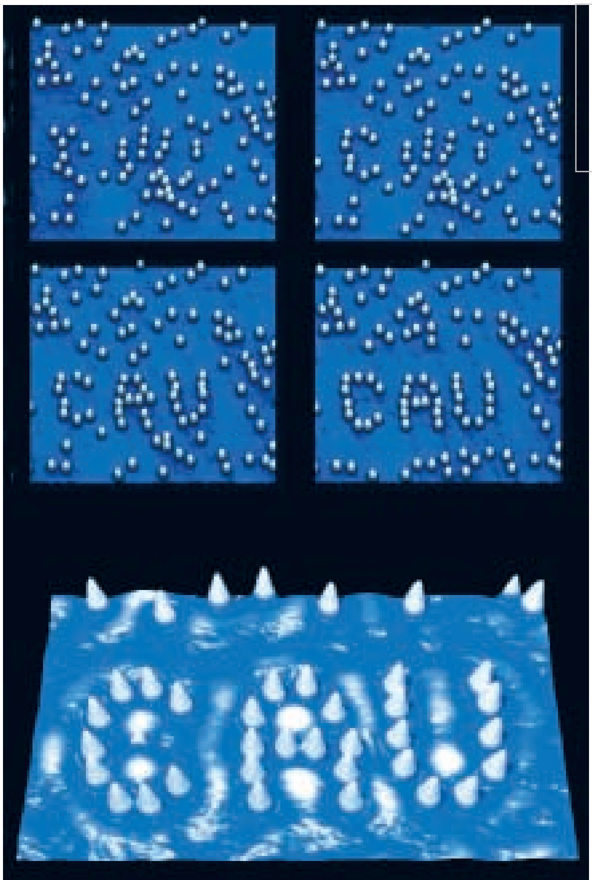


Simple patterns are however not always the ones that are most easily reproducible. Driven by forces of self-arrangement, the matter of the Earth has over billions of years taken on a fantastically complex and, in some cases, even living form.

Modern analytical devices can now visualise such highly complex components of living matter down to a scale of nanometres.

Finally, in the 1980s, an instrument was developed, known as the scanning tunnel microscope, that can not only visualise the individual atoms within a crystal – many people considered the first images to be a hoax – but can also poke and prod them around.

The stage was now set for a radical new departure: nanotechnology.



Manganese atoms are used by Professor Berndt in Kiel to reproduce the logo of the Christian-Albrechts University.

Journey into the nano-cosmos

Nanotechnology in nature

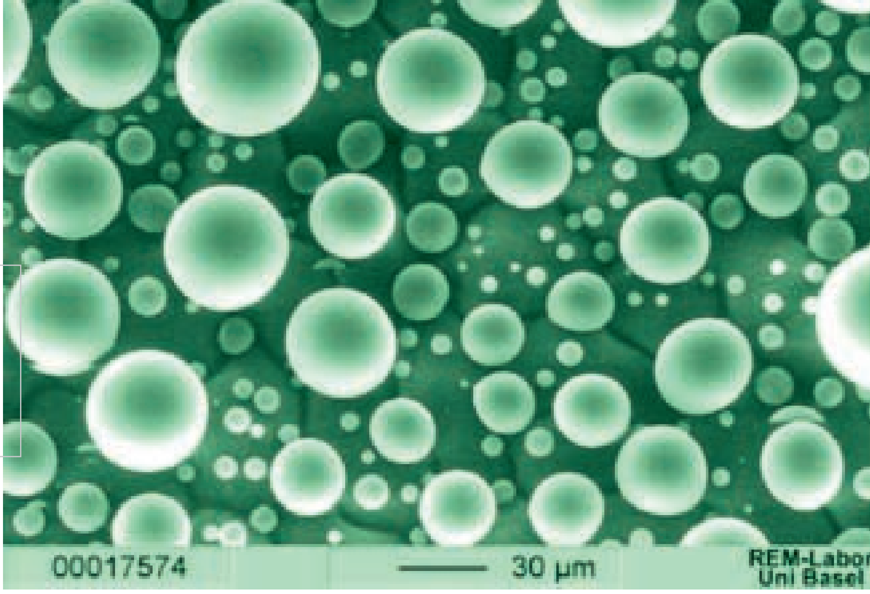
Nanotechnologists hold living nature dear to their hearts. In the four billion years of its existence, nature has created some astounding solutions to the problems it has encountered. One typical feature: life structures its matter down to the finest detail, right down to the level of the atom. This is what nanotechnologists also aim to do.

Atoms are not generally loved. When we hear about them, we tend to think of terrible explosions or dangerous radiation. But this only refers to technologies involving the atomic *nucleus*. Nanotechnology is concerned with the *shell* of the atom, this is the scale at which nanotechnology comes into play.

In order to remove any doubt we might have that atoms are everyday things, which in the right combination can even taste good, let us take as our point of departure into the nano-cosmos a mundane item such as cheese.

Mimolette is a product of Flanders and the tiny holes in the surface gives away the cheese's secret: it is inhabited! The producers recognise that the activity of the mites improve the aroma of Mimolette cheese. The mites are about a tenth of a millimetre in size. The ESEM (Environmental Scanning Electron Microscope), a special scanning electron microscope, can view even living mites. Like other living things, mites are also composed of cells. The scale of the cell is the micrometer. A cell is equipped with highly complex machinery. An important component of this machinery is represented by the ribosomes, which produce all possible protein molecules according to the specifications of the genetic material DNA. The order of size of the ribosome is around 20 nanometres. Parts of the ribosome structure have now been identified down to the level of individual atoms. The first fruits of this type of nanobiotechnology research have already been harvested in the form of new medications capable of blocking bacterial ribosomes.

The lotus blossom cleans its leaves with the aid of the eponymous lotus effect.



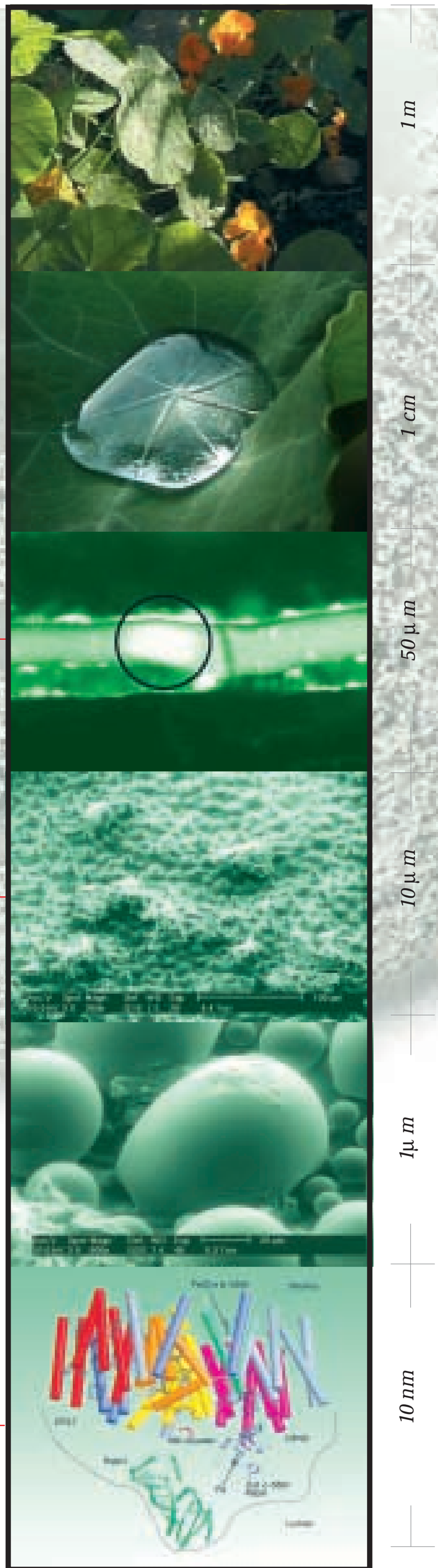
Water droplets on a nasturtium leaf, imaged with the aid of the Environmental Scanning Electron Microscope (ESEM).

Lotus effect & Co.

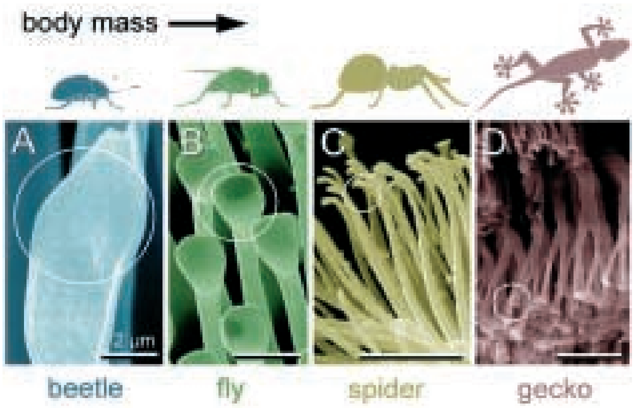
The nasturtium keeps its leaves clean with the aid of the lotus effect. The ESEM Environmental Scanning Electron Microscope shows how water droplets are kept away from the surface of the leaf. This is due to the downy surface of the leaves that causes the water droplets to run off at high speed, taking with them any dirt on the surface of the leaf. The lotus effect, which has been researched extensively by Professor Barthlott and his associates at the University of Bonn, has already been used in a range of products, such as façade coatings, where the water runs off carrying away dirt. Sanitary ceramics that utilise the lotus effect are very easy to keep clean.

Plant leaves also make use of other types of nanotechnology. Their water management system is often controlled by forisomes, microscopically small muscles, which open up channels in the capillary system of the plant, or close them off if the plant is injured. Three Fraunhofer institutes and the University of Giessen are currently trying to develop technical applications for plant muscles, such as microscopically small linear motors, or perhaps a complete laboratory-on-a-chip (lab-on-a-chip).

One of the most refined technology on an atomic scale is the photosynthesis process, which collects the energy for life on Earth. This is a matter for every individual atom. Whoever can copy it using nanotechnology will have unlimited energy for all time.



Nanotechnology in nature



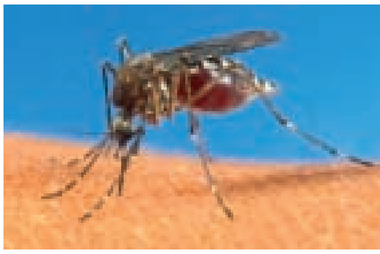
Beetles, flies, spiders and geckos have revealed some of the secrets of their sticking powers at the Max-Planck Institute for Metal Research in Stuttgart. They hold on by means of tiny hairs that form a van-der-Waals bond with the surface they are in contact with. The heavier the animal, the finer and more numerous are the hairs.

Nanotechnology on the ceiling: the gecko

Geckos can run up any wall, run upside down across the ceiling, and even hang from it by a single foot. This is done with the aid of – you guessed it – nanotechnology. The gecko's foot is covered in very fine hairs that approach the surface to within a few nanometres over large areas. This allows the so-called van-der-Waals bond to come into action and despite the fact that it is actually very weak, it supports the gecko's weight due to the millions of adhesion points. The bonds can easily be broken by "peeling", in the same way that one removes a strip of adhesive tape, allowing the gecko to run along the ceiling. Material scientists are already looking forward to producing a synthetic "gecko".

Sticking to life

Life exists because its components are held together by sophisticated nanotechnological adhesion methods. Even in the case of injuries, such as an insect sting: the point of the sting turns red, because tiny blood vessels expand, through which swarms of leukocytes, or white blood corpuscles then flow. Cells at the sting point secrete a pheromone. Depending on its concentration the cell linings of the blood vessels and the leukocytes deliver adhesive molecules, which delay the passage of the leukocytes along the vessel wall by their adhesive effect. At the maximum pheromone level, the leukocytes stick firmly; other adhesive molecules then draw the blood corpuscles through the vessel wall to the point of the sting, where they attack any intruders – the art of perfect adhesion. Man-made nanotechnological imitations are now being researched under the heading of "bonding on command".



Close-up of a fly's foot

Mussels – masters of the art of bonding

The common mussel – as cooked with vegetables and eaten every day in restaurants – is a master of the art of nanotechnological bonding. When it wants to attach itself to a rock, it opens its shell and pushes its foot onto the rock, arches its foot to form a suction cup, and injects streams of adhesives droplets, micelles, into the low-pressure area through tiny cannulae, where they burst to release a powerful underwater adhesive. This immediately creates a foam that serves as a small cushion. The mussel then anchors itself to this shock absorber with elastic byssus threads, so that it can be tossed about by the tide without harm.

Mussel with byssus threads and foot

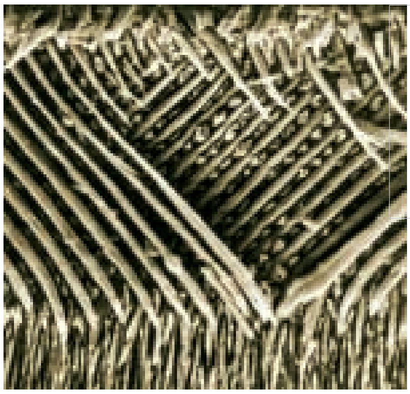
The Fraunhofer Institute IFAM in Bremen is researching into modified mussel adhesives, with which it hopes to make even the finest bone china dishwasher-proof. The “New materials and biomaterials” working group in Rostock and Greifswald also has mussels under the microscope.

The Venus flower basket – this deep-sea sponge is currently being studied as a biological model for fibre-optics.

Biomineralisation

Mussels are capable of even more. Their mother-of-pearl consists of innumerable minute chalk crystals in the form of the mineral aragonite, which on their own would be very brittle. In the mussel however, they are held together by screw-shaped, highly elastic proteins. Three percent by weight of protein is more than enough to make the shell of the abalone mussel three thousand times tougher than a pure calcite crystal. Sea urchins also use this technique to strengthen their 30-cm long spines so that they can withstand the pummelling of the waves.

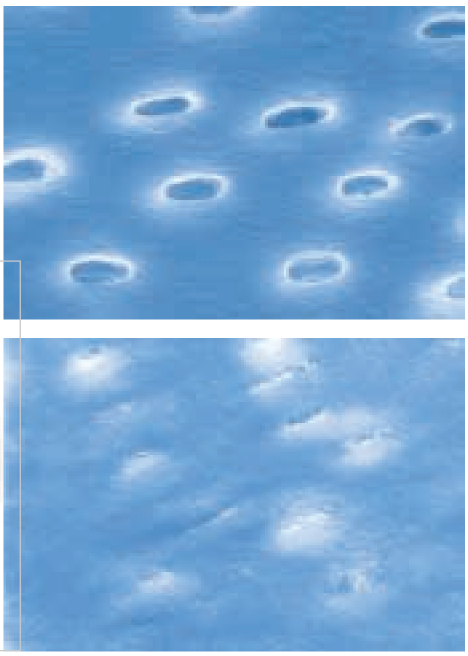
Biomineralisation can also create very delicate structures. On a small part of the ocean floor close to the Philippine Islands lives a sponge called the “Venus flower basket”. This creature is curved like the sheath of a Turkish dagger, but circular around its long axis. The sponge owes its name to the structure of the inner skeleton of its mantle. This consists of a tissue of fine silica needles, perforated like the wickerwork of a wooden chair back. This tissue is interwoven both in a right-angled network and diagonally. The Venus flower basket is considered a masterpiece of biomineralisation: tiny elementary building blocks of silica (silicon dioxide) three nanometres in diameter first connect the cells of the sponge together in superfine layers. These are then rolled up to form the silica needles, the basic element of the wickerwork structure, which can withstand high pressure variations.



The three-dimensional biomineral network in the tooth enamel of the vole’s molars protects the working surface against damage.

Technical biomineralisation: Nanoparticles repair teeth

If teeth are very sensitive to cold or bitter foods this can cause pain and is usually due to tiny channels – open dentine tubuli – in the tooth enamel. With nanoparticles of calcium phosphate (apatite) and protein produced by the firm of SusTech, these channels can be closed off ten times quicker than with conventional apatite compounds. The remineralised material layer behaves just like the body’s own tooth enamel in the mouth.

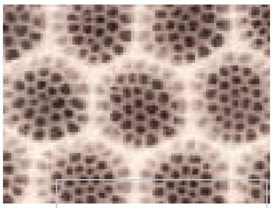


Nanotechnology in nature

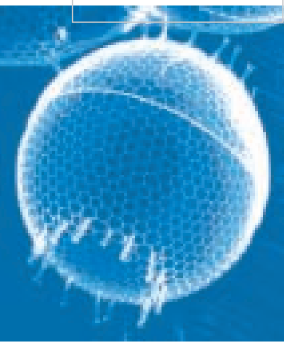
The starfish „Ophiocoma wendtii" is equipped with a perfect micro-lens system for optical vision. Above: its appearance in daytime, and below: at night.

Of (formerly) strategic importance was the bio-mineralisation of diatoms. These microscopically small creatures protect themselves by means of a silicic acid shell, whose main component is SiO_2, or silicon dioxide. Like quartz glass, which also consists of silicon dioxide, silicic acid shells are also relatively resistant to many corrosive acid and alkaline solutions, which is why nanotechnologists hope to use them as reaction vessels for nanometre-size crystals. One trick for creating nanoparticles by chemical reactions is to limit the reaction volume. When the reaction material within is used up, the crystals created by the reaction remain small. Diatoms contain many such nanoscale pores, or nano-reactors.

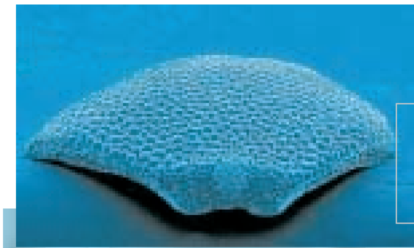
How do these sometimes very visually-attractive diatoms come into existence? The first clues have been found. Researchers at the University of Regensburg have discovered that members of a well-known protein group, the "polyamines", can produce nanoparticles, in the right silicic acid concentration, with a controllable diameter of between 50 and 900 nanometres – quite spontaneously under the forces of self-arrangement. According to simple growth models, diatoms occur just as spontaneously.



Diatoms – above similar to a "Menger sponge" (see also p. 21) – have maximum stability with the lowest weight due to their optimum shapes and – probably – light-collecting systems for their photosynthesis apparatus, chloroplasts.



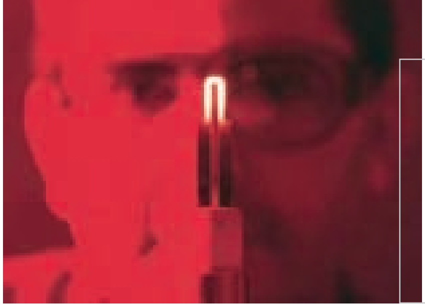
Why were diatoms supposed at one time to have had "strategic importance"? In 1867, the Swede Alfred Nobel discovered that infusorial earth, diatomaceous earth from fossil deposits of diatoms, absorbed nitroglycerine, thereby inhibiting the tendency of this explosive to detonate spontaneously. Nobel gave this mixture the name "Dynamite", whose roaring sales laid the basis for the foundation which today finances the Nobel Prizes.



Armoured scales and micro-lenses in one

Nanotechnology in nature: *Ophiocoma wendtii*, a plate-sized hairy star, presented a puzzle for a long time. This creature, from whose disc-shaped armoured body five arms extend, hurries into cover at the approach of potential enemies, although it apparently does not have any eyes. These were eventually found in the creature's armoured shell, which is studded all over with perfect micro-lens fields, turning the whole body of the hairy star into one complex eye. The nanotechnology? The individual lenses are crystallised in such a way that the characteristic of calcite to create a double image does not come into play – crystallisation control at the nanometre level. The lenses are also corrected for "spherical aberration" by the subtle addition of magnesium, in order to prevent undesirable colour fringes. Ophiocoma therefore uses nanotechnological refinements that once helped Carl Zeiss to achieve fame.

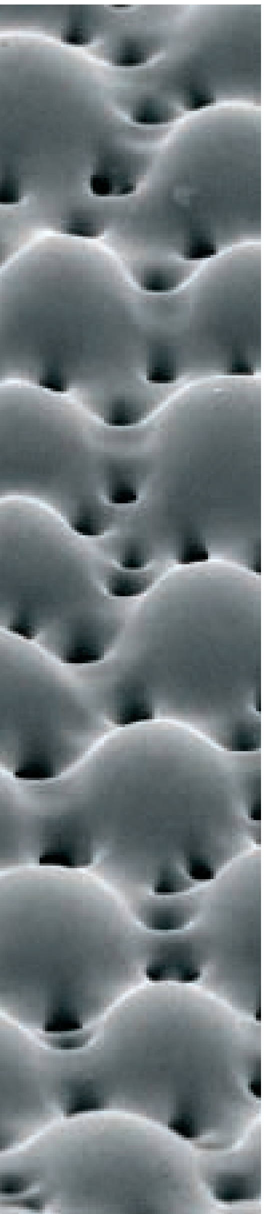
The Institute for New Materials (INM) in Saarbrücken has developed nanoparticle processes for applying counterfeit-proof, wear-resistant holograms to metal components.



Even nature cannot do this: ceramics treated with nano-soot for corrosion-proof glow-ignition systems, such as for gas heaters. The adjustable conductivity of the ceramics avoids the need for a transformer.

Exploring the limits of nature

Nanotechnology is based upon pure nature: yet the capabilities of living nature are restricted, it cannot work at either high temperatures, such as those needed for ceramics, or with metallic conductors. Modern technology on the other hand has a wide range of artificial conditions available – extreme purity, cold, vacuum – under which matter reveals some surprising properties. These include, in particular, quantum effects, which sometimes appear to be in stark contradiction to the laws of our day-to-day world. In this way, particles of the nanocosmos can sometimes take on wave-like properties: an atom, which is apparently a "solid" entity, can pass through two small gaps at the same time, like a wave, subsequently emerging again whole on the other side.



Particles acquire completely new properties when their size approaches a nanometre. Metals become semiconductors or insulators. Some substances, such as cadmium telluride (CdTe), fluoresce in the nanocosmos in all the colours of the rainbow, while others convert light into electricity.

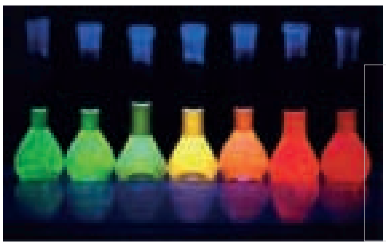
When particles become nanoscopically small, the proportion of atoms on the surface increases greatly in proportion to those inside. Surface atoms, however, frequently have different properties to those in the centre of the particle, and usually become much more ready and prone to react. Gold for instance becomes a good catalyst for fuel cells at nanoscopic sizes (see also Mobility). Nanoparticles can also be coated with other substances, allowing materials of such composite particles to combine several properties. One example: ceramic nanoparticles with organic shells, which reduce the surface tension of water, for the coating of non-misting bathroom mirrors.

Magnetite nanoparticles in oil. The fluid can be controlled and shaped magnetically.

Specially-coated nanoparticles of magnetite, an iron oxide, in oil create a ferro-fluid, a liquid that can be shaped magnetically. Ferro-fluids are being used in an increasing number of applications, such as sealing agents in rotary seals for vacuum containers and hard disk housings, or in adjustable vibration dampers for machines and cars.

Magnetotacticum bavaricum. Magnetic bacteria can synthesise chains of nano-magnetites and be used as a compass needle.

Yet nobody should be intimidated by the complexity of nanotechnology. Even an apple is complicated – cells, ribosomes, DNA – which has in no way impaired the popularity of this fruit.



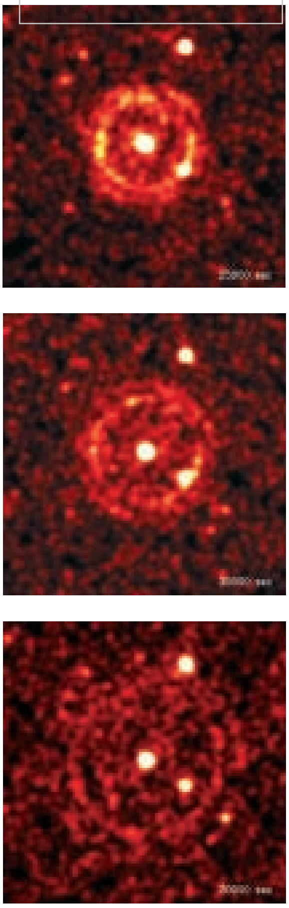
Cadmium-telluride particles fluoresce, the colour depending only on the particle size.

Instruments and processes

Eyes for the nano-cosmos

Nanotechnology in space: The reflectors of the European "Newton" x-ray telescope are polished to an average smoothness of 0.4 nanometres, enabling them to see sources of x-ray radiation in the Andromeda cloud

A scientific sensation: a flash of gamma radiation burns rings in a galactic dust cloud.



What does the European "Newton" x-ray telescope have to do with nanotechnology? It gathers the x-ray radiation from distant objects with 58 waste-paper basket-sized reflectors nestling inside each other like the layers of an onion and coated with gold vapour. The reflectors have an average surface unevenness of only 0.4 nanometres – a masterpiece of technology in which Carl Zeiss AG played a major part.

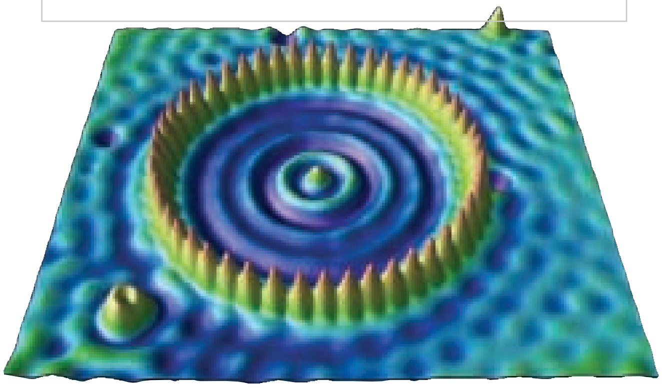
Precision x-ray reflectors for x-ray spectroscopy and microscopy are built up of several hundred layers of two different heavy elements. The demands placed on such reflectors are even more extreme, and the layers may only deviate from the ideal by fractions of the diameter of an atom. This technique is being mastered at the Fraunhofer Institute for Material and Beam Technology in Dresden.

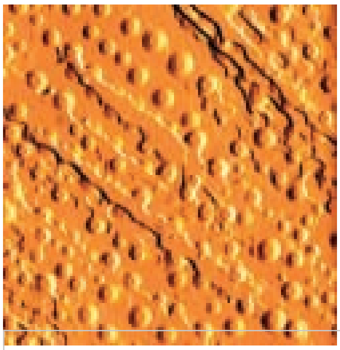
The trick of the layered reflector has also been discovered by nature for the spectrum of visible light: the nocturnal squid *Euprymna scolopes* directs the light from luminous batteries downward with tiny mirrors of reflectin proteins, imitating a patch of starry sky to any predators swimming below it. This example of biological nanotechnology was discovered recently at the University of Hawaii.

Scanning probes

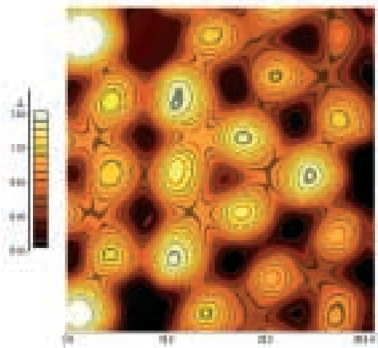
Scanning probes as the eyes for the nano-cosmos might appear less spectacular, although they ultimately won the Nobel Prize for the development of the father of all scanning probes, the scanning tunnel microscope. In scanning electron probes, piezo crystals guide a scanning head repeatedly and slightly

"Quantum Corral", by Don Eigler, IBM. The waves on the inside reflect the likelihood of encountering an electron.

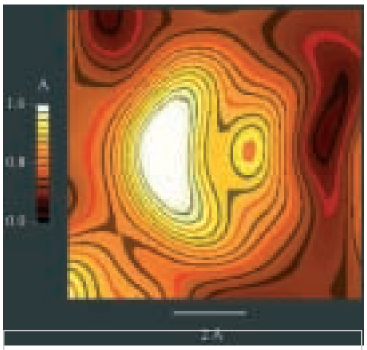




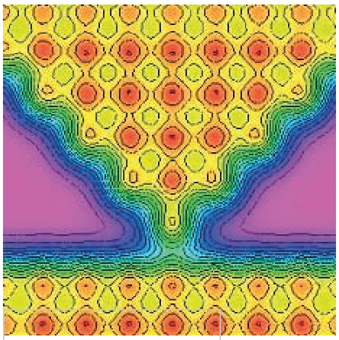
Potassium bromide crystal with atomic terraces. The salt on your breakfast egg looks similar.



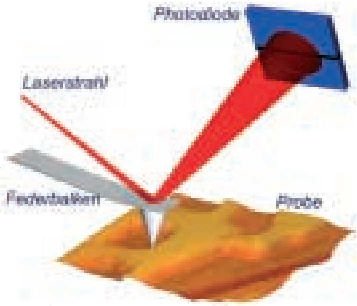
Silicon in close up, electron density contours under the scanning force microscope.



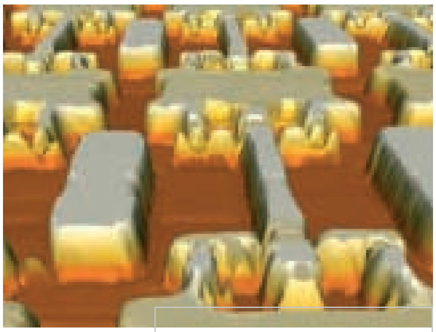
The foremost atom of the sensing head emits two electron clouds, orbiting just as described in the textbooks.



Schematic view of the classical tip of a scanning tunnel microscope.



The scanning force microscope: the deviation of the sensor needle is transmitted to a photocell by a laser beam.

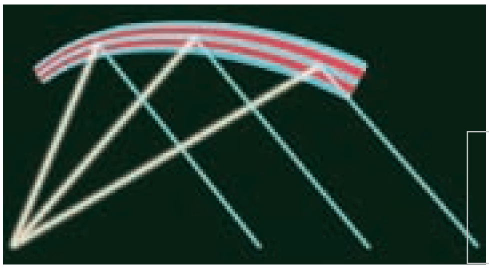


"Capacitive" probes can also be used to represent the switching processes on a chip.

offset over the subject of interest, such as the fields of atoms. The movements are minuscule, and the distance of the head from the atom field usually less than the diameter of the atom. In this region something happens: sometimes a current flows, sometimes minute magnetic fields are detected. Computers interpret the measurements graphically on a surface, creating an image, accurate down to the last atom, depending on the measurement principle.

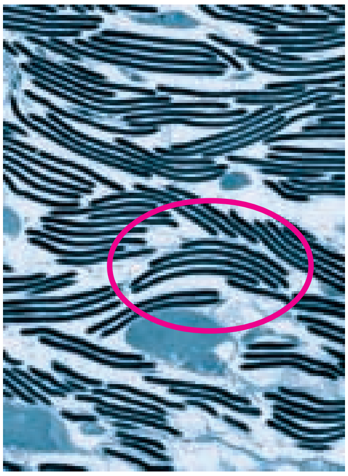
An especially subtle process is used by the scanning force microscope. This senses the minute forces exerted on the foremost atom of the sensing head by the atoms in the atomic field.

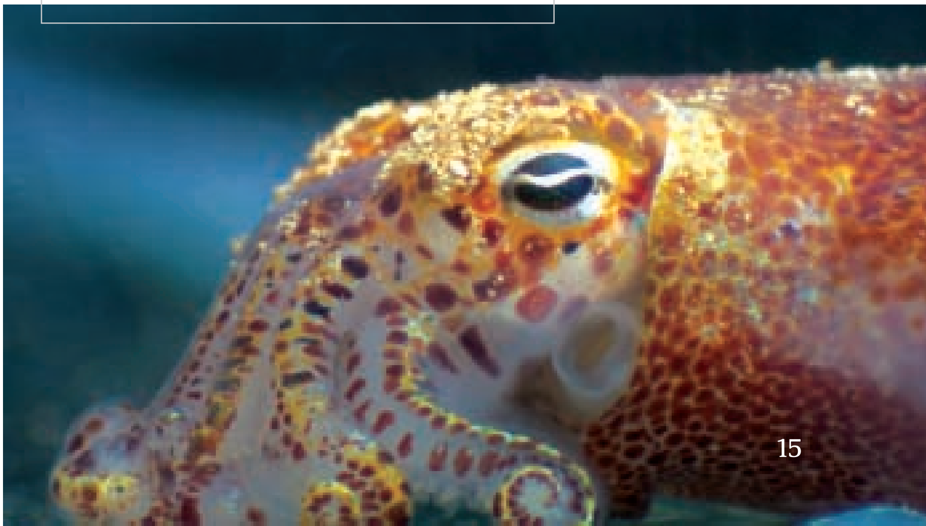
The process can even obtain a view into the electron shells of the atoms – revealing the secrets of the ultimate level of matter. The current world record for resolution is held by the University of Augsburg.



Curved multi-layer reflector for high-performance x-ray analysis.

„Euprymna scolope" confuses its enemies with multi-layer light reflectors of reflectin protein. The light is provided from luminous batteries.





Writing implements

The lithography process: A chip is a three-dimensional structure in which all the switching elements are arranged in individual layers. For a modern, high-performance chip, 25 to 30 such layers are needed, which all require their own lithographic mask. The structures of the mask are projected onto the wafer by the light and lens system of the wafer-stepper, an apparatus similar to an overhead projector. Every new mask of a set adds new functionality to the chip, increasing its complexity.

Lithography

In the world of computers, lithography stands for the technique of producing computer chips with the aid of light. In this process, the highly polished surface of a semiconductor material, a silicon wafer, is coated with a light-sensitive protective coating onto which the image of a circuit is projected. The development of the protective coating reveals the exposed (or unexposed) areas of the wafer, which are then given the required electrical properties by processes such as etching, implantation of foreign atoms and deposition. The repetition of the process with new patterns and circuits ultimately creates some of the most complex structures ever created by man: highly integrated circuits, or chips. Transistor densities have now increased to the point where a half a million or more transistors could fit within the dot made by a pencil.

Modern chips have structures which are even smaller than the wavelength of lithographic light: these use krypton-fluoride lasers with a wavelength of 193 nanometres in order to create structure widths of 130, and soon 90, nanometres, which is made possible with a range of ingenious optical tricks such as “optical proximity correction” and “phase-shifting”. The foundations are currently being laid for Extreme Ultra-Violet (EUV) lithography, which uses wavelengths of 13 nanometres, and which will ultimately be able to produce structures of only 35 nanometres in width in the silicon. The demands on the mask material are naturally tremendously exacting: a 10-cm long plate must only expand by a few tenths of a nanometre when warmed by one degree Celsius, i.e. by only a few atomic diameters. The required evenness of a few atomic diameters also lies at the limits of what is in principle feasible.

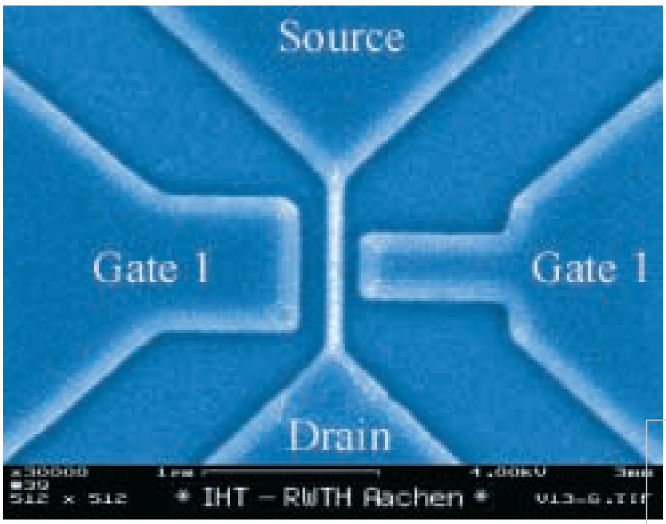
The rise of Dresden as an electronics location is a success story for German research support. Around 16 000 jobs have been created in the region, providing a great innovative effect throughout the German economy. In projects supported by the German ministry for research (BMBF), 44 partners from industry and state research institutes, including 21 medium-sized companies, have developed the standard for the future use of 300-millimetre diameter silicon crystal wafers for the production of highly complex integrated circuits. The Advanced Mask Technology Centre in Dresden, where the means of structuring future nanoelectronic chips are being developed, has a key role to play.

Prototype of an EUV wafer-stepper system for the production of future chip generations.

Nano-imprinting for medium-sized companies

Anyone who thinks of nanoelectronics probably has expensive facilities in mind that require investments of millions or billions of Euros but which nevertheless provide affordable products due to the shear volume of their output. There are however ways into the nano-cosmos available to medium-sized companies. These methods might look archaic at first glance; in the UV-nano-imprint process for example, the nano-structures are actually pressed mechanically into a coating covering the electronic carrier material, such as silicon. The template containing the delicate nano-structures is made of quartz glass, and quartz glass is transparent to UV light. When the stamp has been lowered into the paint, a UV light impulse causes the light-sensitive coating to polymerise, i.e. to harden. The template is then withdrawn, and the coating relief beneath is thinned. The silicon revealed can then be processed as required; by repeating the process many times with different templates, the complex structure of a chip is finally created, with transistors, circuits etc. Tiny structures of only 10 nanometres have already been achieved in laboratory trials. The process is not restricted to electronic components, and can also be used for the structuring of metals and plastics. The process could also lead to the creation of the lab-on-a-chip. The cost of a nano-imprint machine is currently estimated at less than one million euro, a fraction of that for similar equipment used in a modern conventional chip production factory. However, the UV nano-imprint technique will not necessarily provide cheaper products, since the throughput is much lower. For special mini-series – “mini” being measured in comparison with the large-series volumes of major processor producers - the UV nano-imprint technique could become the technology of choice.

Zerodur for lithography masks, this special ceramic remains stable even at nanoscopic sizes.



Imprinting the nano-cosmos: At the Institute for Semiconductor Electronics (IHT) of the RWTH Aachen, chip structure widths of 80 nanometres are already feasible with the aid of mechanical/optical methods. Applications: small-series, high-complexity circuits.

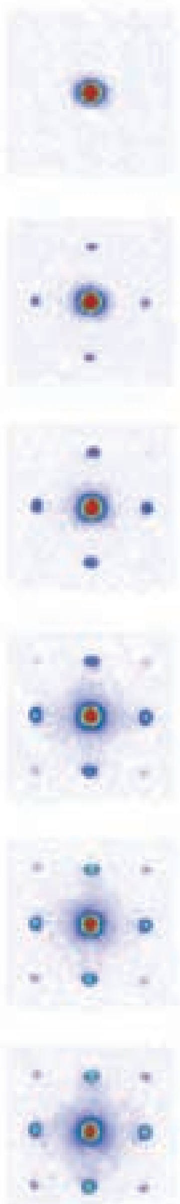
Instruments and processes

New impulses for science

Conventional spectrometer for x-ray structure analysis. Science owes much of its knowledge of the nano-cosmos to such instruments.

Underground racecourse for fast electrons

Quantum effects

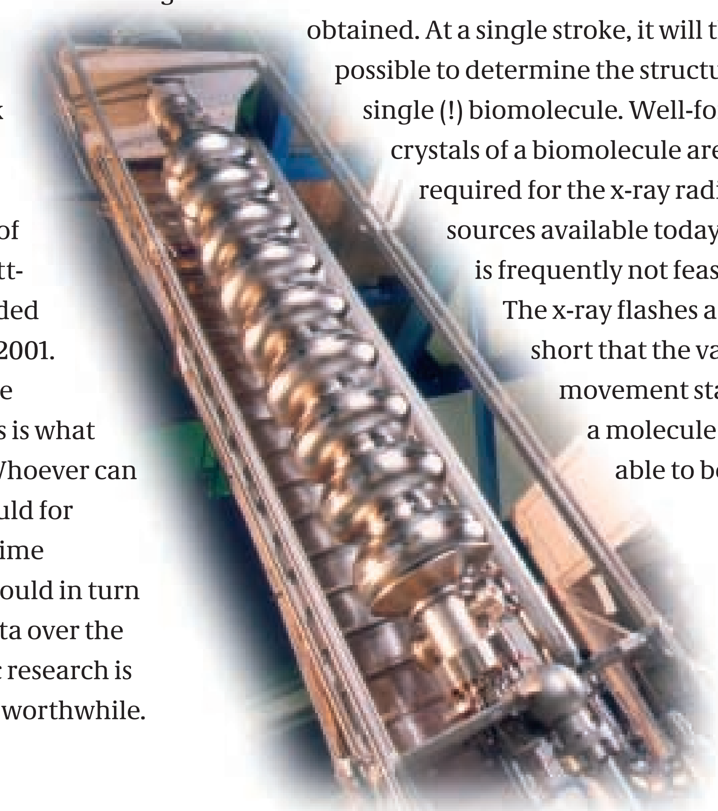


At the Ludwig-Maximilians University in Munich, matter is routinely being pushed to extremes of nanotechnology, under which it can sometimes reveal bizarre properties. For example, when vapour consisting of hundreds of thousands of rubidium atoms is cooled down to only one-millionth of a degree above absolute zero (-273°C) and forced together by a magnetic field, the atoms come together to form a “Bose-Einstein-condensate”, in which the atoms form a single unit, like a rank of marching soldiers. The quantum scientists at Munich can force such a block into a three-dimensional network of standing laser waves and manipulate it, e.g. by making the light traps so strong that the unit of the block breaks down into a “Mott-condensate”. This work was awarded with the nobel prize in physics in 2001. Why? Research of this type fills the quantum theory with life, and this is what has the say in the nano-cosmos. Whoever can fully understand and master it could for example develop more accurate time standards. More accurate clocks could in turn help to accelerate exchange of data over the Internet – this apparently esoteric research is therefore proving itself to be well worthwhile.

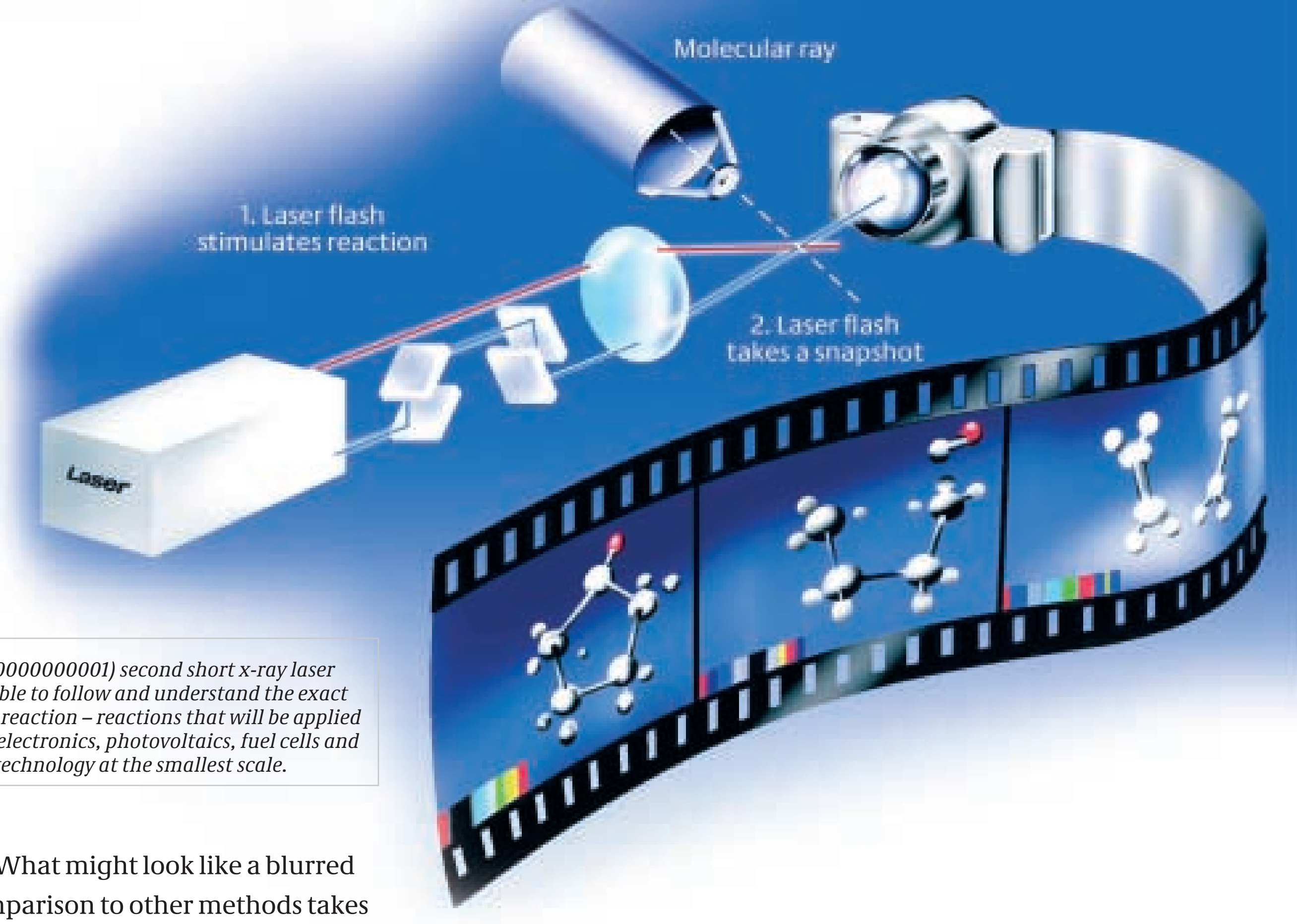
“Mott-condensate” – exotic matter for ultra-accurate time measurement

The XFEL x-ray laser – a leading light in nanotechnology

If everything goes according to plan, a few billion electrons are going to experience something very exciting in 2012. Starting on the DESY site in Hamburg-Bahrenfeld, they will be accelerated to very high energy by a superconducting electron accelerator, to be systematically diverted into swerving paths by magnets 3.3 kilometres further down the line. This will generate short-wave x-ray radiation of a very special sort: laser radiation. This radiation will be the most valuable that scientists have ever obtained. At a single stroke, it will thus be possible to determine the structure of a single (!) biomolecule. Well-formed crystals of a biomolecule are required for the x-ray radiation sources available today, which is frequently not feasible. The x-ray flashes are so short that the various movement stages of a molecule will be able to be



Superconductive elements for electron acceleration



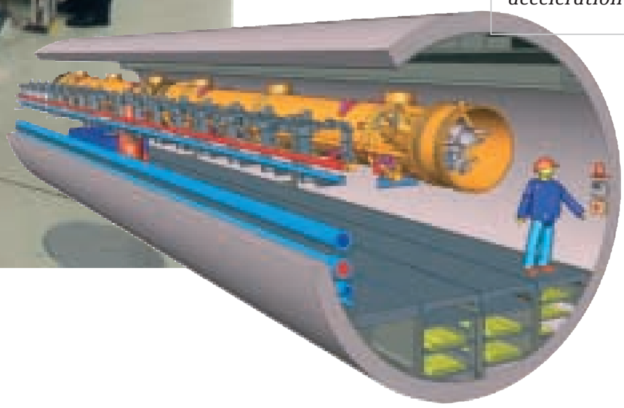
The femto (0.000000000000001) second short x-ray laser flashes make it possible to follow and understand the exact course of a chemical reaction – reactions that will be applied for example in opto-electronics, photovoltaics, fuel cells and solar cells and nanotechnology at the smallest scale.

properly filmed. What might look like a blurred whirlwind in comparison to other methods takes recognisable shape with the aid of the x-ray laser.

The secrets of friction can be decrypted. What creates friction, and how, will be determined by nanoscale groups of only a few hundred atoms.

The properties of individual clusters, agglomerations of a few hundred atoms, can also be better researched with the XFEL than with any other instrument. In short: science and technology will be given a powerful boost with Europe's greatest project in the field of nanotechnology. The planned overall costs of 684 million euro (as of 2003) will, in all probability, prove to have been more than worthwhile. Not just in terms of pure knowledge, but also in hard cash.

The free-electron laser under construction.

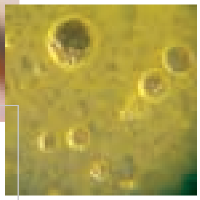


Graphic of the underground electron acceleration path

Material design on the nanoscale

Sol/gel processes for new materials

Sauce Béarnaise was created in honour of Henry IV, King of France, and was so called because he came from Béarn. This sauce represents a very good (and very tasty) example of a colloidal system. A colloid refers to a sub stance in which many fine particles are suspended in a stable condition in another substance.



Sol/gel for a King: Sauce Béarnaise, created in honour of Henry IV of France

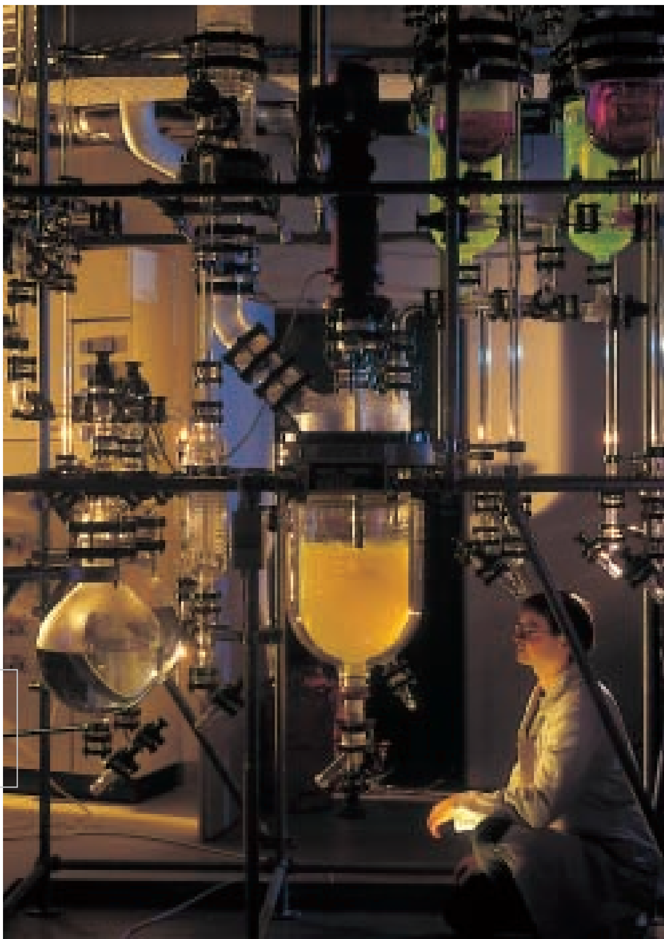
In the case of béarnaise sauce, these are droplets of vinegar suspended in melted butter. Creams and paints are further examples of colloids. With sol/gel technology, colloids also lead directly to the field of high technology.

In sol/gel technology, a (usually colloidal) sol is produced from soluble compounds such as those of silicon, in which droplets containing silicon are suspended in a carrier solution. When these are then sprayed onto a plate and heated, the carrier solution evaporates, and the silicon droplets gel to form a network. This gelled network then solidifies to form a hard ceramic layer. The plate is thus protected against corrosion and scratches.

Sol/gel technology comes in hundreds of variations for different materials. Gelled sols can also be formed into threads, which when fired are converted into ceramic fibres. Sols can also be used to produce nanoscale powders, which can be fired much more easily and at lower temperatures than conventional powders, and which can withstand the highest pressures and temperatures.

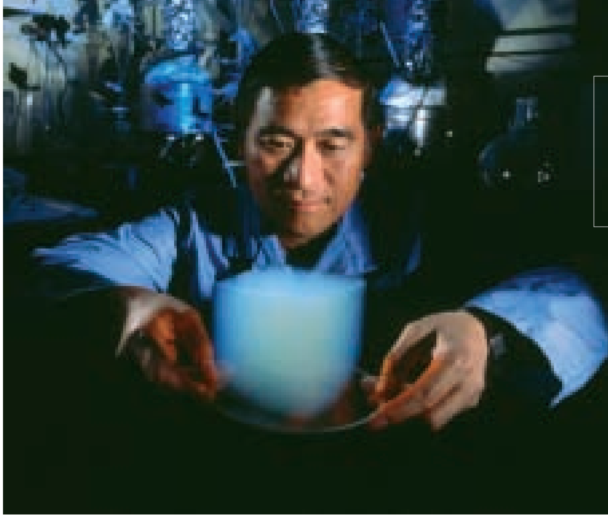
Sol/gel technology is also suitable for the manufacture of sophisticated optical components such as fibre-optic cables, frequency doublers, and micro-lens fields. This type of nanotechnology promises nothing less than a revolution in materials technology.

The gel solvent can also under certain circumstances be removed in such a way that the gel retains its original volume, producing a high-porosity material of very low density, an aerogel.



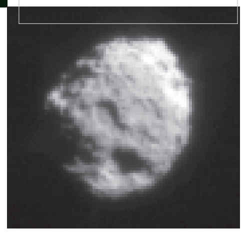
Fit for the finest particles: Sol/gel particle reactor

Double-glazing filled with an aerogel reduces heat losses.



Aerogel as a scientific dust-trap. Particles are securely trapped in a melted aerogel compound.

The comet "Wild 2" has been visited by an aerogel.



Aerogels

Aerogels are everyday objects, which have been used by bakers for a long time in the form of meringue. This is egg white, which is sugared, whipped up and baked. Anyone holding it in their hand will immediately feel how their fingers become warm. This is due to the fact that the air in the meringue is locked inside millions of microscopically small bubbles. It cannot therefore circulate or exchange heat, making the meringue an excellent heat insulator, just like polystyrene. Similarly constructed aerogels of foam glass also make first-class heat insulators.

Egg white is colourless, although meringue is white. This is due to the compartmentalisation of the whipped egg white into bubbles only micrometres in diameter. In such fine structures, light is refracted into all the colours of the rainbow, but the overall result is white. Nanometre-sized pores no longer refract the light. Foamed glass material with nanometre-sized pores is almost as clear and transparent as normal window glass. Double-glazing filled with such foam produces good window glass with outstanding heat insulation.

Because such foams consist almost exclusively of air, they are referred to as aerogels. The designation "gel" comes from the production process: a catalyst is added to the aqueous solution of a suitable material, which creates tiny, thin-walled cavities that join together to form chains, and then groups of chains, a gel, which on drying then becomes a feather-light aerogel.

The most travelled aerogel was that used in the CIDA dust-analyser of Hoerner & Sulger GmbH, which in January 2004, after a journey of five years and a distance of 3.22 billion kilometres, collected dust from the comet "Wild 2".

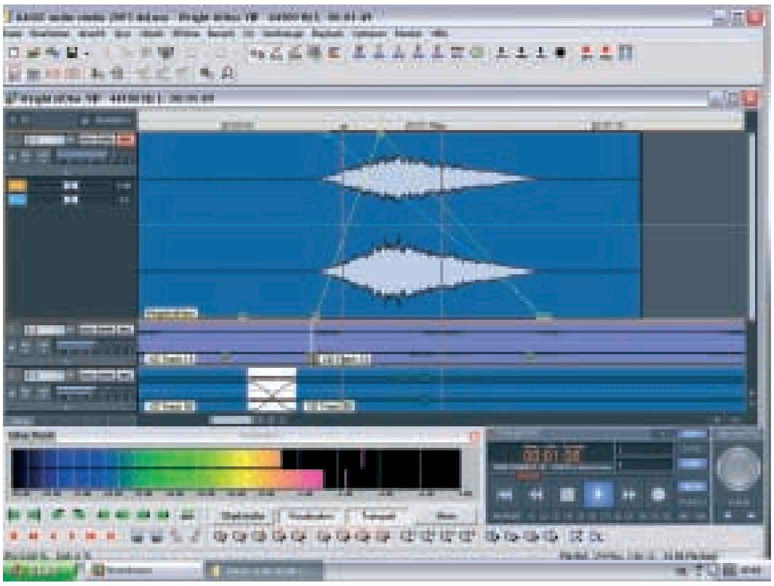
A material interspersed with a large number of bubbles has a large internal surface area. The greatest possible internal surface area, i.e. infinite, is that of the Menger sponge, thereby making its volume zero. The sponge exists only in the minds of mathematicians. The actual internal surface area of aerogels is however still large enough to produce some astounding effects. A sugar-cube-sized piece of aerogel made of carbon material may have an internal surface area of as much as 2 000 square metres. This and other properties ensure carbon aerogels have a secure place in the energy technology of the future. They can be used to construct condensers with a capacity of up to 2 500 farads as energy accumulators for peak power requirements, such as those in an electric car. This amazing foam will also enable the design of better lithium batteries, new types of fuel cells, etc. Seldom has anything of such little actual substance demonstrated such versatile potential.
How typical of nanotechnology!

The Menger sponge is used by mathematicians as a "universal curve". This is created when the procedure shown below is repeated infinitely.

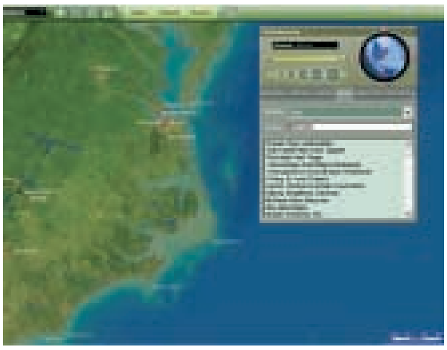
Nanotechnology in society

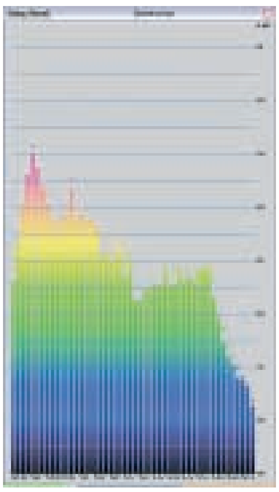
The networked world: Nanoelectronics

From the notebook in the studio to studios in the notebook – the status of the technology



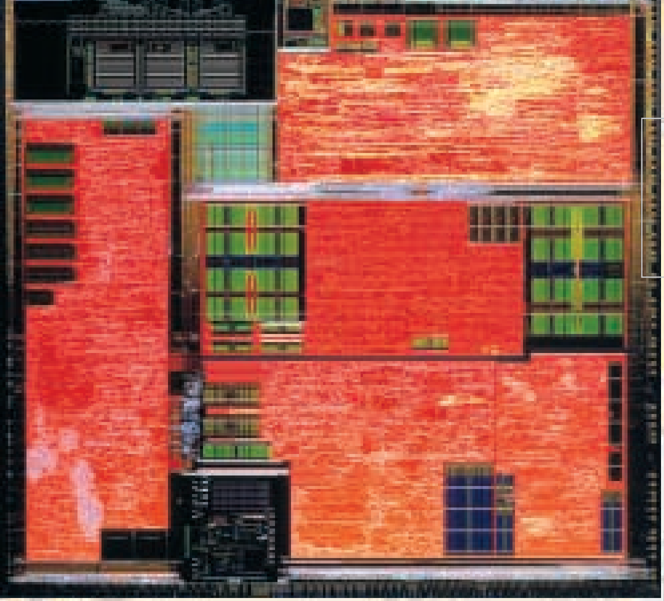
The task: Four-and-a-half minutes of radio about the first powered flight of the Wright brothers, accompanied by a little atmosphere. Armed with the notebook PC, what does a radio writer do, assuming that he takes pride in his job? First he takes a look at the place where it happened. The virtual globe shows Kittyhawk lying on a strip of land a few kilometres wide along the shores of the North Atlantic, bordered by the Kill Devil Hills, so the Wrights would have been able to hear the rumble of the breakers. That can be obtained from the sound archives, as well as the stiff breeze that was blowing for the first flight, as described by the *Encyclopaedia Britannica*, together with the rustling of the grass on the dunes. The engine turned at a speed of 1 200 rpm, and the sound archives provide a vintage Chrysler, which is droning nice and deeply. The spectrum analyser in the sound program shows plausible frequencies, all OK so far. The first flight lasted for twelve seconds, so a passage is selected in which the sound falls off at the end, because of the Doppler effect as the aircraft passes the microphone. Everything is put into the sound program and overlaid on different tracks. The aircraft flies from left to right, which can be set up with panorama curves. The engine noise rises and falls, adjustable with volume curves. And then Orville Wright is seen, flying very convincingly over the Kill Devil Hills in the Flyer One, just as on 17th December 1903, with the noise of the surf and the whistling of the dune grass – all on the notebook. (Other aviation pioneers, like the German Gustav Weisskopf, has already flown in 1901, although they were unable to make their inventions practical.)





Twenty years ago, this task would still have been unaffordable for a single person, and would also have needed tonnes of equipment: today, all that is needed is a notebook PC, a small desk and a few hours of time. The encyclopaedia has been put onto a DVD, which replaces the 30 heavy tomes and is much more convenient for a quick search than its paper counterpart. The sound program too comes in immaterial form on the hard disk, and from its many virtual racks offers an infinite range of effects. The development of the modern computer has set in motion a wave of dematerialisation, which will also result in a reduction in energy consumption. The price reduction in hardware and software has also placed amazing production facilities in the hands of creative people who no longer need huge resources.

In future, the library worn on the wrist will be nothing unusual, in the same way as interactive mobile communications.



A TV studio small enough to fit on the fingernail: Multimedia chip with controller for high-resolution display control, with the power consumption of a pocket torch.

Go Nano! The coming years

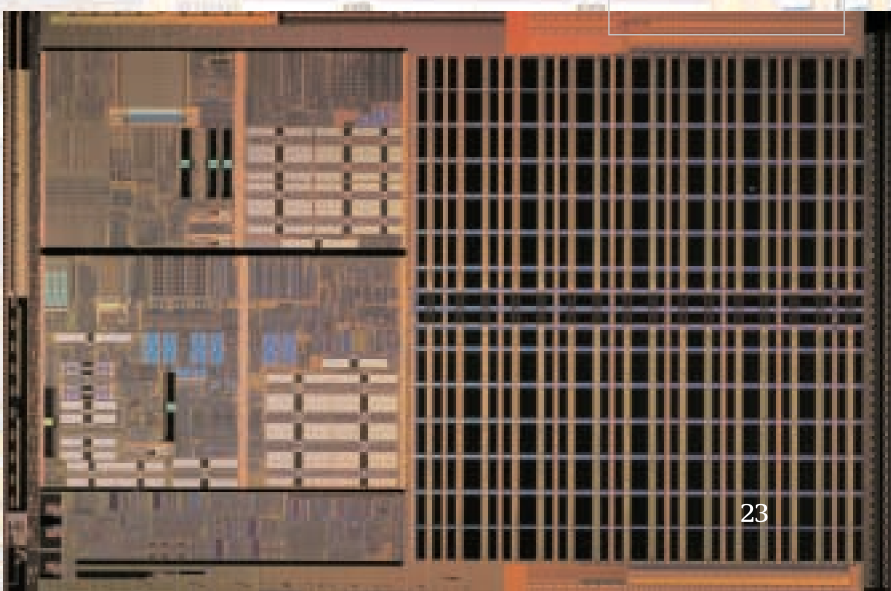
The transistor technology used today in computer processors is called CMOS (Complementary Metal Oxide Semiconductor), and was developed, amongst other things, for the first electronic wristwatches, since it used much less power than its predecessors. Since the 1970s, experts have been forecasting again and again that the technology would reach its limits of development within 10 to 15 years, and are still doing so today. This time of course, the electronics industry has a compelling reason to anticipate a break with the tradition of the continuing miniaturisation of its components: on the way into the microcosm, the actual building blocks of matter, its atomic structure, is gradually becoming visible. The electronic shells of atoms are however the smallest components that can be joined together under normal conditions to form technical structures. A fundamental limit is therefore in sight. A conductor path cannot be any thinner than an atom.

CMOS technology has already long been subject to limits that sometimes seem very curious. The circuits connecting the transistors of a chip are already so fine that aluminium atoms would be unstable in such an application. They would simply be washed away by the electron flow like gravel in a stream: the specialist term for this phenomenon is "electro-migration". The answer: copper circuits, which are even better conductors, thereby speeding up the flow of signals on a chip. The circuits have now also been pushed so close together that this creates a detectable capacity, as in a capacitor. If this effect were not taken into account in chip design, the chip could get out of sync.

Certain components of chip transistors are gradually being reduced to a size of less than 20 nanometres. This comes into the realm of quantum theory, where the tunnel effect starts to come into play: currents start to flow in larger transistors where there should be no current – the electronic gateway system springs leaks. Although the currents are tiny, with millions of transistors they add up to considerable losses, and the processor becomes hot. These uncontrolled charges also cause logic errors, which can be fatal.

In the case of very fine structures, the wave characteristics of the electron ultimately start to become visible – as described by quantum theory. Many scientists however see this situation as an opportunity to develop a completely new type of electronics, which could produce a quantum computer that could open up a totally new mathematical universe.

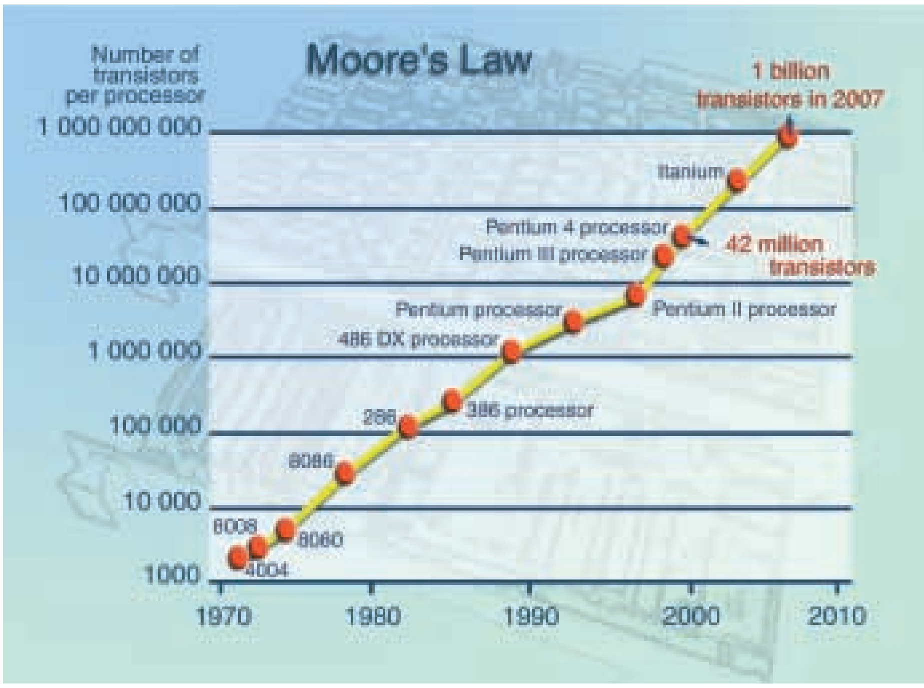
64-bit processor from AMD for PC applications with 106 million transistors using 130-nm technology.



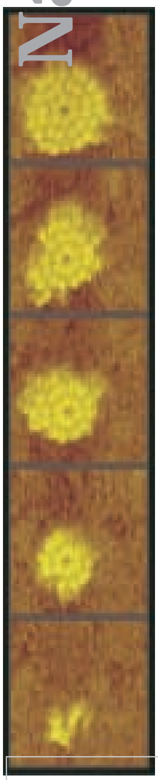
The networked world: Nanoelectronics

Moore's law reaches its limit

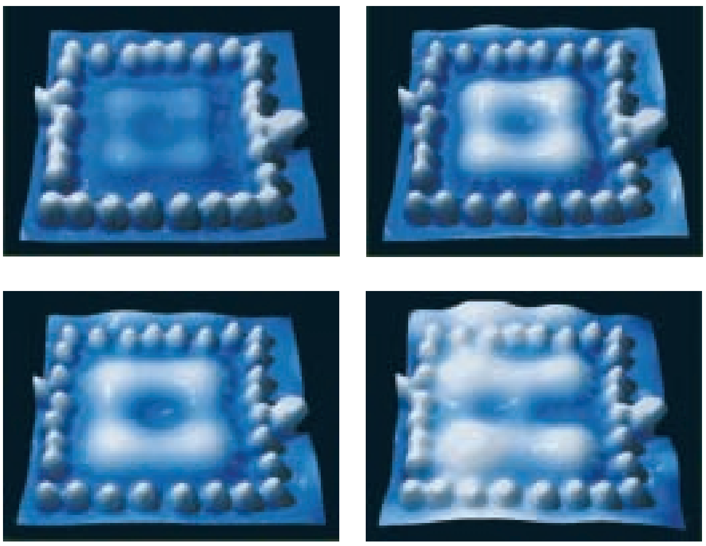
As early as 1965, Gordon Moore, co-founder of the firm of Intel, realised that the capacity of microchips was doubling about every 18 months. This "law" is now also being brought into question by a very human problem. While approximately 50 percent annual growth in the number of transistors on a chip is being achieved, analysts complain that chip design productivity has only increased by 20 percent per year. The industry has attempted to counteract this trend by continually increasing the size of design teams: now consisting of from 250 to 300 people, these have attained a head-count that is simply no longer manageable.



Unlimited growth is contradictory to Moore's Second Law, which states that the reduction in the size of structures and an increase of the price of the production plant go hand in hand. Until these limitations seriously limit further development, nanotechnology will continue to play an important role in the area of nanoelectronics. In fact, current CPUs are already fabricated with structures of under 100nm and containing more than 100 million transistors. If one believes the Roadmap for the Semiconductor Industry, whose forecasts are mostly based upon realistic technical developments, we expect to realize 45nm structures within a few years (2010), implying more than one billion transistors per chip. This will open up possibilities that we can only dream of today.



A tiny island of silicon on a silicon crystal gradually dissolves at 450 degrees. The knowledge of such processes is important for the quality of thin layers.



Manganese atoms on silver at the Christian-Albrechts University of Kiel. The electrons enclosed by the cage of manganese atoms form distribution patterns, which depend on the electrical voltage applied. Effects such as this will be important for the electronics of tomorrow.

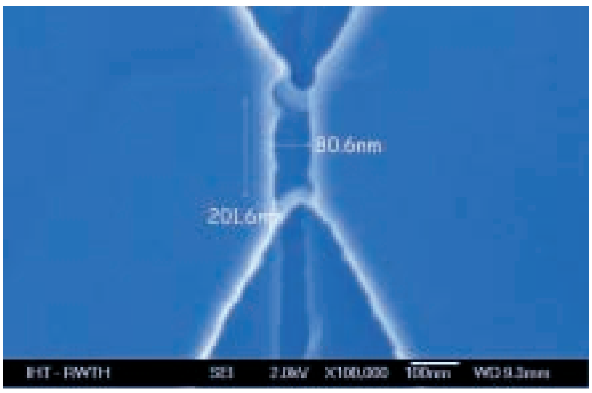
Phase Change RAM

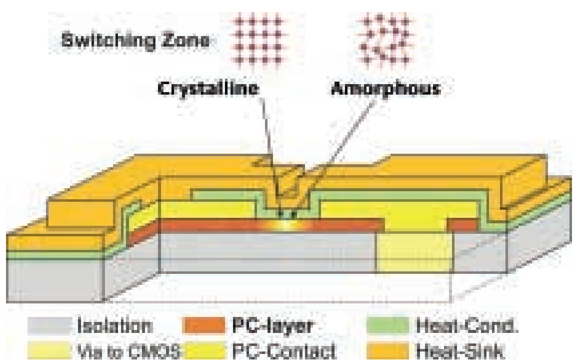
Today's data storage devices are based on various technologies that have their respective advantages and disadvantages. While magneto-mechanical hard disk drives (used typically in today's desktop computers) have a very high memory density and store data without the need for a constant source of electrical current, they are very slow in terms of data access. In contrast, DRAM (Dynamic Random Access Memory) is quick but the data needs to be constantly "refreshed" using pulses of electrical current. Flash Memory, which is found, for example, in MP3 players, mobile telephones and digital cameras, retain data without a constant supply of current but are not as fast as DRAMs and can only be used approximately 1 million times. Future nanotechnological storage concepts, which should combine the above-mentioned advantages: high memory density, speed, data retention without current supply and a long lifespan, are from today's viewpoint MRAM (Magnetic Random Access Memory) and, as described in the following, Phase Change RAM.

Solid substances can occur in two extreme conditions: the crystalline state, in which the atoms are neatly arranged in a regular structure; or the amorphous state, in which the atoms are arranged irregularly. Common amorphous solids include types of glass including, for example, quartz glass. The same substance, silicon dioxide, can be found in its crystalline form in the mineral trade, where it is known as rock crystal. Crystalline – amorphous, a great deal more will be heard of these two material conditions in future, because they will probably determine the mass memory of the future. Some solids allow themselves to be changed more or less willingly from the amorphous to the crystalline state and vice versa; this phase change, which is generally achieved by the effects of heat, has found wide application in optical storage media. For instance, when a rewritable DVD is written, a special coating on the DVD changes its phase locally from "crystalline" to "amorphous" by means of the heat shock of a laser impulse, thereby also changing its reflection properties, so that a readable bit pattern can be written. Longer and stronger laser exposure makes the amorphous areas crystalline again, so that the DVD can be rewritten.

Phase-change materials in all probability now have a long career ahead of them in electronic memory systems, or phase-change RAM. In this case the phase change will not be carried out optically, but electronically. Short current impulses make the material amorphous with a high electrical resistance, longer impulses make it crystalline again with low resistance. The resistance of the memory elements is queried in order to read the information.

With phase-change RAM, it should be possible to achieve storage densities that enable a terabit to be stored on an area the size of a postage stamp – ten hours of uncompressed video with the finest quality. Notebooks with this technology would simply start up again where their owner left off – booting-up would no longer be necessary.





Right: PC layers for bit storage can be switched to and fro between the amorphous and crystalline state with current and heat impulses of different lengths. This patented design by the IHT of RWTH Aachen makes possible fast memory coupled with low power consumption.

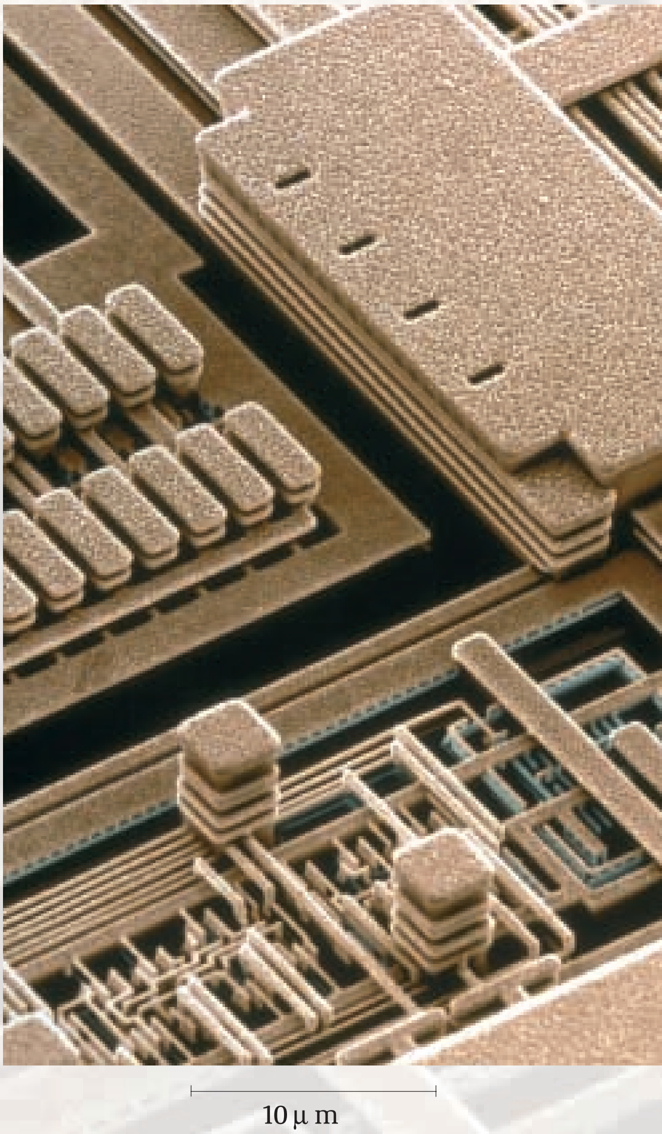
Left: Actual design of a phase-change RAM component

The networked world: Nanoelectronics

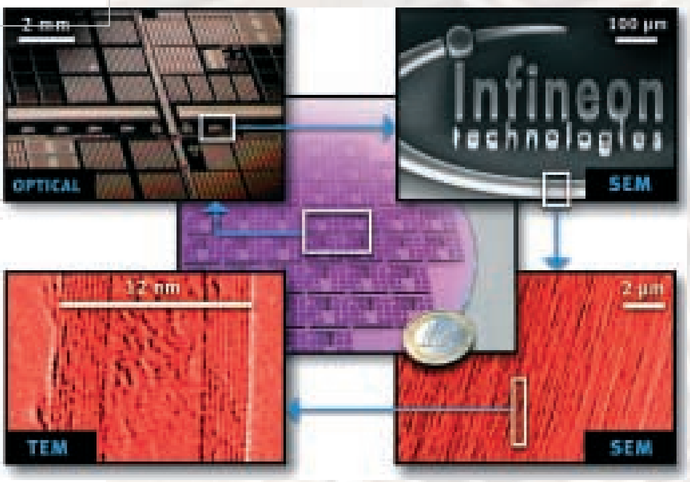
On with 3D – Chips are growing in height

Skyscrapers were the economic solution of choice on the scarce property market of Manhattan when the need was to create new office and residential space. Chip designers had naturally also thought of the third dimension at an early stage, although the efforts came to nothing due to a whole range of problems.

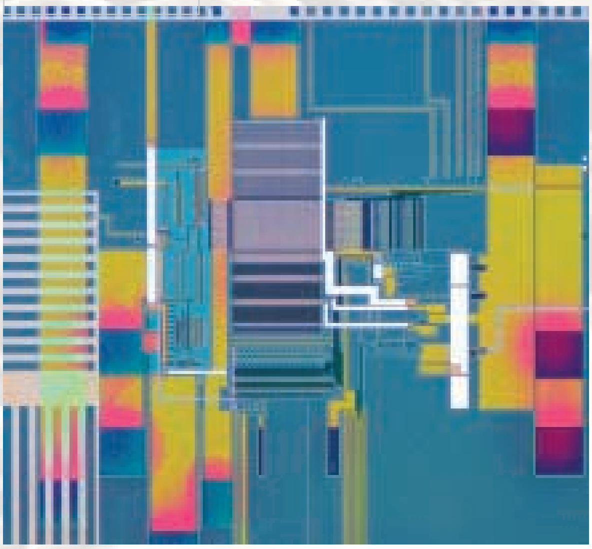
A way could now have been found into this third dimension by Infineon AG of Munich, which has succeeded in growing carbon nanotubes (CNTs) on wafers – polished silicon plates on which the computer chips are installed. The Carbon nanotubes are first-class conductors, and therefore produce little waste heat, and can also be used as connections (VIAs) – that can also handle mechanical stress – between the different wiring levels of a chip. In the long term, Infineon researchers consider it possible to develop a genuine 3D technology for chips with the aid of CNTs, especially since CNTs, as excellent heat conductors, could also dissipate heat from the inside of 3D chips.



Specific growth of carbon nanotubes at pre-defined points of a silicon wafer by means of a microelectronics-compatible process.



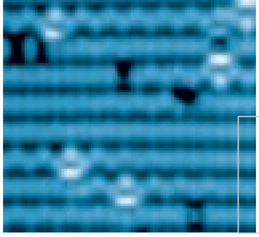
Modern art: Experimental structures for spintronic RAM



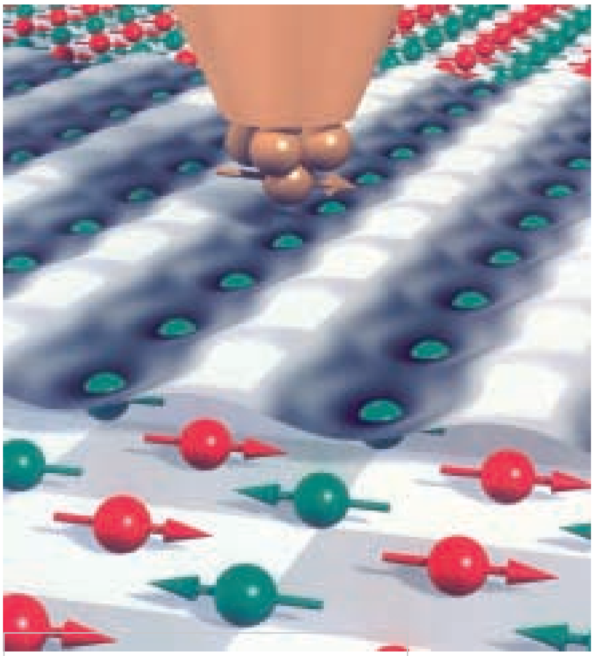
As complex as a miniature city – etched copper circuits of a chip (IBM), viewed with the aid of a scanning electron microscope. Modern chips have up to nine circuit levels.

Spintronics – Computing with spinning electrons

A genuine revolution, which could carry Moore's law on well into the future, could be initiated by spintronic components, which in addition to the electrical properties of the electron also make use of their magnetic characteristics, their spin. The electron spin manifests itself as minute magnetic inertia, which reacts in a complex way with other magnetic conditions, and can therefore be used for electronic functions. One application of "spintronics" or magneto-electronics has already found its way into everyday use: new hard disks have "spin valve" thin-layer reading heads, which on the basis of the huge magnetic resistance discover very small magnetic domains, thereby enabling very high storage densities.

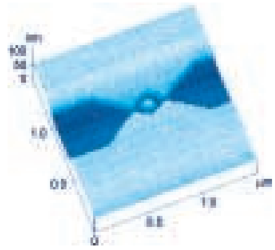


Individual organic molecules on silicon. Scanning tunnel microscope image, Ruhr University of Bochum.

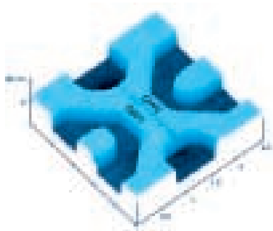


The magnetic probe of a spin-polarised scanning tunnel microscope scans the magnetic properties of individual atoms.

Finger exercises for the quantum computer: "Aharonov-Bohm interferometer", created at the Ruhr University of Bochum with a scanning force microscope.



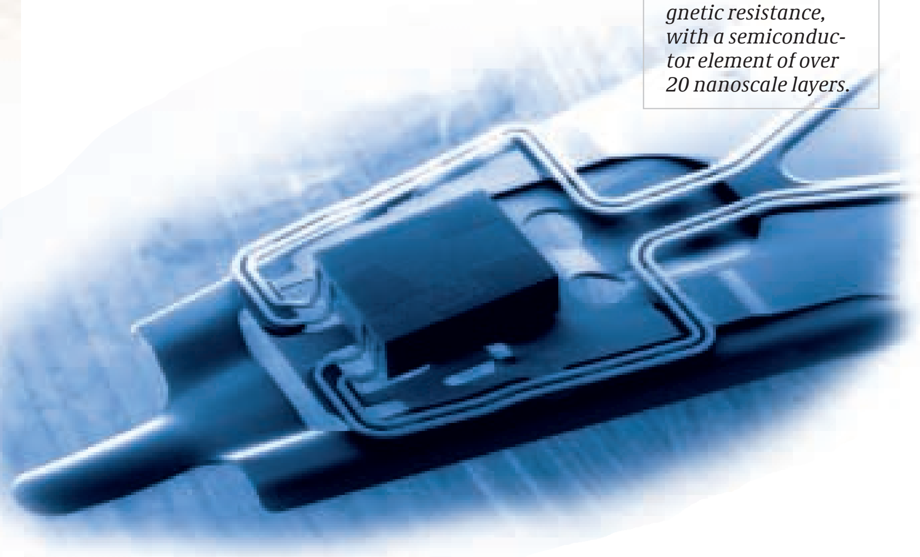
Tunnel-coupled quantum wires – electrons travel through passages that would be blocked according to classical theory. Nanotechnology experiments are beginning to overtake the theory.



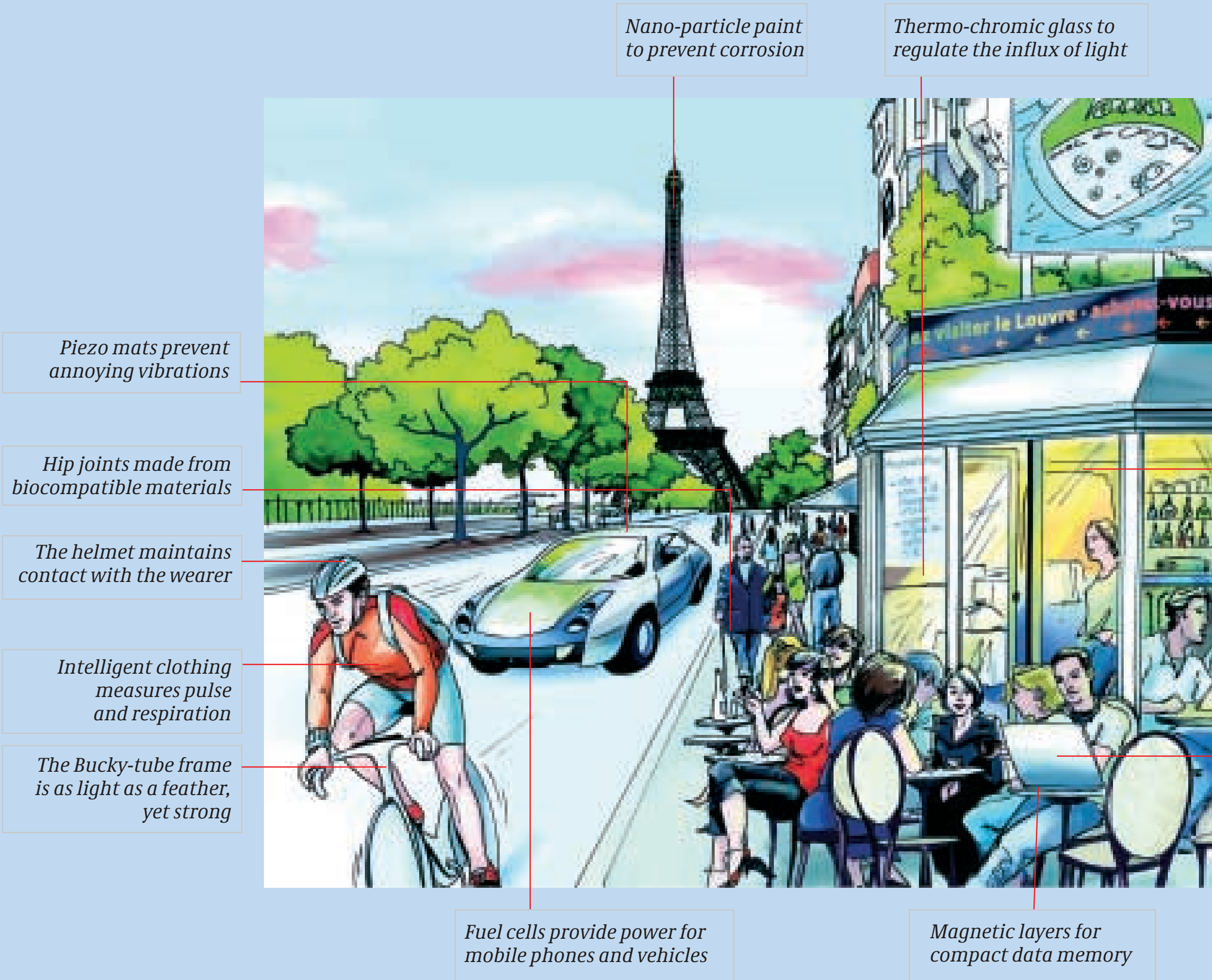
In MRAMs, magnetic memory chips, the information is stored in the spin of the magnetic layers. This development is of great interest for non-volatile main memory, and could in the long term lead to the replacement of mechanically-operated hard disks.

"Spintronics" is also being considered as the technology for a quantum computer at places such as the University of Würzburg.

New effects for powerful hard disks: the reader head uses the enormous magnetic resistance, with a semiconductor element of over 20 nanoscale layers.



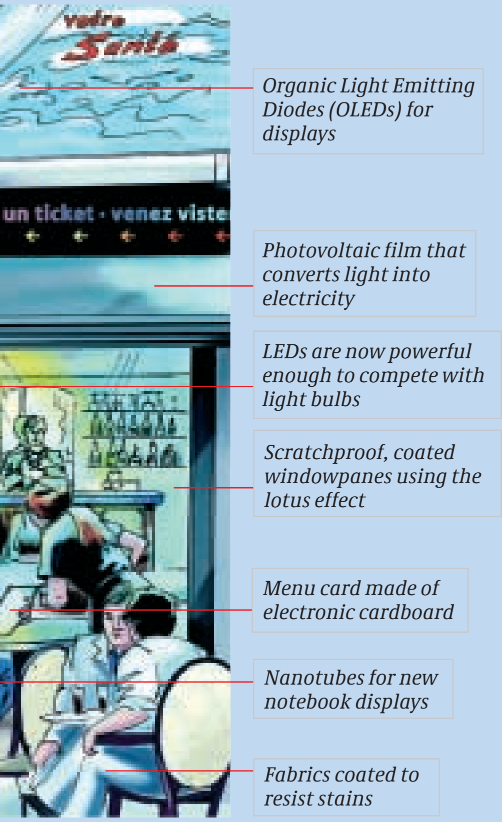
Nanotechnology in future everyday life



If nanotechnology becomes a part of everyday life, nothing would have to change dramatically on the outside. People will still like to sit at a street café, perhaps even more so that now, for the droning of internal combustion engines has been replaced by a discreet buzzing and swishing, like that made by the bulkhead doors on the Starship Enterprise. The stink of burnt petrol has given way to an occasional, hardly noticeable whiff of methanol used to power fuel cells. The service will be very quick: typing the order into the electronic menu has even automated the kitchen. The bill will be paid simply by pressing a cash card against the euro symbol printed on the corner of the menu. Tips will still be given in cash, because it clinks so nicely, although it will be hygienically coated with antibacterial nanoparticles. The windows of the café have become very expensive, because they provide so many functions – which ultimately makes them cheap again: they are resistant to dirt and scratches, they darken automatically when it becomes too bright, convert light into electricity, and light up as a huge display when required: it is fun to sit in the café or in front of it with other people to watch the World Championships.

Mature nanoelectronics offers the prospect of devices of captivating elegance, such as a genuine PDA (Personal Digital Assistant) in credit-card format (not that it couldn't be made smaller, of course, but because human hands still need something large enough to hold).

The object could be a matt black monolith without recognisable structures, the black surface gathers sunlight and converts it into electricity; it would be scratchproof and covered with a wafer-thin diamond layer, and under that a thin piezoceramic layer that converts sound into electricity and vice versa, in order to enable voice



communication. Naturally, it would also be capable of data transfer by light and radio.

The object could also see by means of a flat lens and a high-resolution image converter chip, would light up as a display on request, and would thus be a tape recorder, camera, video recorder, TV, mobile phone, and, via the European Galileo positioning system, an orientation aid all in one, and would on request read, translate and explain the menu in a Paris café, give the order in friendly, colloquial French, and then pay the bill.

It would also be able to recognise the voice and fingerprints of those allowed to use it, thereby protecting itself against misuse.


Nanoparticles in nano-solutions fluoresce in UV light, but are otherwise completely invisible. Finely distributed in fluids, they can be applied with inkjet printing technology, without changing the design or function of the marked object. Nano-pigments are therefore ideal for use in forgery protection.

"Photo-chromic glass": the trans-parency of such types of glass is electro-nically controllable – for the office climate conditioning of tomorrow.

The virtual keyboard: touching a projected key is recognised by the system and interpreted as a press of the key.

Nanotechnology in society

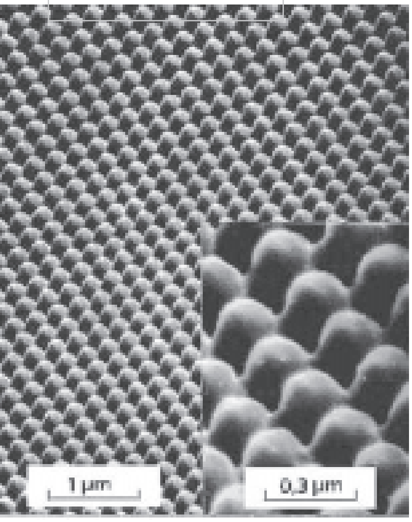
Mobility

As in other machines, nanotechnology will also replace quantity with quality in the car. The benefit of technology is that you can get by with less material, because the technology is reconciled with nature.

Nanotechnology in the car

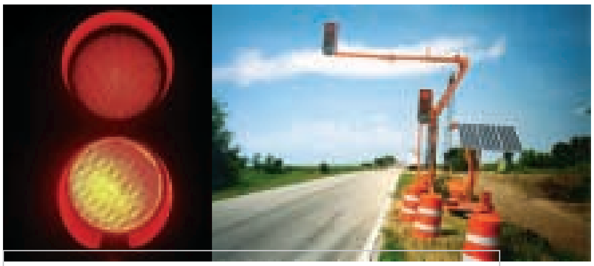
Windscreens can be made scratch-proof with coatings produced using sol/gel techniques, which contain hard, nanoscale particles – and still remain completely transparent, because nanoparticles are so small that they do not scatter the light. The principle already works for glasses, even though not yet fully perfected. The car finish could be provided with a lotus leaf structure that makes dirt simply run off.

Small structures for the bigger picture. With the aid of regular, microscopic surface structures, distracting light reflections on displays and windows in the car can be prevented. The analogy provided by nature is the eye of the moth, which at night needs to see as much as possible, without being seen itself.



Windscreens with nanoparticle coatings could also help in climate conditioning for cars by reflecting light and heat radiation, either to a greater or lesser extent, under electronic control. When applied to offices, such technology would help to save huge amounts of energy.

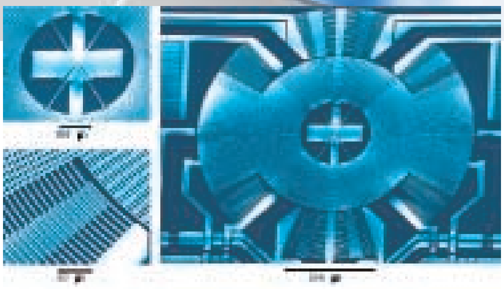
The lighting needed by a car is today already generated with a generous helping of nanotechnology: like all LEDs, the light-emitting diodes of quality brake lights have sophisticated, nanometre-size coating systems that convert electricity into light very efficiently. Another plus: LEDs convert electricity into light visible to humans almost immediately, while conventional brake lights fitted with bulbs need a little longer. The difference can mean several metres of braking distance. The luminosity of LEDs is now so great that groups of them can now provide dimmed daytime lighting for headlights.



LEDs in traffic lights save service time and energy. The amortisation time is no more than a year.

Current electronic safety systems such as antilock braking systems (ABS) or electronic stability program (ESP) come into action in critical driving situations; future systems will be able to avoid dangers automatically.

Injection nozzle for diesel vehicles. Future systems will be equipped with diamond-like wear protection layers only a few tens of nanometres thick.



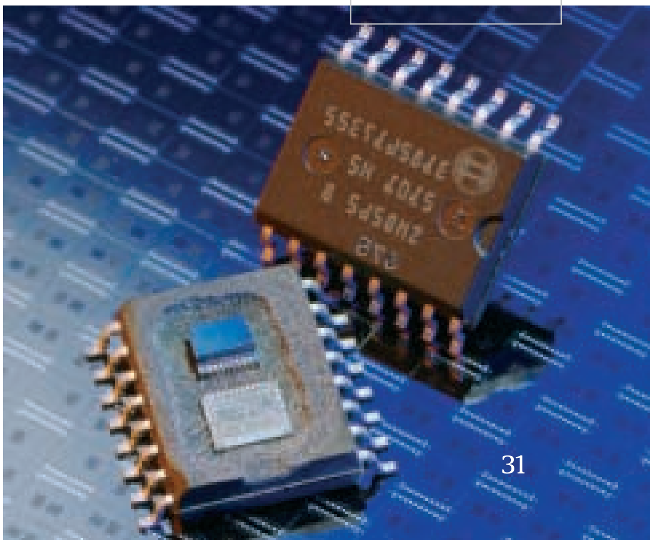
Balance organs of silicon: rotation rate sensor for vehicle stabilisation

White LEDs are now so powerful that they can be used in future as the light sources for headlights.

Paint finishes could also be designed nanotechnologically as a solar cell (an option that has not yet been developed). This power could be used to recharge the battery when the vehicle is parked – a feature that is already available using conventional solar cells – or to keep the interior cool using a heat extraction pump. The pump could in turn consist of a semiconducting, nanotechnology layer system without any moving parts. If the reverse is done, and the substantial waste heat from an internal combustion engine fed via such a semiconductor, it can be converted back into electricity – see also “Thermoelectrics” under “Energy and the environment”.

Fuel cells (see p. 33) will turn cars into a totally pollution-free means of transport. If the hydrogen fuel is also obtained from renewable energy sources, this source of power will be extremely environmentally friendly.

Electronics for vehicle safety: Acceleration sensor for a front airbag



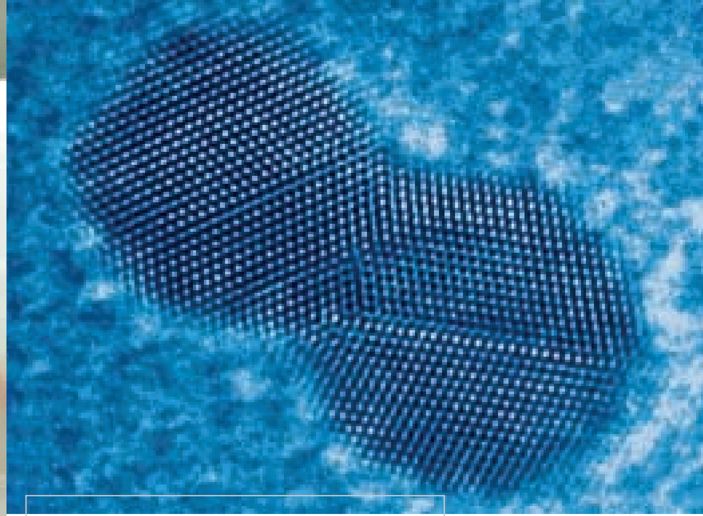
Nanoscale perfume capsules give leather the right feel.

Gold catalysts

Nanotechnology can also help gold on a new career path. While "plain" gold comes far behind platinum as a catalyst, gold nanoparticles on a porous carrier material provide a practical catalyst for cars that even during a cold start breaks down nitrous oxides and carbon monoxide into harmless substances. Gold nanoparticles are also promising new catalyst candidates for fuel cells.

All these advances will naturally also benefit other means of transport that have nothing to do with cars. Bicycles for instance would benefit from nanotechnology, especially with fuel cells and solar cells, creating an "eternal motion" machine that could travel across the country powered only by light, air and water, all light as a feather thanks to its carbon nano-fibre frame, LED lights and more.

Service area urinal with vandal-proof micro-system technology. Nano-scale "lotus effect" coatings will also further simplify maintenance and cleaning.



Nanoparticles of gold for new catalysts

Gold for the prevention of odours

Gold nanoparticle catalysts are currently also being tested as odour-preventers. In small air-conditioning systems such as those in cars, they can prevent smells created by bacteria in the system. In Japan they are already in service in toilets.

Nanotechnology in the service station

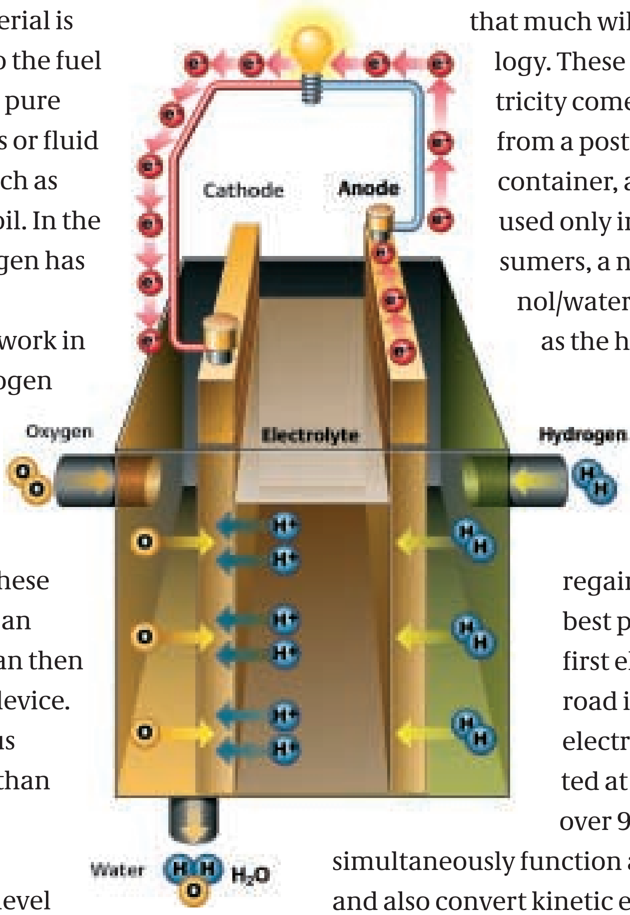
Car drivers can already come across micro-system technology in motorway service stations. The urinal bowls of advanced toilets are equipped with sensors, which signal any temperature increased to the associated electronics, initiating a flush. The electrical power required is supplied by a mini water turbine operated by the flushing process. Unlike systems with infrared sensors, the system cannot be put out of action by a piece of chewing gum.

Nanotechnology urinals on the other hand work in a much simpler yet more sophisticated way: Thanks to the lotus effect on the bowl wall, fluid runs off easily, percolates through an odour-preventing fluid layer and disappears without leaving any traces behind – how true this is remains to be shown in practice. This technology is naturally also suitable for private households.

Thanks to their nano-porosity, metallic "nano-cubes" from BASF can store large quantities of hydrogen.

Fuel cells – a device with a thousand uses

Fuel cells are similar to batteries: they supply electricity. However, while the chemical ingredients of a battery will be used up sooner or later, energy-rich material is continually resupplied to the fuel cell. This material can be pure hydrogen, or another gas or fluid containing hydrogen, such as natural gas or rapeseed oil. In the last two cases, the hydrogen has to be separated out in a "reformer" before it can work in the fuel cell. When hydrogen and oxygen combine, electrons are transferred from the hydrogen to the oxygen. In the fuel cell, these electrons are forced into an external circuit, which can then power a motor or other device. The reaction product thus formed is nothing more than pure water.

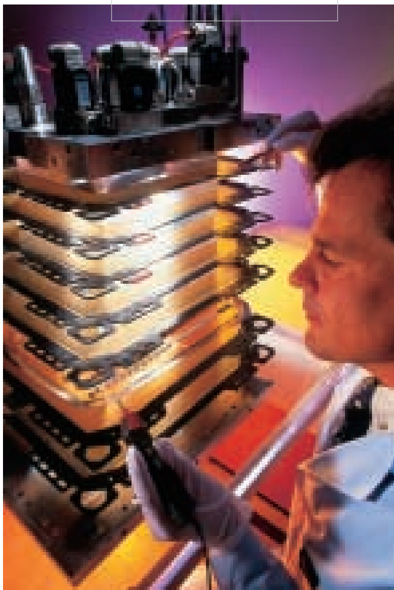


Fuel cells work at a high level of efficiency that, depending on the type, is also largely independent of the size. They are produced in many different variants. Nanotechnology can contribute much to this technique, such as ceramic films, nano-textured surfaces and nanoparticle catalysts.

In recent years around six to eight billion dollars has been devoted to developing fuel cell technology worldwide, and there is no reason to doubt that much will come of this technology. These quiet suppliers of electricity come in all sizes ranging from a postage stamp to a shipping container, and will by no means be used only in cars. For smaller consumers, a non-inflammable methanol/water mixture could be used as the hydrogen source, and would be filled up in the supermarket.

The fuel cell will help the electric motor to regain its pole position as the best possible motors of all (the first electric car took to the road in Paris in 1881). Only the electric motor can be operated at an efficiency level of over 90%, and only it can simultaneously function as a generator, and also convert kinetic energy back into electrical energy, such as when braking a car. The extremely good magnetic materials of new electric motors and generators are, naturally, also composed of nano-crystals.

Fuel cells will also be used in the household, supplying both electricity and heat at the same time.



Health

A breakfast with consequences in 2020:

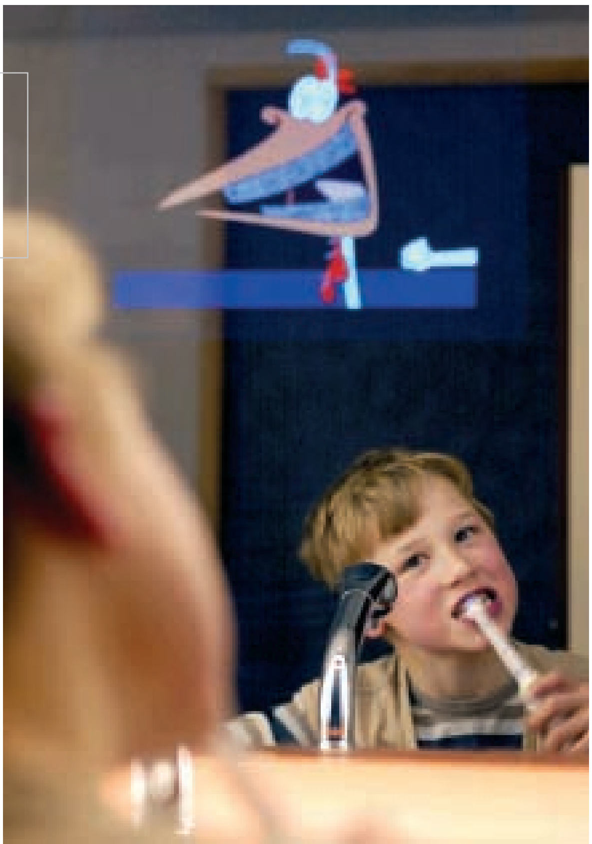
Is there any more coffee? Of course, and orange juice? Naturally, but there could be something very special about the packaging, such as an "electronic tongue" on the inside, which tests the juice to make sure it is still drinkable.

Top left: Film with nanoparticles keeps food fresh longer.

Top right: Intelligent packaging with polymer-based transponder chip.

Or a sensor on the outside, which determines any possible calcium or other deficiencies from the fingers holding the packaging, which could then be remedied by "functional food". Or conventional goat's cheese – the OLED (organic light emitting diode) label on the packaging would recommend the correct one.

The bathroom mirror is equipped with nanoelectronics, provides the user with information on request, and is somewhat reserved with regard to the orange juice, because orange juice is sugary, and sugar helps cause tooth decay. Once again nanotechnology is needed: the toothpaste (already available) contains nano-sized particles of apatite and protein, the natural material of the tooth, which helps it restore its normal condition (see also Biomineralisation).



The intelligent environment – the smart mirror equipped with nanoelectronics gives teeth-cleaning lessons.

The day cream (already available) contains nanoparticles of zinc oxide to combat harmful UV radiation. Being nanoparticles, they are completely invisible, so the cream is not white, but completely transparent.

Spies on the fingertip

With nanotechnology, nanoelectronics and micro-system technology, complex analysis equipment will become available that will also be within the price range of the private household. A tiny jab in the finger will be enough for future blood analysis. Are the cholesterol levels okay? Is the sugar level within the normal range? The findings could be emailed via Internet to the nearest nano-medical centre, where a more accurate analysis could be demanded or a completely individual medication put together via micro-reactors. In the body, the medication transports nanoparticles, which are coated in such a way that they only act at the source of the illness. "Drug delivery", accurate to the smallest detail. Doctors are watching the developments with great interest.

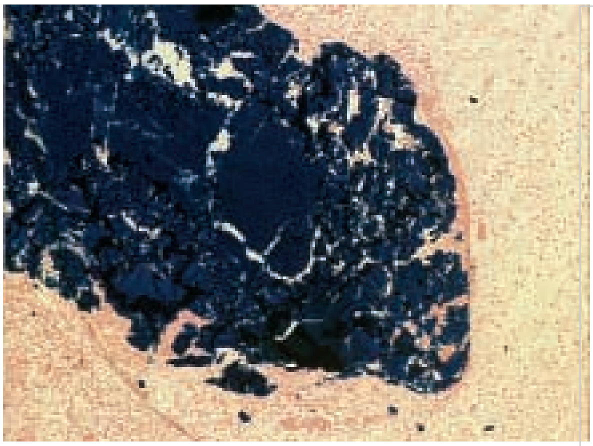
The diagnostics of tomorrow. The increasingly costly methods will be kept affordable by means of nanotechnology.

Supra-molecular medication capsules

The medications administered can in turn be extraordinarily sophisticated. They would be carried in supra-molecular hollow molecules (under development), nanoscale transport containers, which have antennae, to which antibodies of similar sensory proteins are attached. When they come into contact with structures typical of the agent responsible for the illness – for example, the outside of cancer cells or bacteria – they dock onto it and send a signal to the hollow molecule, which then opens up and releases its contents. With such nanotechnology, medications could be delivered in high doses direct to the source of the illness, without placing any stress on the rest of the organism and minimising side-effects.

Magnetic particles for cancer therapy

Similar tricks can be used to direct magnetic nanoscale particles to cancer sources, which are then warmed up by an alternating electromagnetic field and can destroy the tumour. Nanoparticles are also capable of passing through the "blood-brain barrier" filter system, so that they can also be used for combating brain tumours. This so-called magnetic fluid hypothermia was developed by the working group under the direction of the biologist Andreas Jordan. Clinical testing is now beginning.



Cancer cells in a glioblastoma brain tumour have "stuffed themselves full" with specially coated magnetite nanoparticles right up to the boundary with the healthy tissue. If the particles are now warmed up by an electromagnetic field, the tumour becomes susceptible to further treatment. Medical approval for this technique is already scheduled for 2005.

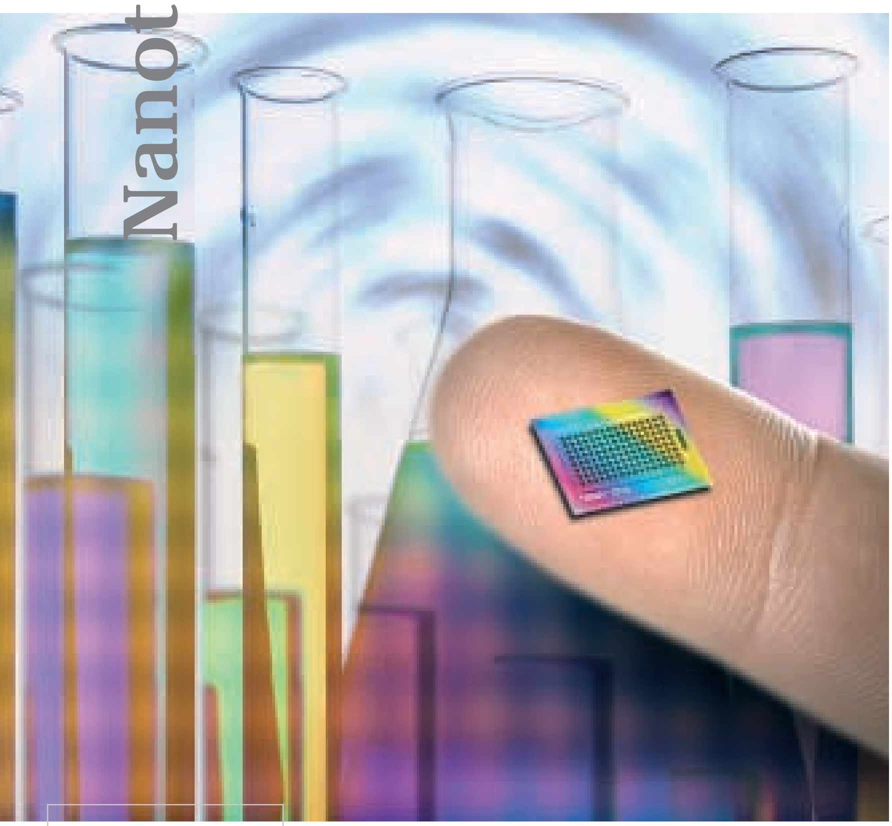
Turnstiles on a chip

Micro-system technology and nanotechnology – the boundaries between them are fluid – will pay for themselves in the medical sector, if in no other way, by miniaturising existing techniques and making them cheaper, sometimes by a factor of a hundred thousand or more. This would apply amongst other things to sophisticated machines that can check millions of cells, such as blood cells, for particular features at a rate of thousands

Health

Nanoparticle powders can be used to fire (sinter) perfect, reliable ceramic products, such as those used for implants.

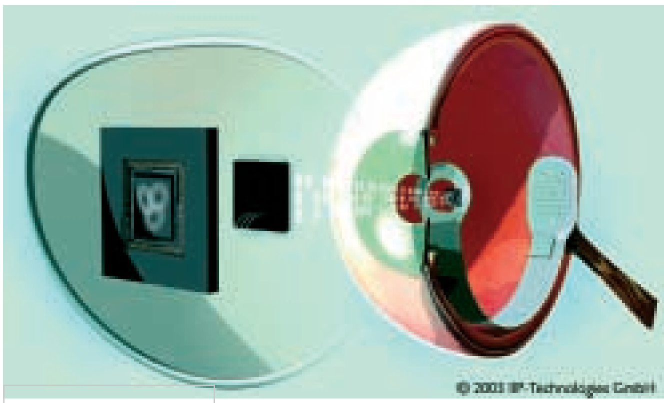
per second, and sort them in the living state. This could be done as follows: antibodies are added to the blood, which attach themselves to the cells of interest – and only to these cells – and at the same time carry a dye, which lights up or fluoresces under laser light. In the cell-sorter, the cells, encased in droplets, would be directed past such a laser; when a fluorescent signal is spotted, electrical fields steer the droplet and the cell into a collection vessel – the technique has been partly



Tiny but sophisticated, the “lab-on-a-chip”, a laboratory the size of the fingertip.

borrowed from the inkjet printer. Cell-sorters are very sophisticated devices, combining micro-mechanics, optics and the most refined electronics, and such machines are correspondingly expensive. Nanotechnology will reduce these turnstile-sized cell-sorters down to the dimensions of a postage stamp, perhaps even making them disposable products. This will speed up medical progress significantly.

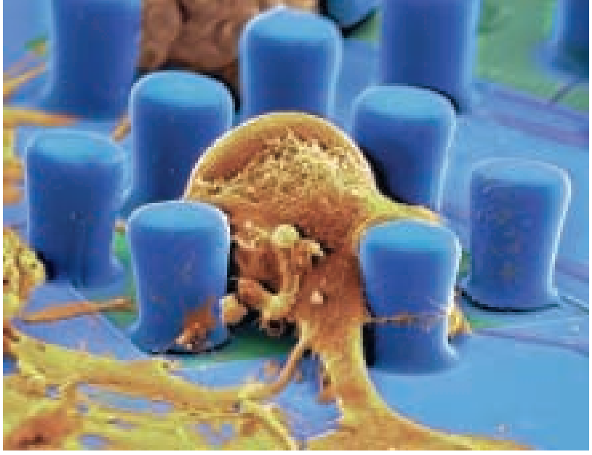
Even more sophisticated nanotechnology is planned for the lab-on-a-chip. According to leading developers, these will contain millions of nano-devices that work together in co-ordination to achieve their tasks. The chips would be several square centimetres in size, making them gigantic in comparison with the nano-machines they accommodate. This is due to the fact that fluids would have to circulate inside them, which in the nano-cosmos become as viscous as honey, and therefore need room to flow. Labs-on-a-chip will revolutionise biology, if scientists can in future use the nano-lab to follow what is going on step-by-step in individual cells. This would allow a sort of video to be reconstructed – a video of life. And scientists would not be satisfied with simply observing the cell, but would poke and prod it to see how it reacts, thereby decoding the mystery of life.

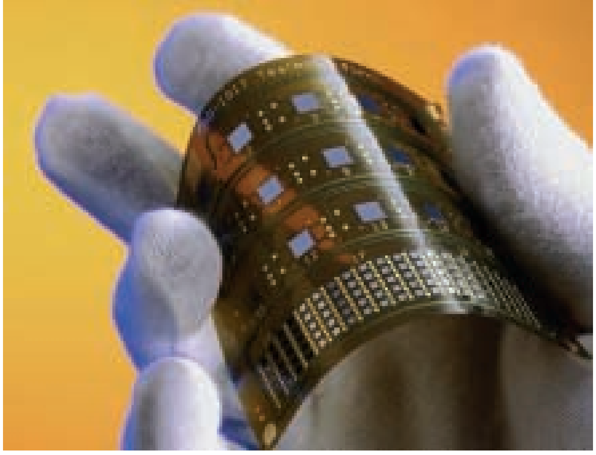


A retina implant.

Neuro-prosthetics

One extremely demanding application for micro-system technology and nanotechnology is currently entering the trial stage, the adaptive retina implant. This aims to restore partial vision in cases of blindness caused by *retinitis pigmentosa*. The system





Left: Coupling of nerve cells to electrical contacts.

Right: Wafer-thin silicon chips on flexible carrier material, for use in such things as intelligent labels, which can be incorporated into foodstuffs packaging or clothing.

consists of a tiny camera in the frame of spectacles, which transmits images of the surroundings to a special adaptive signal processor. The processor transmits this image data by wireless to the inside of the diseased eye. Here, a flexible film containing miniaturized electrodes in contact with the retina stimulates the optic nerve accordingly. If this development is successful, this will be the world's first "man-machine-interface" for the sense of sight. Many deaf people have already been helped by means of a cochlea implant. With nanotechnology, implants of this type will be able to be improved further.

Home care

Better nutrition and increasingly sophisticated medical care are enabling more and more people to live to an even greater age. This very desirable development however also brings with it the natural disadvantage that more and more people will need to rely on assistance. This will be able to be provided partly by nanoelectronics, and ideas under consideration include sensors and mini-computers woven into clothing and that would enable the continual monitoring of the state of health of elderly people – pulse, respiration and metabolism. If problems occur, the "MediVest" would automatically notify the family doctor or relatives. The location of the patient would also be reported by an integrated GPS or Galileo system module (Galileo is the future European version of GPS).

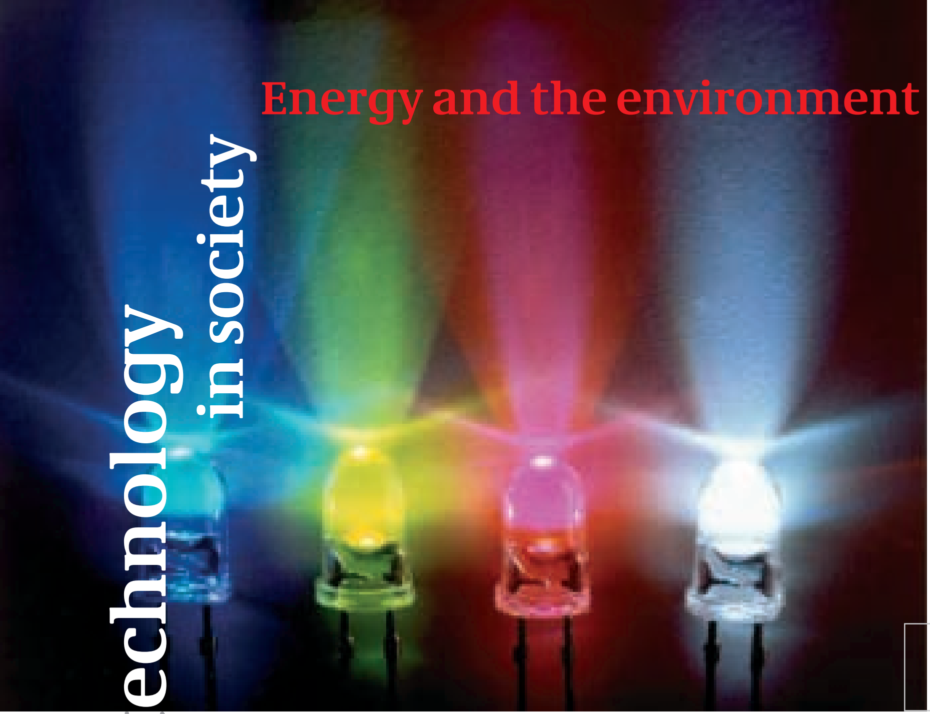
Automatic nurses

Old Europe" still has a rather reserved attitude toward mechanical helpers, although in Japan, mobile robots are approaching the industrial mass-production stage. It is quite possible that this could give rise to the development of automatic nursing machines suitable for everyday use, and work is already underway in this direction. Robotics will be able to handle the steadily increasing computing performance of nanoelectronics without any problem.

Robots with a sense of empathy from Oxford University. Enough for guarding ducks, but much more will be expected from automatic nurses.

Intelligent clothing: Integrated electronics play MP3 music files, provide directions in town and monitor the pulse – added value that can be experienced close up.

Energy and the environment



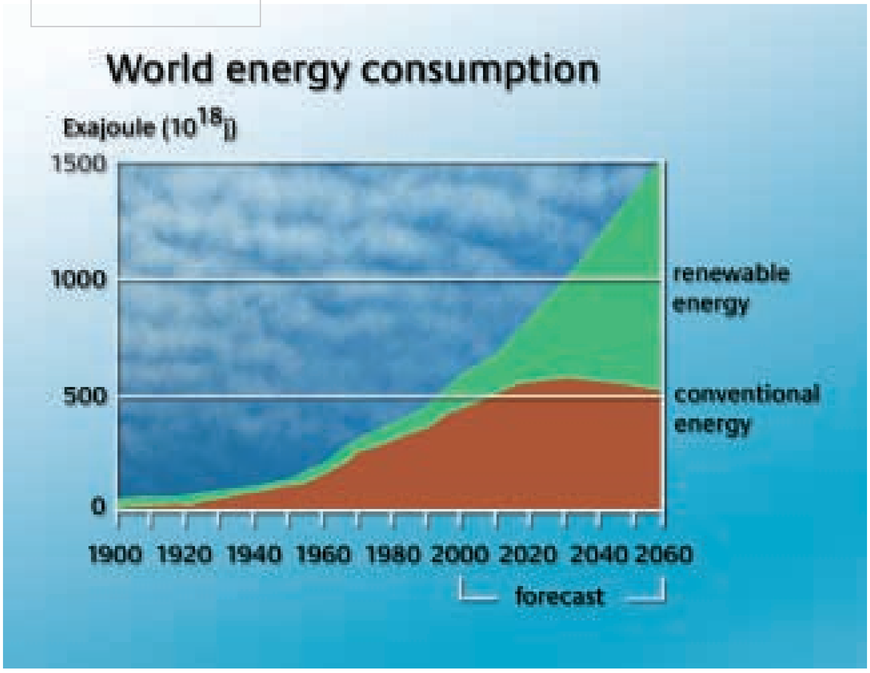
Efficiency revolution through LEDs.

In contrast to the previous history of technology, nanotechnology can combine economic growth with a reduced consumption of materials.

Business management à la nano: More convenience with lower material costs.

In Europe, about 10 percent of the electrical power produced is used for lighting. LEDs (light-emitting diodes) can now produce white light, and are therefore capable of replacing the conventional technology. Such a switch would result in substantial savings, because LEDs need only about 50 percent of the power required by a normal bulb in order to produce the same amount of light. This promises a considerable energy-saving potential for the lighting sector.

Forecast by Shell AG: Nanotechnology will be the technology of choice for renewable energies.



In private households, there are millions of television sets using cathode-ray tubes that will soon be replaced by sets using LCD (liquid crystal display) technology, and in the longer term also OLED technology. Both technologies have the potential of reducing the energy consumption by 90 percent. LEDs and OLEDs are produced with the aid of nanotechnology. If millions of households save a few kilowatts each, the result will be Gigawatts – the capacity of several large power stations.

The performance of fuel cells can be regulated quickly and easily. The first natural gas heaters equipped with fuel cells are now coming into use in the household, generating both controlled heat and electricity. Once millions of households are equipped with these devices, these heaters will be able to be combined via the national grid and the Internet into virtual major power stations, with a theoretical maximum capacity of

The complete spectrum: The glass facade of one of the halls of the Hotel Weggis on Lake Lucerne, illuminated in all the colours of the rainbow with 84 000 LEDs supplied by Osram.

hundreds of Gigawatts. In the long term, natural gas could also be replaced by hydrogen from renewable sources. Nanotechnology is ready for this development with new materials and catalysts.

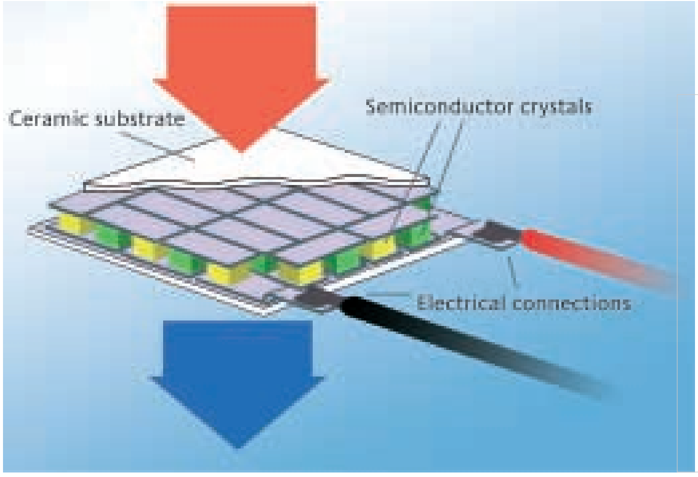
Ceramic membranes with nanoscale porosity are becoming increasingly important in the treatment of liquids, and also for the supply of clean drinking water. Bacteria and viruses can simply be filtered out with the aid of such membranes.

Nanotechnology will make solar energy a viable and lucrative proposition. Connective semiconductors of indium, gallium and nitrogen have already demonstrated performance figures that make solar cells with an efficiency level of 50% seem feasible. Efficiency is however only one criterion, nanotechnology will also enable a dramatic reduction in the cost of light collectors, either by thin-layer or particle technology. Laboratory samples of solar cell films produced with coating techniques similar to those used for LEDs and OLEDs, offer a performance of 100 Watts with a material weight of only 30 grams – a radical material reduction in energy production achieved in Leipzig by Solarion.

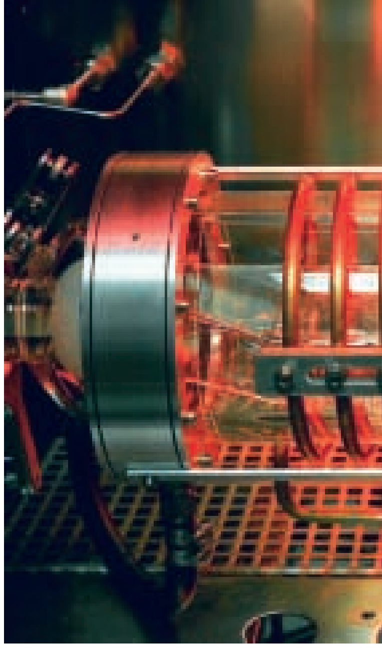
Siemens researchers claim an efficiency level of five percent for the latest organic solar cells, which can be printed on plastic film, and should become very affordable. The photoactive layer is only about 100-nanometers thick, and the working life is already several thousand hours of sunlight. The first products using this technology are expected to be on the market by 2005.

OLEDs (organic LEDs) will be used in many future displays.

Energy and the environment



Conventional thermoelectric module: a flow of heat is converted into electrical energy by blocks of semiconductors. Nano-structures are helping this technology achieve high levels of efficiency, thereby opening up new markets.

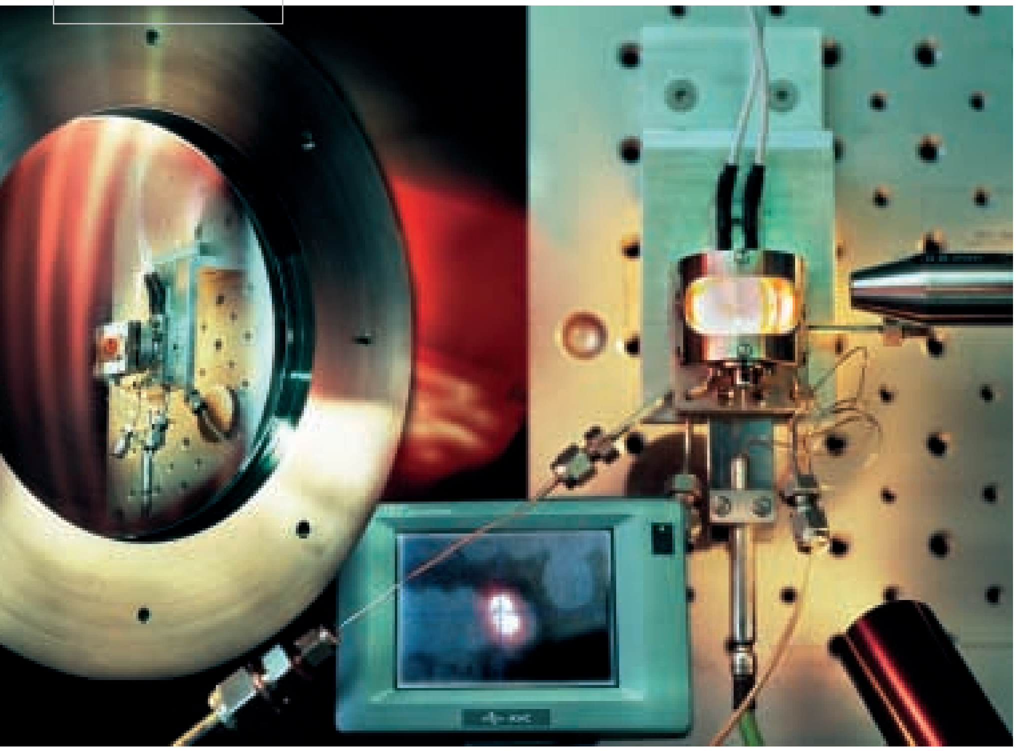


Nanotechnology is breathing new life into many old ideas that would otherwise have gone by the wayside due to the inefficiency of the available materials. One of these is the idea of thermoelectric electricity generation:

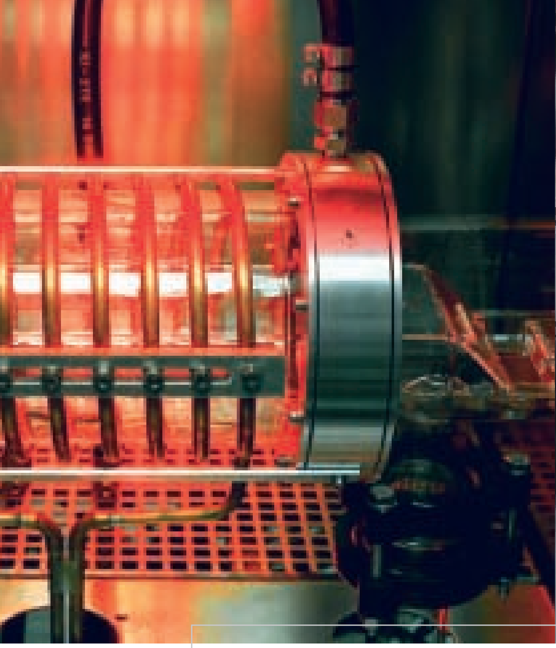
Electricity from heat, heat from electricity – Thermoelectrics

There is a wide range of known physical effects, hardly noticed by the public at large, that have performed only modestly in their various market niches. For example, the cooler bag, which is connected to the power supply system of the vehicle, and then really cools properly. Inside this, invisibly, works the legacy of Jean-Charles-Athanase Peltier, a French scholar, who in 1834 discovered the effect which now bears his name: a flow of current through the contact point between two different metals produces heat on one side of the contact, and cold on the other. Thirteen years earlier, the German Thomas Johann Seebeck had discovered the reverse effect, whereby a flow of heat through the contact point between two different metals generates electricity. Both these gentlemen are achieving new fame thanks to nanotechnology, which is now enabling the development of new materials that finally enable both these effects to work with very good levels of efficiency.

Chemical micro-reaction technology for the efficient production of even the most exotic substances.



The production of such materials again involves the same sort of machines used to manufacture LEDs. These machines apply a layer measuring five nanometres of antimony telluride to a nanometre-thick layer of



Aixtron reactors for research (left) and for the accurate production of thin layers of connective semiconductors (right).

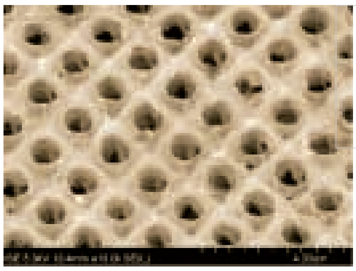
bismuth telluride, and then repeat the process until a semiconductor film has been created that would have amazed and delighted Messrs Peltier and Seebeck: when electricity flows through it, one side of the layering becomes hot, the other cold. The film can be structured very finely, so that it can be used for the accurate cooling of chips, or in a lab-on-a-chip in order to operate tiny reaction vessels, in which DNA is reproduced by means of rapid temperature change. It is quite conceivable that the dramatically increasing efficiency levels will in future make Peltier elements the technology of choice for the whole cooling industry. On the other hand, anyone with cheap sources of heat such as geothermal heat can produce electricity very economically with such thermoelectric layers. Iceland could become as rich as Croesus in terms of energy, thanks to electrolytically generated hydrogen.

In the chemical industry, techniques like this will be able to covert huge amounts of waste heat into electricity – silently, almost invisibly, and efficiently – with nanotechnology.

Thermo-photovoltaics

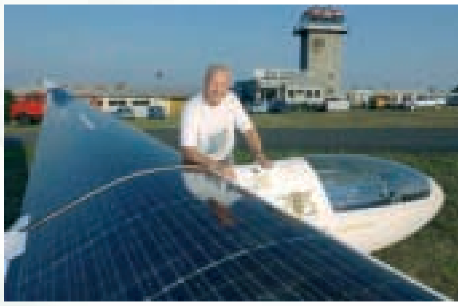
Thermo-electrics is not the only means of converting waste heat elegantly into electricity. Thermo-photovoltaics (TPV) use the (invisible) heat radiation, infrared radiation, of hot objects. The nanotechnology resides in the structures of the emitters, which adapt the spectrum of the heat source to the spectral sensitivity of the thermo-photovoltaic cells.

Candlelight is enough for thermo-photovoltaic cells to produce enough power to operate a radio.



Tungsten emitters with nano-structure surface for the adaptation of the infrared spectrum.

Nanotechnology for sport and leisure



The continual refinement of technology, which now includes the nanometric scale, is bringing back to life old ideas that would previously have been unfeasible. Amongst these is the concept of flight by means of solar power.

Icaré II, a solar-powered glider, can take the same stresses as a normal glider, and can start off under its own power.
Top: At the end of an unofficial record flight from Stuttgart to Jena.

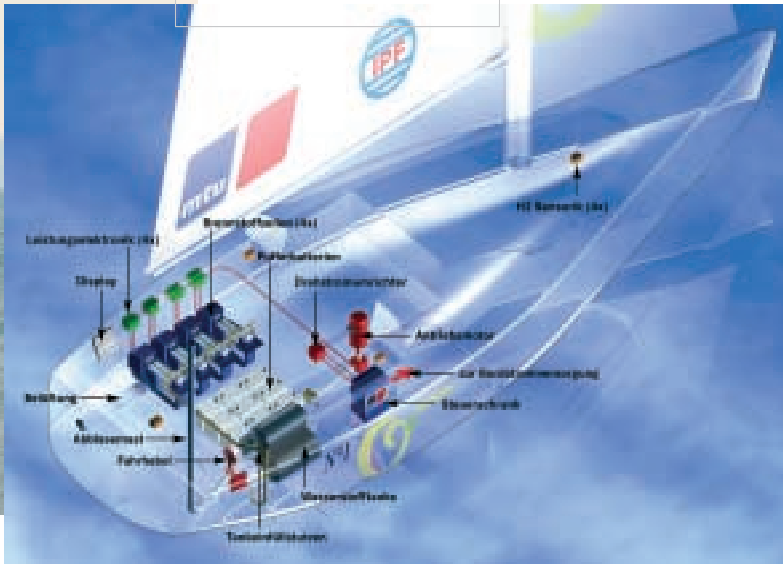
In June 1979, Bryan Allen propelled himself through the air in the Gossamer Albatross under pure pedal power across the English Channel to win the £100 000 Kremer Prize. The featherweight construction of the Gossamer Albatross by Paul MacCready was made possible by new materials. In 1981, a long-distance flight was made under pure solar power, although the aircraft, the Solar Challenger, was terribly fragile.

At the beginning of the 1990s, in memory of its unfortunate aviation pioneer Albrecht Ludwig Berblinger ("The tailor of Ulm"), the city of Ulm organised a competition to develop a practical solar-powered aircraft. In July 1996, the powered glider Icaré II built by the University of Stuttgart emerged as the clear winner.

NASA has designed a potential substitute for satellites in the shape of the HELIOS experimental solar aircraft, which is kept in the air by day by solar power, and at night be means of a "rechargeable" fuel cell unit. Maximum altitude: almost 30 000 metres.

In 2003, experts in thermodynamics, aerodynamics, electrical systems, composite materials, photovoltaics, energy conversion and computer simulation – nanotechnology is well represented in almost all these fields – met in Switzerland to discuss a project aimed at getting new technologies off the ground for an environmentally compatible future. Off the ground in the literal sense: around 2009, this ambitious project aims to take Bertrand Piccard and Brian Jones, who went around the world in a balloon in 1999, around the globe once more – this time non-stop in an aircraft powered only by solar energy!

Yacht with fuel cell engines by MTU, Friedrichshafen, Lake Constance. Nanotechnology can help such vehicles to combine efficiency with elegance: another conceivable idea is sails made of flexible textile solar cells, although the material would in this case have to be dark.

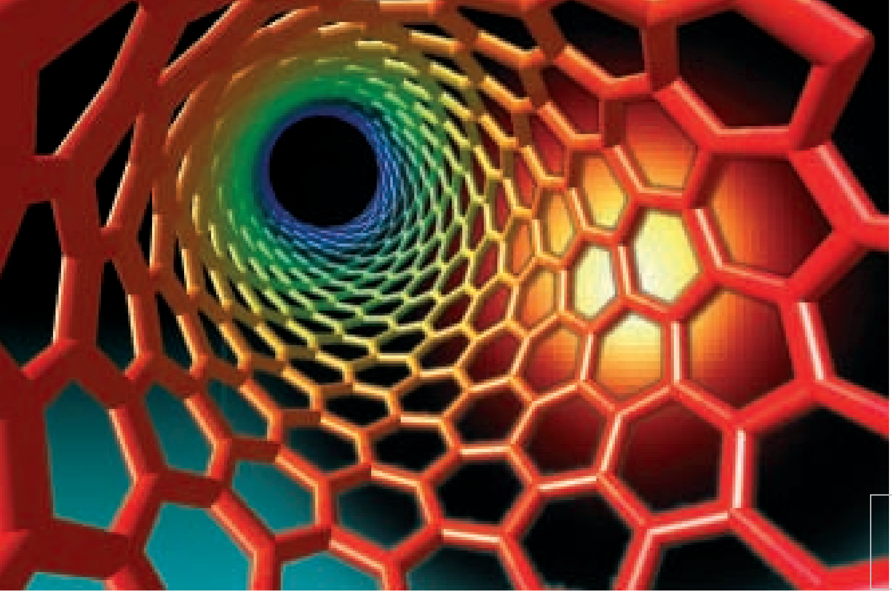


The "air worm" of the University of Stuttgart. This is planned to be used as a relay station for radio telephony.

Design study by the firm of Fuseproject, a fuel cell powers the scooter silently through the city.

The project could well earn these new technologies the respect they deserve, and also give rise to a whole range of new vehicles, such as solar-powered aircraft controlled by computers, sensors and GALILEO, which could also take novices into the air silently and without any exhaust gases. Freedom above the clouds will become boundless. Solar catamarans could well be planing across the Mecklenburg lakes; pedelecs, electrically assisted bicycles, will help elderly people into the saddle who otherwise might have some difficulty. Small electrical vehicles are deliberately being developed in many places to save the cities of areas undergoing rapid industrialisation from disappearing in a mire of exhaust fumes.

The solar catamaran built by Kopf Solardesign GmbH flies in and around Hamburg.

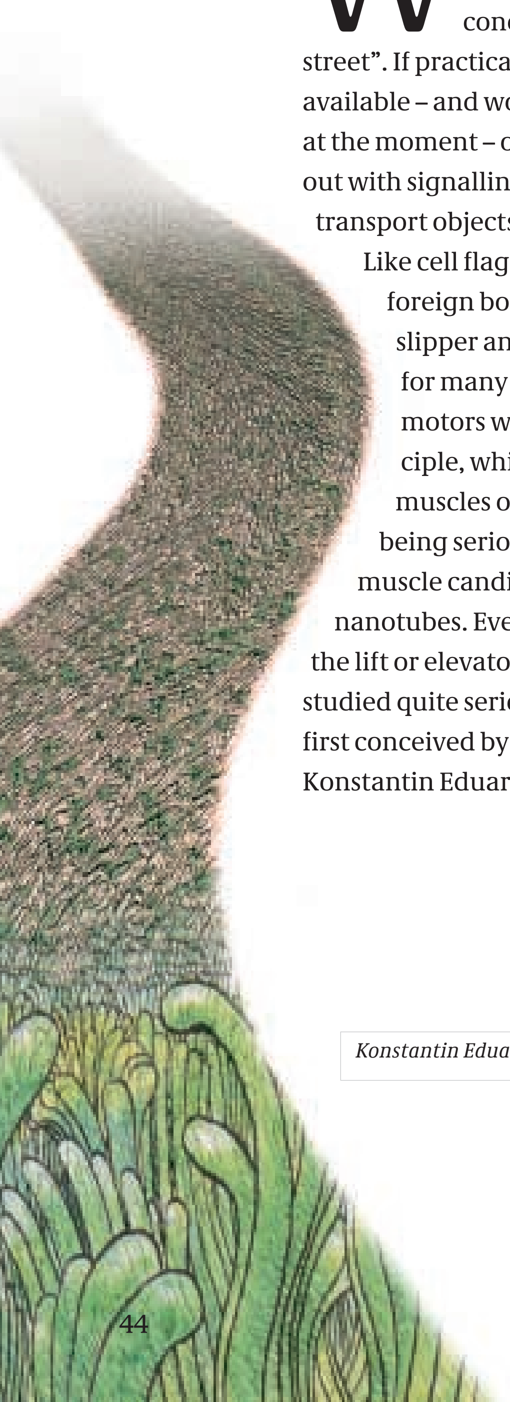


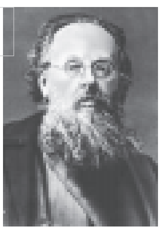
Visions

Nanotubes with Betelgeuse, a giant star in whose atmosphere fullerenes can be found.

The "finger street"

With nanotechnology, even the most utopian transport systems are conceivable, such as the "finger street". If practical artificial muscles become available – and work is going on in this direction at the moment – one could imagine a street laid out with signalling elements, fingers, which transport objects on them simply by beckoning. Like cell flagella, cilia, which fan dirt and foreign bodies out of the lungs, or propel slipper animalcules. The idea has room for many embellishments; tiny linear motors working according to this principle, which operate by means of plant muscles or "forisomes", are in any case being seriously considered. Other artificial muscle candidates include fabrics of carbon nanotubes. Even this idea is not so fantastic as the lift or elevator to the planets, which is being studied quite seriously by NASA, and which was first conceived by a Russian space pioneer, Konstantin Eduardowitsch Ziolkowski.

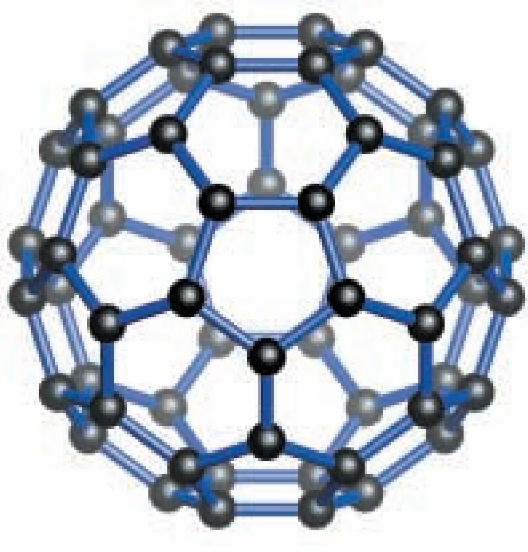




Konstantin Eduardowitsch Ziolkowski

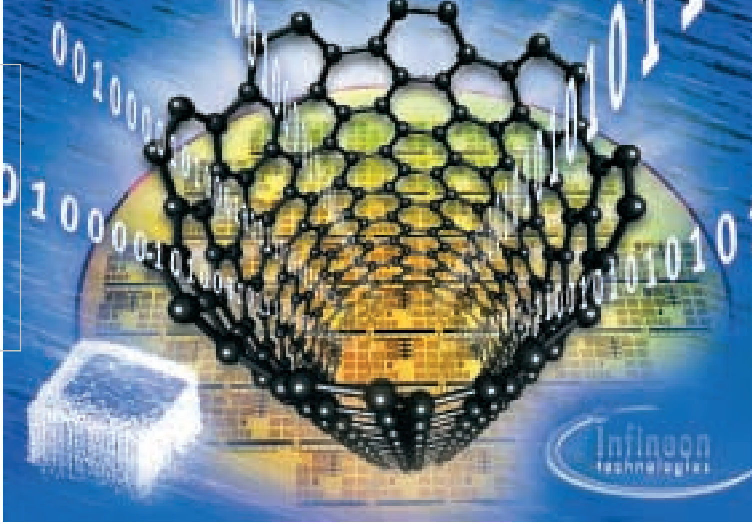
Carbon nanotubes for the lift into orbit

The recipe came from space: in the shells of old stars such as Betelgeuse, a red giant, many different elements circulate. If these react chemically with each other, nanocrystals form, such as silicon carbide, silicon oxide, corundum and even diamond, as is already known from the examination of meteorite that have formed from such dust. In order to find out more, scientists have reproduced the conditions in these star shells in the laboratory – and in 1985 found traces of a completely unknown substance. This proved to be a new compound of carbon: a hollow molecule very reminiscent in shape of a football. A recent look into the heavens showed that this molecule is also formed in the shells of stars.



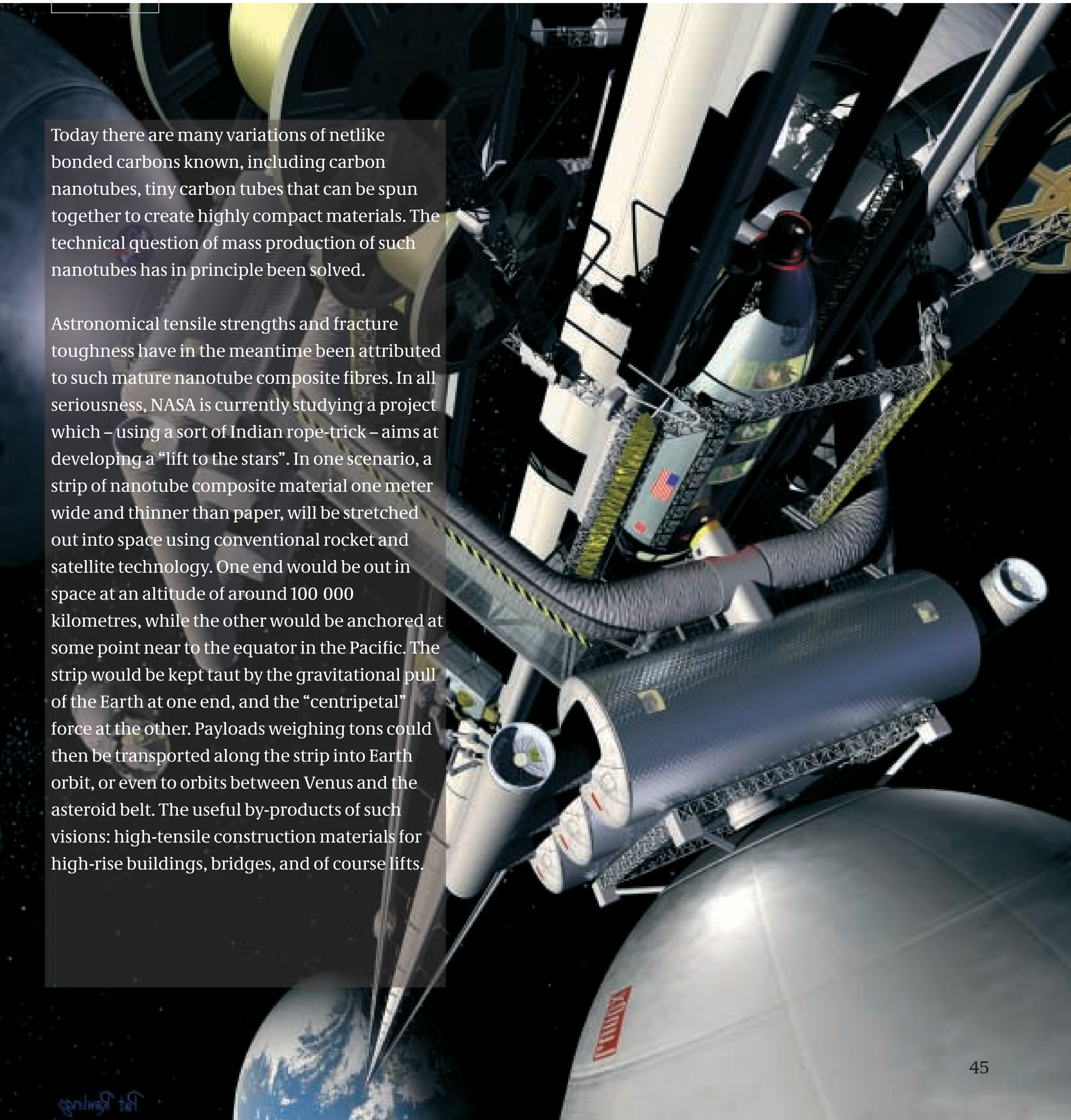
Fullerenes, cavities of carbon networks, hopeful prospects in the search for exotic materials.

Robert Curl, with fullerenes on his fingertips, which have won him a Nobel Prize.



Giant molecules as master computers: nanotubes could form the basis for the high-performance chips of the future.

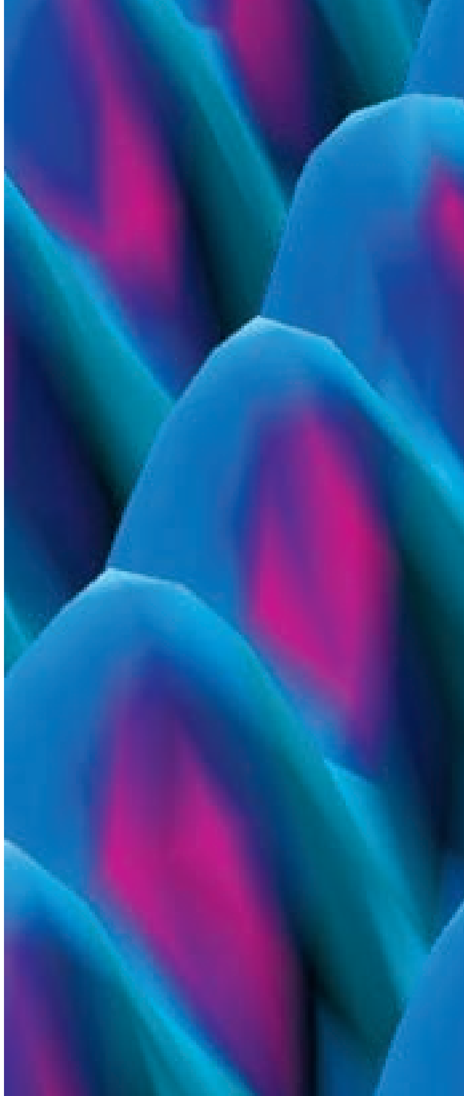
Vision: a lift to the planets.



Today there are many variations of netlike bonded carbons known, including carbon nanotubes, tiny carbon tubes that can be spun together to create highly compact materials. The technical question of mass production of such nanotubes has in principle been solved.

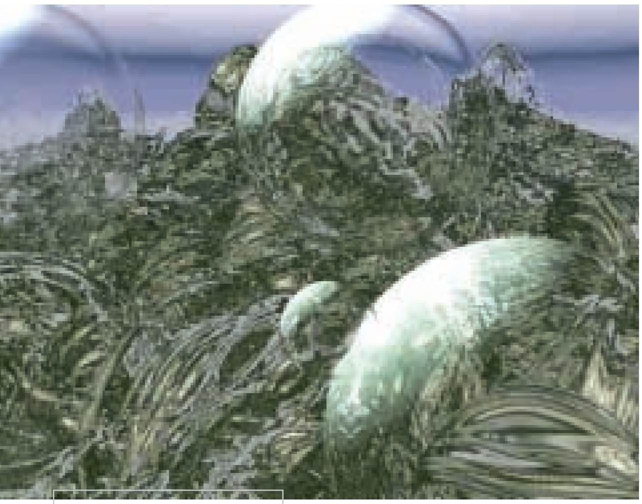
Astronomical tensile strengths and fracture toughness have in the meantime been attributed to such mature nanotube composite fibres. In all seriousness, NASA is currently studying a project which – using a sort of Indian rope-trick – aims at developing a “lift to the stars”. In one scenario, a strip of nanotube composite material one meter wide and thinner than paper, will be stretched out into space using conventional rocket and satellite technology. One end would be out in space at an altitude of around 100 000 kilometres, while the other would be anchored at some point near to the equator in the Pacific. The strip would be kept taut by the gravitational pull of the Earth at one end, and the “centripetal” force at the other. Payloads weighing tons could then be transported along the strip into Earth orbit, or even to orbits between Venus and the asteroid belt. The useful by-products of such visions: high-tensile construction materials for high-rise buildings, bridges, and of course lifts.

Opportunities and risks



The potential of nanotechnology for good, or at least to make a profit, is clearly immense. Due to innovations in many areas of application, huge commercial potential is ascribed to nanotechnology. There are already several hundreds of companies in Europe involved in the commercial application of nanotechnology, providing jobs for tens of thousands of generally highly qualified employees. In this respect, scientists and businessmen are unanimous: nanotechnology is much more than just a new “hype”.

Too good to be true? A super-colony, which appears possible as least in theory, has already found its way into literature: In Michael Crichton’s best-seller “*Prey*”, swarms of smart nanoparticles join together to form semi-intelligent beings, who turn on their creators. Another sombre vision of the American nano-prophet, Eric Drexler, sees the world threatened by so-called “gray goo”, a gray cloud of wayward nano-robots.

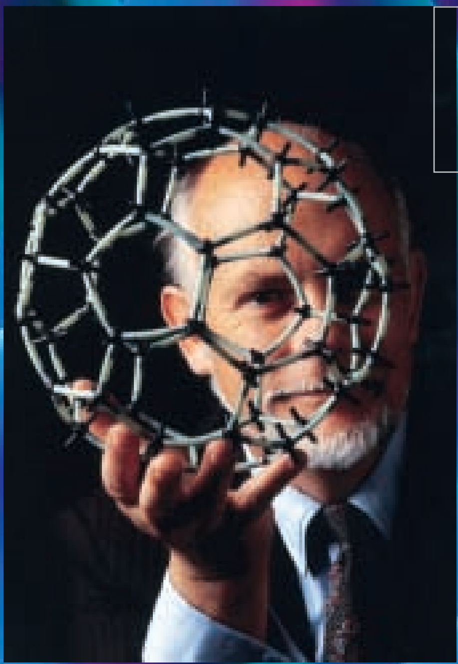


Due to the problem of the ‘fat and sticky fingers, the “gray goo” scenario of Eric Drexler is just as unlikely as the idea that the world could be turned into jelly bears by nanotechnology.

Eric Drexler actually considers it possible to build nanoscale robots of a size of only a few millionths of a millimetre, program-controlled and capable of creating something new and bigger from the raw materials provided. And if the process got out of control, it would create, instead of something wonderful, this gray goo, which could be both contagious and dangerous for both man and machine.

This concept is not taken seriously by most experts. Like Richard Smalley, the Nobel Chemistry Prize winner of 1996, who points out the peculiarity of chemical bonds, which make it impossible for every atom or every molecule to be combined with each other.

This alone would make the idea of a nano-bot, a nanoscale robot or assembler, highly unlikely. In this case, if such an “assembler” were to put together matter atom by atom, it would have to use “fingers” to do this, which in their turn consist of atoms, and would necessarily have to have a certain minimum thickness. And this would not



Richard Smalley, winner of the Nobel Prize in Chemistry, considers the risks of nanotechnology to be containable.

only be to grasp the selected atom, all the atoms of a cubic nanometre would have to checked during assembly, where the fingers would necessarily get in the way. So much for the fat-finger problem. To this must be added the sticky-finger problem, the atoms grasped, depending on their type, could not be simply picked up and put down again, but would start to form bonds – a commonly known phenomenon: it is not so easy to get a sticky globule off your finger again. And these are essential arguments that cannot easily be circumvented. Mechanical nano-bots are therefore an impossibility. Richard Smalley could be right: there is no reason to fear that armies of wayward nano-machines could rampage over the world, turning it into gray goo.

But there could well be good reasons to fear that nanoparticles could also have undesirable effects on mankind and the environment. For instance, nanoparticles could be harmful to health due to their minute size, which even enables them to penetrate into body cells and even break through biological barriers (such as the blood-brain barrier). Since nanoparticles – like other ultra-fine dusts such as diesel soot in vehicle exhaust gases – are substances that can cause unknown side effects, scientific investigations must first be carried out to ensure that such particles are safe. So far, there is very little available knowledge on the safety of nanoparticles, so that outstanding questions must be answered as quickly as possible by means of relevant experiments by nano-researchers and toxicologists. However, the risks appear to be manageable, since nanoparticles found in nature are extremely "sticky". They bond together very quickly into large lumps, which the body can get rid of very easily. We already know of some nanoparticles that they are not harmful to health. They are therefore used in sun-protection creams as the light-protection factor, or are mixed with other materials in bonded form, so that the user does not even come into contact with individual nanoparticles. Industry is also applying suitable safety measures in order to exclude any health risks to its customers or its employees.

While visions of nano-bots are still completely hypothetical, the promises of material scientists working on the nanoscale appear very real. The first products are already in existence, such as high-sensitivity hard-disk reading heads with thin coatings of twenty nanometres or less. Nanoelectronics can already be found in every laptop. As a potent technology, nanotechnology will naturally also have side effects, making many simple tasks superfluous. Many new areas of activity will be created in their place. Lifelong learning is becoming increasingly important, but even this can be fun too – with nanotechnology.

Further information

How do I become a nano-engineer?

Anyone visiting a research centre where intensive work is going on into nanotechnology will be able to see all the disciplines of the natural sciences side by side: biologists, chemists, engineers of every specialisation, crystallographers, mineralogists, physicists – the common denominator is the level of the atom, and an essential part of the common language mathematics. The classical natural science courses can therefore all lead to nanotechnology, although nanotechnology is beginning to establish itself as an independent discipline, such as at the University of Würzburg. Anyone taking up the subject of nanotechnology, says Alfred Forchel of the chair of Physics of the University of Würzburg, need have no fear that they are following a short-term trend, (Extract 'abi 10/2003' of the University of Würzburg).

"Because the trend toward miniaturisation is no scientific fad, but already has a great deal of development behind it, it is probable that in many areas, applications will go down to ever smaller scales, from micro to nano so to speak, in every discipline ranging from information technology to chemistry. One does not need to be a clairvoyant to see that everything will continue to shrink in size – one example being construction elements – and indeed to the smallest size possible."

Physicists, chemists and other natural scientists can with justification claim that they have always been involved in some way with nanotechnology. The subjects of classical atomic physics, the molecules studied by the chemists, are all inhabitants of the nano-cosmos. With the experimental capabilities available today, such as the detailed atomic structuring of clusters, layers, chips as well as the availability of substances of the highest purity and the investigation of the tiniest biological structures – a cornucopia of completely new possibilities has been opened up that is also of great benefit to application engineering. Alfred Forchel assesses the professional prospects or nano-engineers as quite good:

"Of course, the opportunities of finding a job in our sector also depend on the buoyancy of the economy, just like any other field of business. But relatively small matters often make all the difference: if companies receive stacks of applications, it is naturally difficult to make oneself stand out. By offering practical training in industry, it means that there is at least one company that the student knows a little more closely. Our students can also write their diploma thesis while working in industry, putting them another step closer to a job. They also study at least one non-technical subject, such as business management, so that they also have some other basic skills important for professional life."

But for nano-engineers, there is no getting round a sound natural science training, including mathematics, either at Würzburg or anywhere else:

It is not enough to dream of developing a tiny submarine that can travel through veins. A huge amount of time and work must be invested before it gets to that stage. One must learn to describe things mathematically, and have a sound working knowledge of such basic skills as physics and chemistry. However, there is no reason to be intimidated: your nano-fantasies are sure to help you through.

The idea of the submarine in a person's veins was just a film: nanotechnology is a little different, but there can be real money in it.

Contacts, links, literature references

Please note that this brochure originates from the German research ministry BMBF. It was therefore initially written for a German audience. For links to European, other than German courses, literature and websites please check the internet portal on nanotechnology of the European Commission (www.cordis.lu/nanotechnology).

Study courses in nanotechnology in Germany:

Nano-structure technology in Würzburg
University of Würzburg
Website: http://www.physik.uni-wuerzburg.de/nano/
Contact: uerzburg.de" ossau@physik.uni-wuerzburg.de

Bio- and nanotechnologies in Iserlohn
Technical University of Südwestfalen
Website: http://www2.fh-swf.de/fb-in/studium.bnt/bnt.htm
Contact: YPERLINK "mailto:Werner@fh-swf.de"
Werner@fh-swf.de

Molecular Science in Erlangen
University of Erlangen-Nürnberg
Website: http://www.chemie.uni-erlangen.de/Molecular-Science
Contact: hirsch@chemie.uni-erlangen.de

Master's course in Micro- and Nanotechnology in Munich
Technical University of Munich
Website: o/home.htm" http://www.fh-muenchen.de/home/fb/fb06/studiengaenge/mikro_nano/home.htm
Contact: sotier@physik.fh-muenchen.de

Nano-molecular Science in Bremen
International University Bremen
Website: http://www.faculty.iu-bremen.de/plathe/nanomol
Contact: f.mueller-plathe@iu-bremen.de

Nano-structure science – Nano-structure and Molecular Sciences in Kassel
University of Kassel
Website: http://www.cinsat.uni-kassel.de/studiengang/studiengang.html
Contact: masseli@physik.uni-kassel.de

Experimental Bachelor's course with the degree of Bachelor of Science in Biophysics or Nano-sciences in Bielefeld
University of Bielefeld
Website: http://www.physik.uni-bielefeld.de/nano.html
Contact: dario.anselmetti@Physik.Uni-Bielefeld.de

Degree course in "Micro- and Nano-structures" in Saarbrükken University of Saarland
Website: uni-saarland.de/fak7/physik/NanoMikro/InfoMikroNano.htm" http://www.uni-saarland.de/fak7/physik/NanoMikro/InfoMikroNano.htm
Contact: wz@lusi.uni-sb.de

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Technology definition (Vol. 38)
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ZPT, Saarbrücken, 2001.

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Nanophysik und Nanotechnologie
Teubner Verlag 2002

Werkstoffinnovationen für Industrie und Gesellschaft-WING
Pub.: Federal Ministry of Education and Research; Bonn, October 2003.

Internetlinks:

Nanotechnology portal of the EU
www.cordis.lu/nanotechnology

European Nanotechnology Portal
www.nanoforum.org

Nanotruck – The journey into the nano-cosmos
www.nanotruck.net

Internet travel adventure beyond the decimal point
www.nanoreisen.de

News and discussion on nanotechnology
www.nano-invests.de

Nanotechnology sponsorship of the BMBF
http://www.bmbf.de/de/nanotechnologie.php

Nanotechnology portal of the VDI-TZ
www.nanonet.de

Glossary

Byssus threads: Also popularly called “mussel silk” or “mussel’s beard. Technically sophisticated threads created by mussels to anchor themselves to surfaces. They are as elastic as rubber at one end, and as rigid as nylon at the other.

CNTs: Carbon nanotubes

Clusters: Clusters of tiny particles, in this case atoms. Clusters usually have different properties to the solid form of the same materials, amongst other things because clusters contain a larger proportion of surface atoms.

Diatoms: Tiny single-cell creatures occurring in fresh and salt water, with a very elaborate shell of silicon dioxide and water. Diatoms are capable of photosynthesis, and therefore also have light-conducting structures.

DNA: Deoxyribo-nucleic acid. Giant molecule in the form of a double-helix, which contains the information for the design of an organism and formulae for myriads of proteins.

ESEM: Environmental Scanning Electron Microscope – special scanning electron microscope that allows air and humidity in the sample holder. The lenses do not have to be specially treated with, for example, gold vapour.

Fibre-optic thread: Directs light through extremely transparent material over long distances, usually for data transmission, but increasingly also for energy transmission.

Forisomes: So-called plant proteins named after the Latin word for “door leaf”, which are being researched as candidates for nanoscopic artificial muscles.

Free electron laser: Generates laser light by means of an accelerated bean of electrons travelling in a vacuum tube.

Frequency doubler: Here, material that doubles the frequency of light, for instance converting infrared light into green light.

Fuel cell: Device in which hydrogen and oxygen (usually from the air) react without combustion to form water, producing electrical energy with a high level of efficiency.

Lab-on-a-chip: Highly complex chips, now in the final stages of development, which with the aid of micro-mechanics, micro-fluids, nano-sensors and nanoelectronics, can carry out complex examinations of cells that would other wise require the resources of a complete research institute. The name is also used for comparatively simple microscopically printed object carriers.

Leukocytes: White blood corpuscles, which defend the body by absorbing foreign bodies in the blood such as viruses and bacteria, and also cell remains or cancer cells, or as lymphocytes, produce antibodies. Antibodies are very specific, adhesive molecules.

Lithography: Here, the technique of producing microscopic structures, usually by means of photo-reactive coating, which is inscribed with beams of light or electrons, developed, and then reveals or conceals required parts of the surface for etching and other processes.

Mask: A type of transparent film containing the design and layout of a computer chip, which is then transferred lithographically onto wafers.

Micelles: Tiny spherical structures used by nature, in this case the mussel, as transport containers.

Micro-lens fields: Micro-optic elements important for such things as information transmission by means of light.

Phase: Here: Condition or state, such as arranged/random, or crystalline/amorphous

Photosynthesis: Green plants, algae and cyanobacteria (blue algae) obtain their energy by means of photosynthesis. With the aid of sunlight, they convert carbon dioxide and water into sugars and oxygen. Photosynthesis works at an astonishing primary energy yield of over 80 percent.

Piezo crystals: Piezo elements generate electricity when they are compressed or stretched, such as the ignition sparks in "electronic" lighters. Conversely, a piezo-electric crystal can be shaped by electric current down to fractions of the diameter of an atom.

Proteins: Large molecules composed of ribosomes from amino-acids, which act in cells partly as nanoscopic tools, partly as building materials, for everything from eye lenses to fingernails. The decryption of the proteome, the sum of all proteins and their interactions in a cell, is only just starting.

Quantum computer: Uses the characteristic rules of quantum mechanics in order to solve problems, such as information encryption, that are practically insoluble with conventional computers. Still in the theoretical stage.

Reflectins: Special proteins used by organisms to create light-reflecting structures.

Ribosomes: Nano-machines that can produce myriads of proteins, and controlled by a molecular strip with information from the genetic material DNA.

Semiconductor: Material whose electrical properties can be specifically adjusted, making it either an insulator or conductor. Semiconductors have become one of the most important components of modern industrial products such as computers and mobile phones.

Tunnel current: Current that should actually not flow, because it passes an insulating gap, but can flow in the nano-cosmos, although it then depends significantly on the size of the insulating gap. This effect has made the scanning tunnel microscope possible.

UV radiation: Short-wave radiation that enables the production of very fine chip structures.

Van-der-Waals bond: Weak chemical bond between molecules, whose ultimate cause is the properties of the empty spaces of the molecules. Van-der-Waals bonds also determine the properties of water, and thus all living processes.

X-ray radiation: Short-wave, electromagnetic radiation used amongst other things in crystal structure analysis to determine the nanoscopic shape of molecules.

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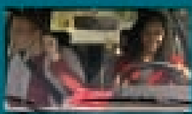

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The aim of this brochure is to illustrate to the public what nanotechnology is and thereby to stimulate the discussion. By describing the scientific background, technological developments, areas of application, and potential developments of the future, this brochure provides a complex and comprehensive picture of nanotechnology as we see it in our days.

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