Joint EC/NSF Workshop on Nanotechnologies

Organised by
the European Commission and
the National Science Foundation
of the United States of America

Chamber of Commerce and Industry
Toulouse, 19-20 October 2000

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NANO-RESEARCH – THE EUROPEAN IMPERATIVE

In his opening address to the Toulouse Nanotechnology Workshop, Philippe Busquin, European Commissioner for Research, urged participants to explore ways in which cooperation could be developed and improved to mutual advantage.

The infinitely small opens enormous prospects for the future of mankind. The 20th century has seen dazzling technological advances, thanks to the progress of electronics, biotechnology, and the materials sciences. These have all contributed to advances in the quality of life of the citizens, both directly – through improved products and services – and indirectly – through creation of wealth and employment. Today, at the beginning of the 21st century, we see that research in the life sciences, information technologies and materials sciences converges upon a commonality: the domain of the nanometre, and the manipulation of atoms and molecules. In all three areas, continued technological progress is dependent upon achieving know-how and control of materials at the nanoscale.

Nanotechnology cannot be defined in terms of dimensions alone. In fact, it represents a convergence of the traditional disciplines of physics, chemistry and biology at a common research frontier.

European Area of Research and Innovation (ERA)

Economic growth derives from technological progress. Scientific effort will produce the knowledge, while technology will allow its implementation and application in new products and services.

Enthusiasm for science and research is therefore essential and has to be continually renewed, especially among the young generations. The attraction of scientific careers and the visibility of science must be improved.

Science and science policy must be aligned with the social needs of society, with the principles of precaution and sustainable development – and must comply with basic ethical principles.

It is in this context that the European Commission has introduced the concept of a 'European Area of Research and Innovation'. Already approved by the Council and the European Parliament, the ERA has been welcomed with enthusiasm by the scientific community. Its central aim is to establish a coherent European research and technological development (RTD) policy which will transcend the policies of individual Member States and the Commission's Framework Programme.

Nanotechnology is identified as a priority field of research. It will figure prominently in the forthcoming new Research and Innovation Framework Programme, which is a key structural element of the ERA. But this alone will not be enough – it represents just 5% of total EU public expenditure. Member States must participate in co-operation at European level, as a basis for further organisation of world-level research in the most coherent and efficient way possible.

International dimension

The ERA also has a clear international dimension, going beyond the limits of Europe. It is obvious that, on the one hand, European research must be of service to the international community and, on the other hand, that we are confronted with tasks of a global nature. The problems of society, illnesses and epidemics, under-employment, mobility, energy and the environment are global concerns.

Consequently, the Commission will strengthen its efforts to develop the necessary international co-operation agreements. There is a long tradition of collaboration between Europe and the USA, which provides a sound foundation for further progress. This has already led, for instance, to agreement on adopting a common approach in combating diseases such as AIDS, TB and malaria in Africa.

Nanotechnology is a vast field. Working more closely together is vital to achieve the critical mass that will allow us to benefit from the quantum leaps in scientific discovery that are now emerging.

This workshop is therefore highly opportune. The conclusions reached here will guide us in the definition of future initiatives which will enable us to unlock the staggering potential that nanotechnology is beginning to put within our grasp.

Philippe Busquin

EXECUTIVE SUMMARY

The EC/NSF Workshop on Nanotechnology took place in Toulouse, France, on 19-20 October 2000. Jointly organised by the European Commission and the National Science Foundation of the United States, it brought together some of the most eminent European and American scientists in this wide-ranging field.

The workshop was organised at the Chamber of Commerce as a satellite meeting to the major international technology fair New SITEF 2000. Its scientific participants (17 from the USA and 20 from Europe) were joined by representatives of the NSF Divisions of Materials Research and of Engineering, of major European materials science societies and networks (EMR-S, FEMS, EuSPEN, Institute for Nanotechnology), and of the Commission R&D programmes QoL, IST and Growth.

The broad objectives of the workshop were to survey the state of the art in nanotechnology, determine the prospects for development and identify areas for fruitful EU/USA co-operation in research.

Following the opening address by the European Commissioner for Research Philippe Busquin, the proceedings began with keynote speeches by Nobel prize-winner Dr Horst Stormer, and Professor Peter Laggner, head of the Institute of Biophysics and X-ray Structure at the Austrian Academy of Sciences. Spokesmen for the EC and NSF then explained their respective approaches to the support of nanotechnology research and the mechanisms for its funding.

A series of presentations outlined recent work and future prospects in the four main nanotechnology sectors – electronics, biotechnology, materials and nanofabrication. These presentations were followed by group discussions in which the European and American participants sought to establish priorities, define areas of common interest, and suggest practical ways to increase collaboration.

Overall, the results indicate that the workshop made a valuable contribution by identifying complementary expertise in the EU and USA, highlighting areas where shared initiatives could be mutually beneficial and clarifying the criteria for funding such projects. While some practical problems still remain to be resolved, it was concluded that the EC (DG RTD)/NSF Implementing Arrangement in the area of Materials Sciences, signed in December 1999, provides an effective and promising basis for continuing transatlantic co-operation.

PAVING THE WAY FOR A THIRD INDUSTRIAL REVOLUTION

Nanotechnology will be a potent force in shaping the economies of the future. Toulouse, one of Europe's leading centres of research, provided a fitting location for top European and USA specialists to exchange views on the opportunities for co-operation in this vital area.

As the capital of the European aerospace industry and France's second largest university centre, Toulouse is a hub of research and innovation. Last October, the town hosted SITEF 2000, the tenth in a series of international fairs bringing together advanced technologies worldwide. This major event provided an ideal background for a two-day workshop attended by leading nanotechnology specialists from Europe and the USA.

Co-operation agreement

Jointly organised by the European Commission's Competitive and Sustainable Growth (Growth) programme and America's National Science Federation, the meeting was held under the umbrella of the December 1997 Agreement for scientific and technological co-operation between the European Community and the Government of the USA. More specifically, it fell within the scope of the Implementing Arrangement in the area of Materials Sciences, signed in December 1999.

The Agreement recognises the need to work together in the face of globalisation trends, to assemble the critical mass necessary to accelerate the flow of knowledge. This is a flexible accord which is oriented towards the longer term. It includes provision for the funding of joint research projects and networks; the exchange of information; and the training of scientists, engineers and technical experts.

The workshop had four main objectives:

- to survey the state of the art in nanotechnology, taking account of major application domains – electronics, biotechnology, materials and nanofabrication;
- to determine the prospects for development, and the impact on environment and economy in the EU and USA;
- to identify research needs and assign priorities; and
- to obtain the views of the scientific community on areas of nanoscale science and engineering where EC/NSF joint projects could have a particularly high impact.

Wide-ranging debate

Distinguished scientific delegates (17 from the USA and 20 from Europe) represented a very broad spectrum of disciplines and professional backgrounds. All areas of nanotechnology were covered, from current industrial applications of nano-powder processing to post-genomic biotechnology, nano-electronics and the prospects for new materials in chemistry and engineering.

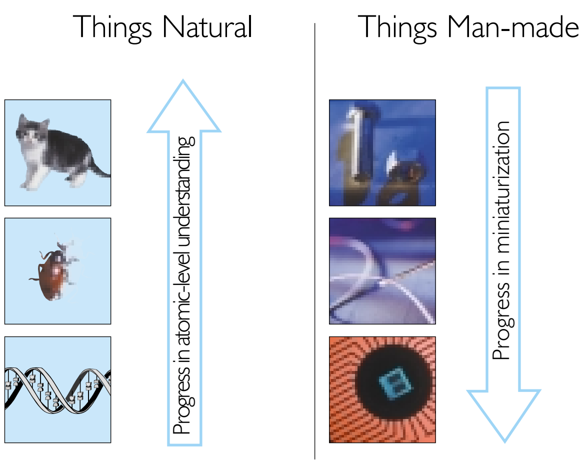
A first co-ordinated call for joint EC/NSF research project proposals had already taken place under the Arrangement earlier in the year. So there was also an opportunity to review the practical experience gained to date, and to explore ideas for improvements.

On the opening morning, participants were joined by journalists from a number of national and international publications, who heard EC Commissioner for Research Philippe Busquin underline the need for co-operation beyond the confines of Europe, and stress the importance of spreading scientific understanding and education globally.

WHAT IS NANOTECHNOLOGY?

The prefix nano- signifies smallness. A nanometre (nm) is one billionth of a metre – around 80 000 times smaller than the width of a human hair.

Nanotechnology involves the study, control and manipulation of materials at the nanoscale, typically from sub-nanometre (the size of a single water molecule) up to 100nm. This is a truly multi-disciplinary area of research and development. Materials scientists, medical researchers, and mechanical and electronic engineers are now teaming up with biologists, physicists and chemists. Their work is unified by the need to share knowledge on tools and techniques, as well as exchanging expertise on the atomic and molecular interactions along this new scientific frontier. The resulting synergy could lead to advanced materials and devices that until now have been the stuff of science fiction.



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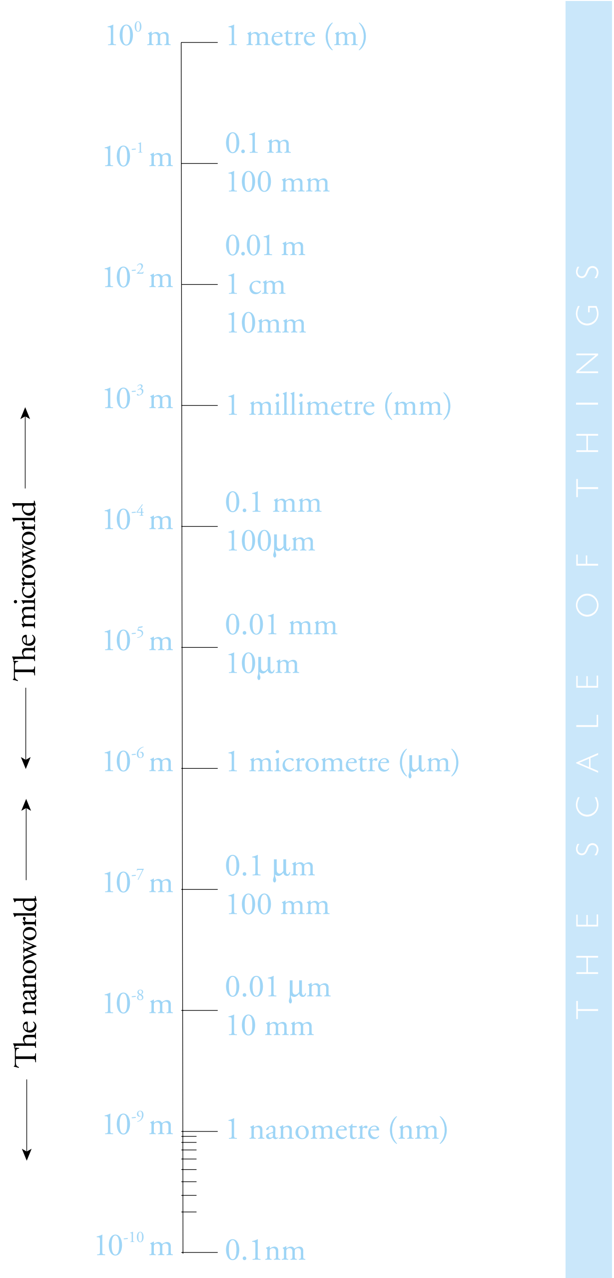


Encompassing both ultra-miniaturisation and molecular manufacturing techniques, the results of this work could have major impacts on virtually every aspect of human life. Although still in its infancy, nanotechnology is thus likely to underpin the next 'industrial revolution', proving as effective in the shaping the 21st century as biotechnology and electronics were in changing the face of the 20th century.

Route to health, wealth and sustainability

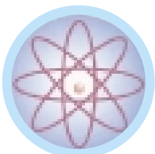
Today, nanotechnology is focusing on four major sectors: nanoelectronics, nanobiotechnology, and nanomaterials and nanomanufacturing.

Nanoelectronics will lead to molecular-sized semiconductor devices and memories with huge computational and storage capacities. As current lithographic production processes approach the very limits of their ability to shrink electronic systems and provide ever-increasing power, nanotechnology could form the basis of tomorrow's computers, telephones, cars, domestic appliances and the automation systems needed for all kinds of consumer and industrial equipment.

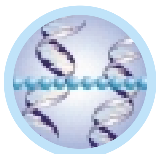
In **nanobiotechnology**, nanoscale engineering is being combined with biology to manipulate living systems directly or to build biologically inspired materials at the molecular level. The biochip arrays currently being produced are revolutionising the design and output of gene analysis. In future, nanobiotechnology will provide even more exciting innovations – from precisely targeted drugs and precision drug-delivery systems to increasingly biocompatible implants and prosthetics – all of which will have far-reaching impacts on medicine and human health.

The fabrication of **nanomaterials** will yield structures with new and improved properties for use in organic solar cells, anti-corrosion coatings, tougher and harder cutting tools, longer-lasting medical implants, and for applications in the transport industry. Nano-particle powders are already being used, for example, to produce scratch-resistant spectacles and highly effective sun protection products – while nano-sized structures have been produced as potential catalysts to reduce environmental pollution.

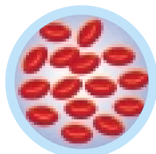
With the diminishing dimensions of the new devices, it will be necessary to replace present-day production technology with new **nanomanufacturing** techniques. The essential challenge is the self-assembly of molecules into preordained configurations that can produce the desired functionalities. Self-assembly encompasses a wide range of concepts and structural complexities: from the growth of crystals to the reproduction of complete biological entities. Significant advances are being made in this domain, although only relatively simple structures have so far been realised. Self-assembly will be a core scientific challenge in winning the battle for controllable nanotechnology.



Less than a nanometre
Individual atoms are up to a few angstroms, or up to a few tenths of a nanometre, in diameter.



Nanometre
Ten shoulder-to-shoulder hydrogen atoms (blue balls) span 1 nanometre. DNA molecules are about 2.5 nanometres wide.



Thousands of nanometres
Biological cells, like these red blood cells, have diameters in the range of thousands of nanometres.

Source: National Science Foundation, USA

ARRIVING AT A CROSSROADS IN SCIENCE

In two keynote speeches to the Toulouse workshop, Dr Horst Stormer, 1998 winner of the Nobel prize for physics, and Professor Peter Laggner, head of the Institute of Biophysics and X-ray Structure at the Austrian Academy of Sciences, gave an overview of the sheer breadth of nanotechnology. Dr Stormer concentrated on nanomanufacturing and the electronics sector, while Dr Laggner chose nanobiotechnology.

Dr Stormer uses a motor-racing analogy to describe nanotechnology as the point 'where the rubber meets the road'. He equates rubber with chemistry and the road with physics. Without effective contact between the various disciplines, he maintains, even the largest engine (of effort or investment) will not provide the driving force necessary to produce the desired results.

Thinking small

There are numerous reasons for thinking small, Stormer observes: first, because at the molecular scale it is becoming possible to do things more quickly. In electronics, reduced size makes circuits run faster. In mechanics, small masses can be moved by small forces. And if 'price per kg' could remain constant, manufacturing costs would be correspondingly lower. Most important of all is the complexity of construction that can be achieved by packing very small objects at higher densities. Building a computer requires millions of transistors – if we can condense more on to a single chip, we can produce more powerful machines.

Nanotechnology occupies itself with science and technology at the nanoscale, dealing with objects and structures ranging in size, for example, from 1 to 1 000 nanometres. The nanoscale lies between the 'atomic scale' on the one hand, and the microscale on the other.

Why was it not until the late 20th century that the scientific community began to regard science at the nanoscale as a rewarding field of study? The answer lies – simply – in the availability of tools.

The optical microscope, invented in the 16th century, has been the primary tool of the micro-world. It enabled man to look at single cells, minute fibres in leaves and microstructures in metals. Techniques based on light – optical lithography – have also enabled the manufacturing technology of the micro-world, in micro-electronics and micro-systems. But, despite continuous improvements, and for fundamental reasons, optics could never open the door to the nano-world.

However, back in the early 19th century, John Dalton, the founder of modern chemistry, already knew about atoms without being able to see them. Subsequently, Mendeleev accurately proposed the periodic table of the elements by deduction alone. At even smaller – sub-atomic – length scales, Rutherford postulated the internal structure of the atom. And throughout the 20th century, an entire arsenal of instrumentation was developed enabling study at the atomic and nuclear level. First synchrotrons, then a wide variety of high-energy particle accelerators, neutron sources, and so on.

So, science had acquired effective instrumentation plus considerable understanding of the microscale world and of the atomic and nuclear worlds, leaving the nanoscale virtually untouched. ⇨

Bottom-up, top-down

Meanwhile, for more than a century, chemists had been synthesising molecules from atoms. Their sophisticated methods created ever-larger molecules which today contain thousands of atoms in complex, reproducible three-dimensional arrangements. Hence, chemistry had begun to penetrate the nano-world from the 'bottom-up'.

The size of such 'designer molecules' extends right into the centre of the nanoscale. Further scaling-up to a macro level is nevertheless difficult to envisage, since the complexity of the synthesis increases rapidly with size, and random errors threaten the reproducibility from molecule to molecule. Consequently, Stormer says, there will never be a single-molecule aeroplane.

In contrast to chemistry, with its 'bottom-up' synthesis techniques, modern physics and materials science has started to approach the nano-world from the 'top-down'. The most prominent manifestation of this is the relentless shrinkage of the circuits on a silicon chip. In the past decade or so, the typical feature size has been reduced from the microscale to the nanoscale. This has been achieved by continuous improvement in photo-lithographic processes, and in particular through utilising light sources of shorter and shorter wavelength, moving from optical to ultra-violet.

New tools

In the 1930s, the invention of the electron microscope first opened up the world of nanotechnology to the human gaze. Yet the techniques were relatively cumbersome, involving the use of high-vacuum and conductive coating of specimens. As a result, the electron microscope did not find great favour with nano-research.

The critical breakthrough came with the invention of the scanning tunnelling microscope (STM) in 1983, by Binnig and Rohrer of IBM. This uses a probe to follow the contours of atoms on a surface, rather like a gramophone needle on a disc.

However, the STM is more than just a surface-viewing instrument. It can also be used to move atoms around on a substrate, and even to observe phenomena occurring at some distance below the surface of a specimen. Because it finally enabled researchers to actually see what they were working with, it had a major impact on nanotechnology – and has since developed into a huge industry of scanning probe manufacture.

The second major advance was in representation, with more powerful computers making it possible to show pictures of great clarity, plot images in high resolution, and rotate and manipulate structures at will.

This capability emerged at around the same time as the STM. Now, with the continuing increase in computer power not only can we see, but we can also calculate, in great detail. The first-ever STM picture, showing the map of a silicon surface, was actually modelled using cardboard and glue. Today, researchers routinely employ sophisticated 3D graphics. The latest virtual reality systems even include tactile feedback to give a realistic 'feel' when manipulating atoms on the screen.

Molecules as electronics

Nanoprobes have already done much for science; now they are equally essential to the technology involved in developing the next generation of electronics.

The validity of Moore's Law, which states that computer power will double every 18 months, is likely to end somewhere between 2010 and 2020, Stormer maintains. Electronics is a US$ 200 billion/year industry, therefore it is essential to consider where it will go and how the Moore's Law curve can be prolonged. Nanotechnology may hold the answer.

Transistors produced by 'conventional' lithography have been sized down to a fraction of a micron. The Semiconductor Industry Association forecasts that, by 2010, extending current technology will reduce their dimensions to 50 x 50nm.

Today's Pentium chip contains 40 million transistors. In ten years, its successor will include 1.5 billion. These could fit on to a 10cm2 surface, have a clock speed of 10GHz and consume 175 watts of power. And by that time, lithography will be approaching the physical limits of its capabilities.

Molecular-scale transistors are very much at an experimental stage. The vision is to make transistors from individual molecules rather than from silicon. These could then be 'sprinkled' on to a pre-prepared surface such as a silicon chip, using a process that enables them to find their place in a predefined structure.

Another possibility, Stormer suggests, is to utilise interconnecting carbon nano-tubes. Nano-tubes are about 1nm in diameter and can be many microns long. With powerful modern computers, we can model the merging of two nanotubes, for example by heating with an electron beam, to make an even larger tube. Therefore, nano-tubes crossing one another, with the intercepts forming an electronic device comprising just 10 atoms, can now be envisaged.

It is not yet certain whether this will work, although the use of molecules as wires and switches is unlikely to be the major stumbling block. More problematic will be the method of wiring for connectivity between the discrete components. In fact, this is already a critical aspect of today's electronic production.

Self-assembly essential

We can move nano-tubes around with the aid of probes, but this is not the way to achieve mass production of electronics, or of other devices and materials.

Today, assembly at the macroscale is inevitably a manual process. It is very unlikely, for example, that one could persuade a car gearbox to self-assemble simply by shaking the components together in a sack. Nature, by contrast, seems to have met the fabrication challenge on any scale, from the biomolecule to the giant redwood tree.

The essence of usable nanotechnology will lie in mastering the art of self-assembly – enticing complex molecules to form larger heterogeneous aggregates that perform intricate functions or constitute new material forms with unprecedented properties.

Chemists can already do much in assembling molecules with complex shapes, so we can hope that work along these lines will lead to the creation of objects able to find their place on particular substrates or within given infrastructures.

Some successes have been achieved in human-mediated self-assembly on a very small scale by making use of hydrophilic and hydrophobic reactions in a fluid medium. With nature's help, man is also able to initiate self-assembly at a slightly larger than atomic scale. Researchers have demonstrated the positioning of 20nm quantum dots on a substrate in a very regular periodic pattern that could have an application in lasers. A similar result has been obtained with metals such as iron and platinum, which may eventually be exploitable in magnetic memories.

Among other infant steps being taken in small-scale assembly are experiments showing that a DNA molecule a few nanometres long can be pulled electrostatically into place to form bridge between two electrodes in the form of nano-tubes grown on silicon towers. Here again, nature does most of the hard work.

The scientists' dream is that all of this will provide a landscape within which it will eventually be possible to move forward to the assembly of objects on the macroscale .

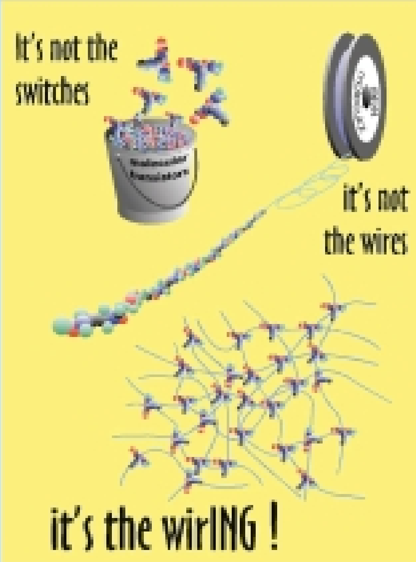
The age of lithography

The silicon chip is the most complex object ever created by man. Today's processors consist of some 40 million transistor switches, connected by almost a km of metal wire in an area of a few cm2 on top of a silicon crystal. Continuing their exponential growth, we expect chips to exceed 1 billion transistors during the next decade, each measuring a mere 50 nm in length.

As the dimensions of switches and the diameters of wires approach the atomic scale, the question being asked is whether silicon crystals and metal wires will continue to be the chosen materials for creating ever more powerful processors. Why not use molecules as switches and polymers as wires? They are smaller still, and chemistry knows how to make billions of identical molecules in no time. First, we do not know how to make a 'transistor-molecule' and we do not know how to make a useful molecular wire, although we are working on it. Will such components provide the passport to the promised land of molecular-sized electronics? Of course, we do not know, but whatever the progress, a bucketful of molecular transistors and a spool of molecular wire certainly will not do. To the building of an electronic circuit they are what a box of screws and a pile of gears are to the building of a watch. Assembly of the components is a challenging task, even for a watch containing a few hundred parts – but it is hopeless when trying to wire billions of molecular transistors with kilometres of molecular wire.

Today's silicon technology achieves this feat by lithography, projecting highly reduced images of complex circuits sequentially on to the chip. This process determines exactly the location of all transistors and uniquely establishes their wiring – millions of transistors, all at once.

A switch is 'boring' – 'on/off' is all it can be. A wire is dull – 'carry-current/not-carry-current' is all it can do. The complexity of a circuit lies not in the switches, not in the wires, but in the wiring. The complexity of today's chips does not result from silicon nor from its copper wires, it is the product of lithography. "We live in the silicon age!" is a misnomer – instead, "We live in the age of lithography!". As



powerful as this technology has proven to be, and as long a life as it may breathe into future generations of Pentium chips, it is unlikely to be adequate for the multi-billion component circuits of our dreams.

The greatest challenge for the electronics industry of the future is not to find a replacement for the silicon transistor nor for the metal wire, but to find a replacement for lithography, the way we create complex circuits from dull components.

'Self-assembly' is the operative term, with an envious peek towards biology, which assembles all these wonderfully complex things from boring atoms. At this stage we have no grand idea how to coerce nature into building an electronic circuit for us. It will take decades of fundamental research at the interface between chemistry, physics, material science and biology to find a way.

Professor Laggner picks up the same theme in the second keynote presentation entitled 'Tools and machinery from nature's game of life'.

With proteins, nucleic acids, sugars and lipids, he notes, over millions of years nature has developed the tools for life on the nanoscale. Copying and integrating these products of evolution into man-made devices, such as molecular motors and nanomachines, photonic devices, chemical reactors, pumps and filters, neural prosthetics or single-molecule sensors, is one of the greatest interdisciplinary challenges of today.

In nanobiotechnology, especially, there are many lessons to be drawn from nature. The benefits of taming this technology should lie in improved medical diagnostics and therapy. Interesting prospects also exist in a whole host of other applications, industrial as well as medical. Desaturase enzyme, for instance, is being engineered to allow crop plants to produce novel oils as renewable foodstuffs, chemicals and plastics.

One of the goals for bio-scientists is to develop a more rational way of designing drugs, based on deciphering the human genome – where all the information relating to functionality is contained in a 'library' that has to be translated into protein structures.

This task can be approached in two different ways. The first, **structural genomics**, involves reading all the genes, translating them into proteins and producing mutants with specific functions.

This is an encyclopaedic method that in practice involves a number of sequential steps:

- take a gene
- try to make a protein
- crystallise it to allow structural analysis
- visualise the 3D structure on a computer
- then try to modify structure and function.

A second, complementary approach is **biomimetics**, which takes the functional elements of a protein and tries to graft them on to a synthetic molecule to produce a purpose-designed molecule.

The logic of nature is chronological, involving series of 'decisions' taken over millions of years and controlled by the boundary conditions of environment. Consequently, we often find that different molecular structures have emerged to serve the same purpose. For example, haemoglobin from a horse and from a lamprey show few similarities in their amino acid sequences, yet they both act as the medium for transporting oxygen around the body.

Evolution thus works differently from an engineer, who is limited by the need to reach a target while expending the minimum of time and money. Given these constraints, Laggner opines, the hybrid approach of biomimetics is likely to prove cheaper and offer better prospects of a successful outcome to human endeavours.

Results in view

Some examples where crystallographic structural analysis of proteins is already leading to important medical developments include:

- development of a virus against the Lyme Disease bacterium, which is now undergoing clinical trials;
- improved understanding of the HIV virus; and
- drug-blocking of the human adenovirus protinase as a means of combating respiratory, eye and intestinal diseases.

Accurately targeted drug delivery is another area in which nanotechnology could prove of great value. To avoid taking unnecessarily large doses the need is for medication that reaches only the diseased cells or tissues, is unnoticed by the body's immune system, and acts where and when it is needed. This is very desirable, but not easy to attain.

Extensive work has been carried out on low-density lipoprotein (LPL), the so-called 'bad cholesterol'. In the human body, this follows a complex metabolic pathway whereby it is redistributed between peripheral tissues such as coronary arteries, and eventually returned to the liver.

LPL is also a transport vehicle for exogenous water-insoluble material. And, as most drugs are water-insoluble organic compounds, it could be possible to encapsulate them in a lipophilic matrix that is transportable in blood.

Although it is not yet entirely clear how LDL might be used as a means of targeting medication at diseased tissue, it is known that cancer cells have a higher local concentration of specific cell surface receptors for LDL than non-malignant cells. It is also possible to depress the LDL receptivity of other cells, so targeted delivery may become a real prospect.

With improved separation techniques it could be feasible to remove LDL from a patient's own blood, introduce a drug and reinject it, thus leaving it unnoticed by the immune system.

An ongoing programme to target LDL-related particles to specific cell types involves taking out parts of the specific protein code, attaching them to other nanoparticles and testing their effects. Particle characterisation by physical chemistry, biochemistry and structure is enormously important. It requires many different techniques – structural, thermodynamic and dynamic – to verify that the reconstituted drug-dosed lipoproteins are externally still identical to the originals.

Before such products can achieve marketability, the process needs upscaling, validation and clinical trials, which calls for co-operation from many different disciplines. Today, such an effort is only possible in a few laboratories.

Mammoth task

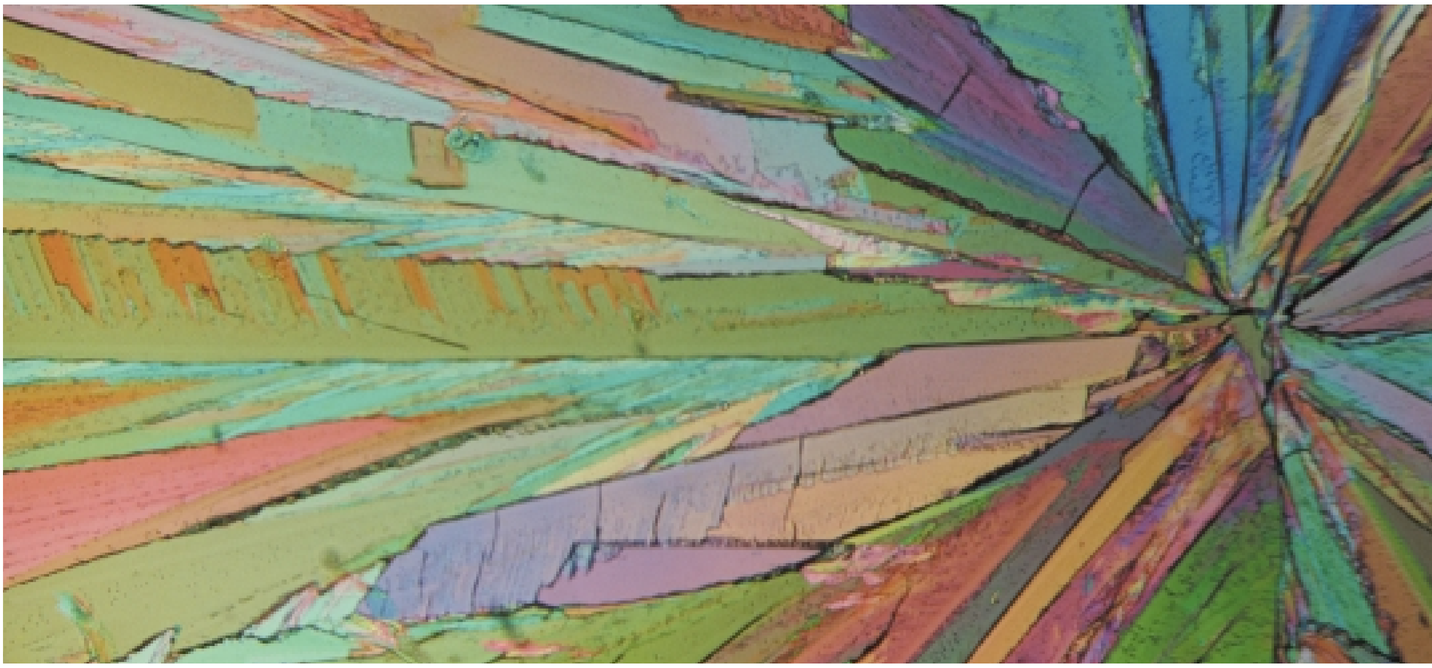
A limiting factor for all disciplines of nanotechnology is that the required infrastructure is not well developed. To benefit fully from the discoveries now being made, Laggner warns that considerable investment will be required in the development of new kinds of instrumentation and the establishment of more widely accessible facilities. There could also be advantages for researchers in adopting new modes of working.

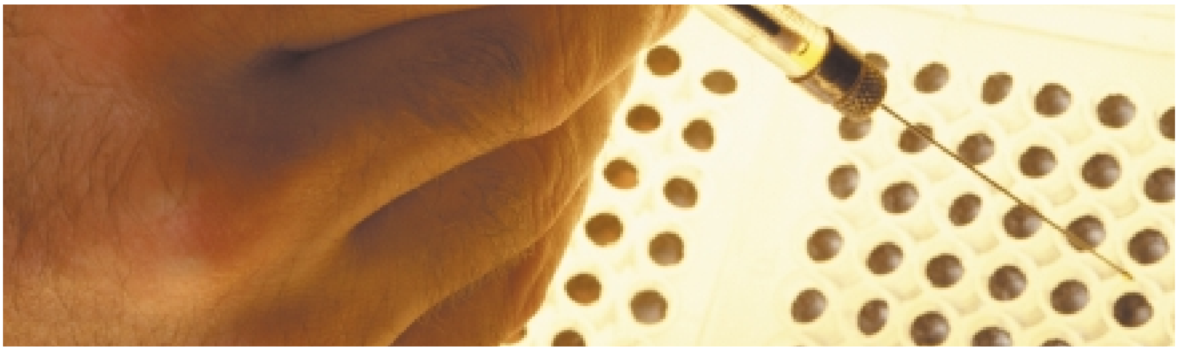
It is difficult to say precisely what infrastructure will be needed, he acknowledges. Nanotechnology is an assembly of many different scientific parts. Success may come from an unexpected source – today's non-runner could be a mega-product of the future.

Solving a protein structure currently requires a relatively modest level of effort. A skilled technician can isolate and grow the crystal. With access to a synchrotron, the crystallographic data can then be acquired and fed into a computer. However, some proteins are difficult or impossible to crystallise, while others crystallise but do not diffract.

Around 200 000 structures will need to be resolved in order to unravel the protein structures encoded in the whole human genome. Solving the problem within the next ten years will entail resolving a minimum of 10 000 structures per year, which is at least one order of magnitude beyond present capability. An enormous upscaling, particularly with respect to synchrotron radiation facilities, will thus be required to reduce this to a reasonable timescale.

At present, synchrotron sources are available only in a small number of locations, often inaccessible to SMEs and to the university and public laboratories. Most scientists do not even know what synchrotron sources can do for them. It could therefore be advantageous to create a series of small synchrotrons dispersed in a network across the various countries.





Another key obstacle to be overcome is that, while the currently available tools of science are very good for examining static objects, it remains very difficult to explore structural dynamics and observe self-assembly in action. The techniques of 'nano-vision' therefore have to be further developed. UV and X-ray light from synchrotron and free-electron laser sources, among others, are assets of the highest strategic importance in this context.

It is also time, Laggner says, to move away from the linear model of innovation, which begins with basic research and advances through applied research, product development, and production, to marketing and incremental R&D. A new and more appropriate strategy is the segmented view which involves a parallelism of horizontal networking in time and space by the essential players – i.e. researchers from different disciplines, engineers, entrepreneurs, etc. This is an unusual concept that demands a degree of structural rearrangement, but it is an ideal scheme to apply to the multi-disciplinary field of nanotechnology.

Following the principle of natural self-organisation, a so-called hypercycle allows integrated and coherent evolution of a group of functional entities. This is a good way to arrange a team or institute in which all the elements are grouped together. Here, the core is the methodologically competent centre. This is surrounded by a second circle, within which resides competence in concepts and specific disciplines such as biology and chemistry. A third circle is the 'where the wind directs' element, dealing with project-related application problems. Although not the most natural way to organise work, Laggner concludes, this creates an excellent environment for triggering ideas and progress.

In brief, the actions he recommends are:

- build the technical infrastructure
- stimulate interdisciplinary education to rekindle the world's fascination with science, as existed in the space age of one or two generations ago
- share knowledge between individual disciplines, and beyond disciplines to educators and entrepreneurs.

FUNDING RESEARCH IN THE USA AND EU

The Toulouse workshop took place against the backdrop of the launch of the 'European Area of Research and Innovation' (ERA) and a USA decision to commit substantially increased resources to nanotechnology research in 2001. The time is ripe for EU/USA cooperation. But to qualify for funding, projects will need to meet the criteria on both sides of the Atlantic.

The ability to rearrange matter on a nanoscale is potentially a very economical way to obtain functionality. In ten to 15 years' time this could lead to efficient methods of production on a macroscale – ultimately offering the highest-ever added value in manufacturing. Nanotechnology therefore figures prominently among the research priorities of governments, institutions and private industry.

Many initiatives are already under way at international, national, regional and in-company levels. In the present pre-competitive phase, there are nevertheless extensive opportunities for wider co-operation. The EC/NSF Implementing Arrangement, while not confined exclusively to nanotechnology, makes it possible to combine European and American resources in meeting the challenges of this broad and multi-disciplinary field.
Decisions on the joint funding of projects under the Arrangement are made by consensus between the two responsible agencies: the National Science Foundation (NSF) in the USA and the European Commission's Research Directorate-General. The strategies adopted by these two bodies with respect to nanotechnology are shaped by their differing historical backgrounds and by the policies of their respective public administrations.

Dr M. C. Roco, Programme Director NSF and Chair Interagency Working Group NNI, explains the USA position – while Mr E. Andreta, Director of the European Commission's Competitive and Sustainable Growth I programme, outlines the EU approach.

Nanotechnology funding by the NSF and other USA agencies
Dr. M. C. Roco

Created in 1950, the NSF is an independent federal agency with a wide-ranging remit to promote and advance science and engineering in the USA. It evolved from recognition of the important part played by science and technology during World War II, and is unique in being 'mission-independent' – i.e. not responsible for a specific sector such as defence or health. The Foundation manages around 25% of federal support to academic institutions for basic research. It also supports educational programmes, co-operative research between universities and industry, and USA participation in international scientific efforts.

Increasing investment

NSF backing of nanotechnology began with smaller scale seed funding, initially for a programme on nanoparticles in 1991 and the National Nanofabrication User Network (NNUN) in 1994. After 1996, NSF and other agencies, co-ordinated by an inter-agency group, developed a vision on the future of nanotechnology, including input from academe, industry and an international survey.

Subsequently, the results have been published in a series of reports: 'Nanostructure Science and Technology', 'Nanotechnology Research Directions', 'National Nanotechnology Initiative', 'Nanotechnology – Shaping the World Atom by Atom', and 'Societal Implications of Nanoscience and Nanotechnology' (see http://nano.gov/ and http://www.nsf.gov/nano/). NNUN user facilities and a nano-database on the website are open to users from the USA and abroad.

A NSF-wide programme on 'Functional Nanostructures' was established in 1998, followed by programmes on 'Nanobiosystems at Nanoscale' and 'Nanoscale Modelling and Simulation'. Where possible, NSF encourages interdisciplinary 'horizontal' co-operation, as well as 'vertical' integration from basic research supported by NSF to applied research supported by a partner. Participants are also encouraged to find industrial and international partners; respectively 25% and 37% of them succeeded in doing so in the 1998 'Functional Nanostructures' call for project funding. Focused competitions on nanotechnology were announced in 1999 and 2000 for the Small Technology Transfer Research Small Business and Innovative Research programmes (STTR and SBIR), addressed to small businesses and their collaboration with universities.

USA federal investment in nanotechnology increased from US$ 116 million in fiscal year 1997 to US$ 270 million in fiscal year 2000. The programmes embrace topics from chemistry, materials, molecular biology and engineering, to revolutionary computing, mathematics, geosciences and social sciences. About 650 projects, with over 2 700 faculty and students, and more than ten centres, were supported in fiscal year 2000.

Major new initiative

In September 1998, the NSTC set up the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN). In August 2000, it was extended in the NSTC's subcommittee on Nanoscale Science, Engineering and Technology (NSET). The goal of this group was to develop a vision for nanotechnology, identify the challenges, and offer budget guidance to the USA government. Working under presidential advisor Dr Neal Lane, it sought to provide a framework for establishing R&D priorities and to consider how government agencies should intervene. It then went on to develop a plan and propose an implementation approach, which it presented as the National Nanotechnology Initiative (NNI), first outlined in March 1999 and published in full in June 2000.

The NNI reflects the scientific drive toward nanoscale in most disciplines, and the immense societal promise of

> "Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight – shrinking all the information housed in the Library of Congress into a device the size of a sugar cube – detecting cancer as tumours when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government."
>
> President William J Clinton
>
> 21 January 2000
>
> California Institute of Technology

Nanotechnology on a global scale
Comparison among industrialised countries

Estimated government sponsored R&D in US$ millions/year

	1997	2000	2001
W.EUROPE	126	184	
JAPAN	120	245	
USA	116	270	423
Total	362	624	

Source: M. Roco, NSF

nanotechnology in the coming decades. This caught the imagination not only of scientists and industry experts, but also of the Administration led by President Clinton. The Initiative thus became a top White House priority.

Acceptance of the proposal was announced in January 2000 – and US Congress enacted a budget of US$ 422 million for fiscal year 2001 in November of that year.

NSF will administer the largest individual portion of this budget, with an investment of US$ 150 million in fiscal 2001. It is joined in the first year of NNI by five other departments and agencies: Department of Commerce, Department of Defence, Department of Energy, National Institutes of Health, and National Administration for Space and Aeronautics (see slide for budget share).

Under the Initiative, NSF launched a Nanoscale Science and Engineering solicitation in October 2000 (the start of fiscal 2001 in the USA). This builds on previous nanotechnology programmes, with the goal of supporting research under six main themes:

- biosystems at nanoscale levels
- nanoscale structures, novel phenomena, quantum control
- device and system architecture; design tools and nanosystem-specific software
- nanoscale processes in the environment
- multi-scale, multi-phenomena modelling and simulation
- studies on societal implications of NSE, education and training

Its strategy is balanced across five main funding mechanisms (see table below):

Budget levels approved by Congress

	Total funding (US$ million)	NSF funding (US$ million)
Fundamental research – providing sustained support to individual investigators and small groups	US$ 145 m	US$ 84 m
Grand challenges – for research on major long-term objectives	US$ 119 m	US$ 8 m
Centres and networks of excellence – for interdisciplinary research, networking, industry partnerships	US$ 66 m	US$ 26 m
Research infrastructure – metrology, instrumentation, modelling/simulation, user facilities	US$ 68 m	US$ 17 m
Social implications, workforce education and training	US$ 24 m	US$ 15 m

Source: M. Roco, NSF

Although the overall Initiative involves diverse agencies with different areas of interest, the Foundation aims to foster a coherent approach using common methods in all fields. The NSF solicitation addresses three modes of support to target new areas and encourage projects that would have a poor chance of success in the existing programmes:

- interdisciplinary research and education teams
- exploratory research
- nanoscale science and engineering centres

Eligible proposals are evaluated in accordance with the general NSF merit review criteria – i.e. what is the intellectual merit of the proposed activity, and what are its broader impacts. In addition, the following criteria are applied:

- potential for significant contributions to the advancement of nanoscale science and engineering in one or more of the six research themes;
- strength of the collaborations planned and the degree of interdisciplinarity;
- value to education; and
- extent and effectiveness of industrial collaborations, collaborations with national laboratories – and with comparable research centres abroad, when applicable.

Grand challenges

Nanoscale science and engineering are now as interesting to the chemistry and geosciences sector as to electronics. Although electronics currently has the highest visibility, more applications are emerging in the chemical area, advanced materials, and drug delivery, etc. This situation will probably continue in the foreseeable future. The common need is for basic understanding and imagination, which demands fundamental research. Consequently, the USA goal is to achieve long-term developments that will have a major impact on manufacturing, the environment and health.

This intent is reflected in the nature of the nine NNI areas of 'grand challenges':

- Nanostructured materials 'by design' – stronger, lighter, harder, self-repairing, and safer
- Nanoelectronics, optoelectronics and magnetics
- Advanced healthcare, therapeutics and diagnostics
- Nanoscale processes for environmental improvement
- Efficient energy conversion and storage
- Microcraft space exploration and industrialisation
- Bio-nanosensors for communicable disease and biological threat detection
- Application to economical and safe transportation
- National security

A priority will be to develop user facilities as centres of excellence to facilitate partnerships among universities, as well as with industry, national laboratories and international collaborators. Co-operation with European partners will actively be encouraged. Besides twinning individual research groups and centre-to-centre collaborations, other opportunities will include exchange visits by younger researchers, topical workshops followed by joint research efforts the addressing grand challenges, and networking at the research/education level.

Training will be equally important. As in Europe, the USA faces a shortage of trained people and needs to reverse the decline of interest in physical sciences and engineering. The aim is not only to encourage education at graduate level, but also to introduce nanoscale concepts in high schools and in first-year university studies. There will be a drive to increase teacher participation, address societal implications from the beginning of the NNI initiative, and a greater effort to inform the public.

Nanotechnology in the EU Framework Programme

Mr. E. Andreta, Director, Directorate Competitive and Sustainable Growth I

To understand the nature of the Research and Technological Development (RTD) Programmes of the European Union, it is useful to understand their historical perspective. The European Union was constructed in the aftermath of World War 2. From the economical and political turmoil of the post-war years, there grew a widespread conviction that only European integration could put an end to a long tradition of warfare between independent nation-states. At the same time, there was an urgent need to build a strong Western Alliance.

The European Coal and Steel Treaty (ECSC), signed in 1951, was an important first step. It aimed to establish a common market for coal and steel. In 1957, the Euratom Treaty was concluded, in order to facilitate co-operation on nuclear technology for peaceful purposes. Both the ECSC and the Euratom Treaty contained provisions for research in their respective sectors.

The 1957, the European Economic Community (EEC) Treaty was different in that it was not sectoral. It sought to establish a customs union and a common market, and it provided for common policy in matters of agriculture, transport, competition and social policy. Research was not part of the EEC treaty.

As time progressed, it became clear that RTD on a European scale needed to be broadened beyond steel and nuclear energy. There were Community policies that required scientific support, and new problems of international nature arose: in energy, in transport, in environment, in materials resources, in the electronics revolution, and so forth. Action at Community level was appropriate, so several sectoral programmes were created.

These sectoral programmes were unified in a coherent approach by putting them into the context of 'Framework Programmes' of four years' duration. In 1986, as part of the Single European Act, the mechanism of the Framework Programmes was included by amendment into the EEC Treaty. Framework Programmes are designed and proposed by the European Commission, and approved in a procedure between the Council of Ministers, The European Parliament and the Commission. The Commission is then responsible for their implementation.

The Framework Programmes represent approximately 4 to 5% of the total of European RTD expenditure. They are used to fund RTD in a large variety of areas (from aeronautics to materials sciences). The major part of the funding is for shared cost co-operative projects involving both academic and industrial partners from several European countries.

From this historical background, one can understand the presence of persistent themes that characterise RTD in the EU: scientific excellence, support to policy, an orientation towards problem-solving at the European level, and support to the strengthening of European integration.

Fifth Framework Programme

At present, the Fifth Framework Programme (FP5) is in operation. The total value of FP5 is € 14.96 billion for the period 1998-2002. FP5 is structured around **four Thematic Programmes**, which represent the major RTD areas:

Quality of Life	QoL	M€ 2 413
Information Society Technologies	IST	M€ 3 600
Competitive and Sustainable Growth	GROWTH	M€ 2 705
Energy and Environment	EESD	M€ 3 104

These four Thematic Programmes are supported through **three Horizontal Programmes**, providing elements common to all RTD areas, such as international co-operation, support for research in small and medium-sized enterprises (SMEs), training and mobility of researchers:

International Role of Community Research	INCO	M€ 475
Innovation and SMEs		M€ 363
Improving Human Potential	IMPROVING	M€ 1 280

Each of these Thematic Programmes is sub-divided into a number of **Key Actions** (typically four to six per Thematic Programme) and **Generic Activities** (typically two to three per Thematic Programme).

The Key Actions provide RTD funding aimed at clearly defined social and economic targets. There are 23 Key Actions in total, with titles representing their objectives, such as 'The Cell Factory', 'Multimedia Content and Tools', 'New Perspectives in Aeronautics', 'Global Change, Climate and Bio-diversity', etc. Key actions implement an integrating vision of the RTD, uniting long- and short-term research, demonstration, training and other elements, but always aimed at focused objectives.

The **Generic Activities** are of a wider scope. They address the necessity for an underlying body of generic scientific and technological knowledge. Research funded through the Generic Actions is usually of medium- to long-term nature. Research projects are mostly application-driven – but they bring together long-term scientific competencies, typically through universities, and strength in applied research, through industrial involvement. The research is often multi-sectoral, or is aimed at emerging sectors.

The primary contractual instrument is the shared-cost RTD contract. Under this modality, research takes the form of projects carried out by consortia of universities, research institutes and industries, from at least two European countries. The funding covers up to 50% of the total cost of the research. Projects are selected from submitted proposals with the aid of independent external experts.

Portfolio build-up

Over the years, and already during earlier Framework Programmes, the European Commission has built up a substantial portfolio of projects involving nanotechnology to a greater or lesser degree. In particular, under the Fourth Framework Programme (1994-1998), it is estimated that a total of about 70 projects were supported. The Brite-EUram programme, which was aimed at industrial modernisation and materials technologies, funded approximately 32 projects with nanotechnology content, in such areas as nano-structured materials for mechanical purposes (nano-powders, ceramics), in advanced functional materials (electronic, optical and magnetic materials), and in materials for chemical technology (catalysis, filtration, etc.). The ESPRIT programme for information technologies supported 21 projects in advanced electronics and opto-electronics including, in particular, the large network 'Phantoms' on mesoscopic physics. The SMT programme supported eight projects in the area of instrumentation and metrology on the nanoscale, while the BioTech and BioMed programmes supported research into nanobiotechnology (drug encapsulation, bio-assays, etc.).

Overall, the funding provided for 'nanotechnology' during FP4 may be estimated at about M€ 35 annually, given that a relatively liberal interpretation of the term is applied. Overall coverage of the fields of nanotechnology and nanobiotechnology was good. However, it was apparent that there were a relatively small number of activities and projects with a truly multi-disciplinary character. Most of the work was well confined within established scientific and technological domains.

Sizeable role for nanotechnology

As nanotechnology is relevant to, and draws upon, all the major scientific and technological domains it is, by design, a distributed entity in FP5. The programme elements that include substantial nanotechnology content are summarised below:

1.The Key Action 'Cell Factory' of the Thematic Programme QoL aims at the integration of innovative research and technologies in life sciences. Exploitation of the research will be in the fields of health, environment, agri-food and high added-value chemicals. The nanotechnology (or nanobiotechnology) portfolio of this activity contains projects on electronic 'noses' for cell culture control, drug design and bioprocess controls, biosensor arrays for environmental detection, as well as nano-composites and nano-particulate coatings for biological compatibility of medical instruments and devices.

2. The IST programme activity 'Nanotechnology Information Devices' is a sub-programme of the IST 'Future Emerging Technologies' Generic Activity. This aims at the development of future information processing or data-storage systems operating on the atomic or molecular scale. The activity covers general nano-electronics, and includes work on single electron devices, quantum devices, nano-mechanical computation and biological approaches, magnetic tunnel junctions, nano-machines and molecular computation. In addition to the devices, particular attention is also paid to those architectures suitable for nano-electronics.

3. The Generic Activity 'Materials' of the Growth programme embraces medium- and long-term RTD on materials and materials processing in a general sense, and covers materials for a wide range of industrial sectors. The scope extends to all advanced functional materials, such as novel (opto-)electronics, magnetics, sensors, and bio-medical. It also includes general development of advanced chemicals and materials for mechanical purposes – such as metallic alloys, polymers and compounds. The portfolio in nanotechnology comprises RTD on materials for light-emitting diodes and lasers, giant magneto resistance, nano-structured carbon, optical and electronic polymers, nano-powders for inks or for compounding, nano-structured catalysts, etc.

FP5 provides wide coverage of the entire field of nanotechnology, with total annual funding of around M€40. The number of projects involving clearly multi-disciplinary research is growing steadily. These represent a spectrum of RTD timescales, ranging from long-term laboratory development (such as self-assembly in nano-electronics) to those developments with a commercial potential in the medium term (such as nano-compound polymeric materials). The involvement of industrial partners in projects indicates in general a favourable potential for technology transfer.

Strong support

In conclusion, the EU Framework Programme contains a solid portfolio of activities in nanotechnology. There is a wide spectrum of RTD timescales, ranging from 'long-term but application oriented' to medium term, where medium term would indicate a commercial potential within some five years. All of the programmes are application-oriented to a high degree, and technology transfer potential is promoted, not least through the high industrial participation in the programme.

Looking towards the next Framework Programme, and in the context of the European Research Area, the objective is to create a favourable climate for nanotechnology research, particularly for research with multi-disciplinary aspects. Strong cross-programme co-ordination, co-ordination with Member States' activities and international collaboration will be essential elements.

Bilateral approvals ensure transatlantic accord

Materials sciences research and development may benefit greatly from co-operation in order to stimulate ideas and creation of knowledge, and to achieve the critical mass for ambitious projects of common interest for added value and mutual benefit.

Within this approach, EU-USA, multi-partner, multinational project proposals in materials sciences are possible. This applies both to collaborative research project proposals, and to networks, including electronic networks, and clusters of research proposals.

All proposals must comply with the relevant EC and NSF eligibility criteria and rules for participation, and will be evaluated according to the respective criteria.

If selected, participants from the European Union and from Associated States will receive funding from the EU budget in accordance with the normal EC rules. Proposals submitted for EC financial support must have a single, jointly developed work plan involving all the partners and which clearly sets out the division of labour, the expected results, synergies and added value, and budgets for each side. Consortia of co-operating partners are expected to be balanced in terms of level of effort and expertise, and to demonstrate the mutual benefits obtainable from complementary international research. In the context of a joint EU-USA proposal, a multi-disciplinary approach combining the strengths of researchers and technologists in the EU and the USA will be favoured. In selecting projects of this type, priority will be given to research of a longer-term nature with breakthrough potential.

Participants from the USA may apply for NSF financial support. If such support is sought, a proposal must also be sent to NSF which will then make a funding decision according to its own applicable terms and conditions. The proposal to NSF must be accompanied by information identifying the counterpart EU proposal or funded project, including a technical abstract.

A separate, but co-ordinated evaluation is then implemented. The 'yes/no' and 'no/yes' cases will receive the greatest attention. Co-ordination in the projects follow-up may also be introduced to help understand points of strength and of weakness in the co-operation. The signature of a consortium agreement among all the partners is strongly recommended, particularly in order to prevent any possible problems bound to IPR issues.

1. NANOMATERIALS FOR THE INFORMATION SOCIETY

The attraction of nano-magnetism

Prof. A. Schuhl, Laboratoire de Physique des Matériaux,
Université H. Poincaré, France

Over the past decade, in the field of magnetic storage, demands for constant increases in information density have resulted in a move from the microscale to the nanoscale. This evolution has derived from important fundamental discoveries in physics, namely nano-magnetism and transport phenomena.

Spin-dependent conduction depends on fact that magnetic media include two kinds of carrier: 'up-spin' and 'down-spin' electrons. The discovery of giant magneto-resistance (GMR) 15 years ago was the first step into this new world. Since then, numerous devices based on this phenomenon have appeared, bringing about ever better performance or new functionalities. They are now used, for example, as read heads for hard disks, as magnetic sensors and as memories.

Today, study of the magnetic recording on a hard disk reveals that none of the critical dimensions exceeds one micron: bit length, track width, media thickness and read-head size are all measured in nanometres.

Spintronic effects

In multilayers consisting of magnetic/non-magnetic layers, the scattering at interfaces is dramatically different for the up-spin and down-spin electrons. Thus, the resistance of the system decreases by a factor of two when the magnetisations of the magnetic layers are fully parallel. This is the magneto resistive effect that has been exploited in the hard disk industry, where high density GMR heads appeared six years ago.

A second spintronic effect, discovered five or six years ago, is spin-dependent tunnelling. A magnetic tunnel junction is made by a thin (1-2 nm) insulating layer between two magnetic materials. Here, the resistance of the device is strongly dependent on the relative orientation of magnetisation of the two magnetic layers. Changes of up to 40% have been observed.

The possibility of putting the device into two different states (parallel magnetisation and anti-parallel magnetisation) led to the realisation of magnetic random access memories (MRAM) that are completely non-volatile and can be reduced to the nanoscale. Such devices, some as small as 400nm, have already been developed for actual applications.

Decade of potential

However the achievable physical size limit for MRAM is far below 100nm. The main problem remaining is that the current contrast is only 40%, and scientists are now looking at various solutions to achieve 100% contrast. One proposal is the spin-tunnelling transistor, an all-metallic device using double tunnel junctions, which enables the spin current to be controlled using the voltage and magnetic configuration.

Nano-magnetism has witnessed intense activity during the 15 years since the discovery of GMR. Based on original fundamental physics, the new devices that have emerged have enabled major progress to be made in the world of information storage, a story which we think will continue for at least the next decade.

Chemical and electrical sensors

| *Prof. Moungi Bawendi, MIT, Chemistry Dept., USA*

Information may be created either within our brains or externally. In order to make use of it, we process it; transmit it either to one another, or to computers or other machines; store it temporarily or permanently; and finally we need to display it. These are distinct areas, and nanomaterials have a role to play in each.

Creation

We may create information from our own knowledge using our brain cells – which are, in fact, nanomaterials. We can also create information from our environment. Here, nanomaterials could have a tremendous impact in some areas, because today's sensors tend to be very bulky.

A large amount of research is being undertaken into chemical and electrical sensors for monitoring materials, the environment, electrical fields, and voltages – and in particular for medical diagnostics. A number of centres in the USA – the University of Rochester, for example – are trying to make diagnostic aids from nanomaterials. Some chemical sensors can already be extremely sensitive, going almost to the single molecule detection level.

Processing

The demands for sorting and mining information will grow explosively as we increase the sensor environment and enlarge the sum of knowledge from our brains. This will trigger a corresponding requirement for greater storage density and speed of mining. We shall therefore need to build parallelism into the way in which we process information.

Many of the nanomaterials so far being considered for information processing still use electrical processes that depend on moving charges around – i.e. they are based on what is already being used. However, looking to nanotechnology as a means of developing a new paradigm for computing, we see that advances in photonic materials take optics down to the nanometre scale, below the wavelength of light. Interest in optical processes died in the 1980s, but this will once again become an area to explore. Spintronics may also be better than charge-based processes in nanomaterials for processing information.

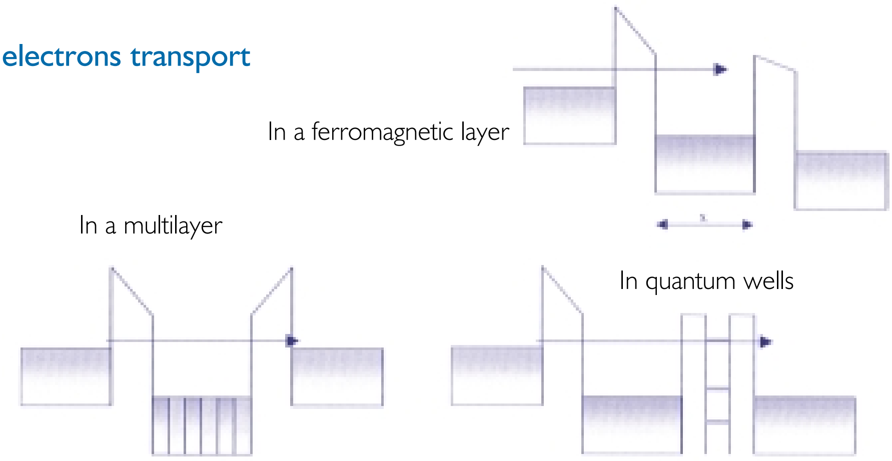
We should consider biological materials which are valuable for highly parallel computing and high-speed processing. Low-performance devices are also important. With a proliferation of sensors, it would be useful to have low-cost, flexible, low-power go-anywhere computers to work with them.

There is much to be done on organic electronics – not necessarily single molecule transistors, but devices made from organic thin films to satisfy the requirements for distributed computing with cheap sensors.

Transmission

The reduced distances in the nano-world should increase the speed of data transmission. This is usually based on the use of electrical or optical signals. Therefore, we need wires to carry charges or spin, or cables to carry light. Industry is actively examining photonic ways of carrying light, and it should be possible to integrate new laser structures and micro-cavity lasers into the nano-computers of the future.

Hot electrons transport



Storage

Devices such as memories are likely to be in first place where nanomaterials are adopted. These could be optical, electrical or magnetic. Some components are already integrating nanomaterials: quantum wells, for example, are used as lasers – and a billion-dollar industry is now based on them. Smaller storage units made possible by nanotechnology will bring higher density and faster read/write speeds. Cheap and flexible, low-cost organic materials could hold the key to the memory devices of the future.

Display

Information can be displayed on screens, or projected into space using holograms. Here, nanomaterials should afford much higher resolution. This may not necessarily be for standard displays, but there is already talk of direct projection into the eye. And that rally will demand high resolution.

Nanomaterials could also extend the range of ways in which we display information. Researchers are currently studying molecular-based methods for very large displays, such as LEDs (Light Emitting Diodes) and particle-based LEDs, although these are very difficult to achieve at present.

The challenge

The challenge is to incorporate nanomaterials in all of these areas. To do that, we need to create knowledge for the sake of knowledge, not simply for solving particular societal problems. Many of the components now being used or considered for solving societal problems were created because people were interested in looking at new materials. Magneto-resonance imaging is just one example.

At this stage, a great deal of science remains to be done. We do not yet know how self-assembly can be made to work. Typically, we return to the architectures we know today, but these may not be the appropriate choices. New ones will have to be discovered or imagined. We need to combine quantum, spin and nanomechanics – which, at present, are viewed as separate entities. The nano-macro bridge is something we must all focus on.

2. NANOTECHNOLOGY AND INTERFACES TO BIOLOGY

Nanoscale devices

Prof. G. Robillard, BioMade, The Netherlands

In introducing a subject as young as nanobiotechnology, we need to answer two questions: "Why do we do it?" and "What do we work with?" We do it for two reasons: first, as a learning process and, second, as a way to develop nanoscale devices or platforms that are useful – now.

The learning process deals with the fundamental issue of constructing nanoscale devices in the vast numbers that will be required if they are to become a significant component of future technologies. A conservative starting point would be the existing nanoscale devices which only occur in natural systems. Decipher the rules that nature employs in their construction and they will form the foundation for fabricating non-natural nanoscale devices. At the same time, while learning these rules, we can work towards developing a broad spectrum of diagnostic and therapeutic applications using the components and systems that nature already provides.

The systems the nanobiotechnologist works with include living cells, biological machines, motors and biological structural components – and the interaction of all of these with solid surfaces of various chemical compositions.

Living cells are too large and too complex to qualify as nanoscale devices, but they will be the targets of diagnostic and therapeutic nanoscale devices and will need to interface and communicate with them. Understanding the constraints on the interaction of artificial devices with biological systems will be critical for their function.

Biological motors, such as the flagella rotor, kinesin, actin/myosin and the H^+-driven ATPase are of a complexity which will not be mimicked in the near future by the nano-engineer. However, unravelling the mechanisms by which they transduce energy, and employing such mechanisms in synthetic machines will be an important milestone in nanotechnology history. Again, while learning the rules, simpler motors can be constructed from existing biological materials such as the protein elastin or mimics thereof. These can be made to undergo expansion/contraction cycles, and thus function as linear nanoscale motors.

Biological machines – enzyme complexes, channel proteins, etc. – are already being pursued as components of nanoscale devices. Special engineering techniques endow proteins with properties that enable them to operate as detectors able to sense and communicate with the macroscopic world in biosensor/diagnostic applications.

Biological structural components of living systems are formed, in some cases, by the controlled self-assembly (crystallisation) of minerals on templates of larger biological structures (biomineralisation), resulting in super-strong structures such as shells, and bone and teeth. While the complexity of the biological components means that it will be some time before the nano-engineer can duplicate these structures, the principle of using organic templates to organise inorganic materials has already been translated from complex to much simpler systems and has been shown to work.

The complexity of envisioned nanotechnology systems would require the biological and organic worlds to interact with solid surfaces. Information transfer and communication with the macroscopic world are two processes that will require such interactions. There will be a need to biocompatibilise such surfaces in order to maximise the efficiency of the interactions and to minimise the toxicity of many inorganic surfaces. A variety of biological molecules – such as hydrophobins from fungi, whose natural function is to interact with surfaces – are providing the clues on how to control and optimise these processes, while also serving as materials which can now be employed in some of these applications.

Making technology more efficient

| *Prof. H. Craighead, Cornell University, USA*

In moving from nanobiotechnology to nanofabrication, it is good idea to combine proven existing technologies – biology, physics, and engineering – in order to share the problems and the solutions. It is important to approach process development with an open mind – people are already thinking seriously about applications in medicine, biotechnology and healthcare, and drug companies have started to adapt processes to smaller scales, with higher throughput.

There is obvious potential in drug discovery, development and delivery, as well as in smart sensors and non-invasive diagnostics. It may even be possible to improve drug efficiency from 50-100%.

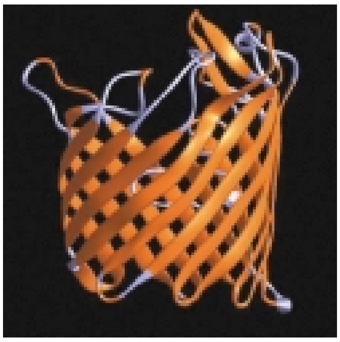
Vision for the future

The microscope is an essential tool for today's life sciences, but in future this instrument will be a variant of the scanning probe microscope. The use of near field optical techniques, scanning and electrochemical probes, all of which have much better resolution than optical microscopes, will provide much richer information. Soon we will have the ability to use optical, chemical and medical probes – perhaps simultaneously, so we should not overlook the opportunities this technology will bring to open up new areas of life science research.

At the other end of the scale, we need to look at currently viable technologies and find ways to use them more efficiently, moving progressively towards the 'lab on a chip'. Nanotechnology could be applied to various techniques, for example in:

- **separation** – analytical chemistry using separation already involves beads and gels that are inherently nanostructures. By thinking about the physics and chemistry involved, we may be able to engineer systems with more desirable functionality.

Biomolecular structures



Matrix Porin (*E.coli*): side

Matrix Porin (*E.coli*): top

Source: Cowan, S. W., Schirmer, T., Rummel, G., Steiert, M., Ghosh, R., Pauptit, R. A., Jansonius, J. N., Rosenbusch, J. P.: Crystal structures explain functional properties of two E. coli porins. Nature 358 pp. 727 (1992). Research Collaboratory for Structural Bioinformatics Protein Data Bank (http://www.rcsb.org/pdb/)

- **detection** – we have already mentioned multi-photon processors, miniaturised optics, magnetic phenomena and other transducing mechanisms. Now we should be thinking about moving them all down to the single-molecule scale.

Sizing down

Managing fluids: the handling of current is well established in electronics, as is the manipulation of photons by means of wave-guides and lenses. However, handling single molecules in fluids will demand the development of new technology. We must look at novel materials, devise new functional geometries and consider how to carry out reactions at increasingly smaller scales, aiming eventually to bring single molecules together.

My group is using DNA to model systems for single molecule technology, as it is a relatively simple molecule to start with. DNA molecules coil in random way, while proteins are more complex and 'intelligent'. If we could determine what happens with DNA, we could perhaps begin to better understand proteins. It is possible to separate DNA fragments by size using a 'filtering' technique: the filter comprises nano-fluidic channels with restrictions rather like 'speed-bumps' to resolve the size fragments.

By employing voltages to control such molecular manipulation, we can achieve things that are comparable to existing technology. In time, we may be able to make multi-functional devices, build in parallelism, and move objects around in space to improve their spatial and temporal performance, which could eventually allow us to make reproducible things that are comparable in size to a molecule.

Fluidic systems are an analogue of wires, with diameters currently sized down to about 25nm. It is possible to force a molecule from an unconstrained to a constrained region, thereby revealing areas of interesting thermodynamics. In many cases, the forces come from entropic terms in free energy.

By positioning a molecule against edge of a device and 'pushing' electronically, fragments of the molecule penetrate the filter. If the whole fragment enters, it remains in place, but if it only enters partially, it retracts when the electronic push is removed. In this way, it is possible to separate molecules of differing sizes, and the size of molecules that can be entrapped increases as the process cycle time is extended.

Micro-electro-mechanical systems (MEMs) are historically well supported. If we can drive them down to a molecular scale, we may be able to do new things. Nano-rods can easily be made at lengths as small as 50nm. It is now possible to imagine making a device with very small mass, which would oscillate as the mass changes, thereby forming a molecular-scale balance. The smaller the mass, the more sensitive the balance would be; by coating it with a biological material, it could become a bio-sensitive device. If we can couple such devices to engineered systems, we would have the power to move objects around. If we can see them, it is not beyond possibility that they could be used as a method of measuring real systems.

Other exciting possibilities involve the production of useful sensors. Electron transport measurements on single electrons uses electron beam lithography to couple down from the macroscopic to microscopic world. E-beam lithography is one process being considered for next generation semiconductor manufacture – because, unlike light, electrons are not subject to diffraction.

3. NANOMATERIALS FOR CHEMICAL AND STRUCTURAL FUNCTIONS

Proving their potential

| *Dr. R. Anselmann, Merck KGaA, Germany*

While there is a great deal of talk about the future potential of nanotechnology, some nanomaterials are already finding everyday application in a number of industrial sectors.

Mica platelets

First, there are platelet materials, of which mica is a very common example. Wet ground mica platelets are used as fillers in plastics and cosmetics. Their thickness is less than 500nm, so this is a nano-material in one dimension, at least.

Coating mica platelets with isolated metal oxide nano-particles produces absorption pigments for cosmetics. The surface of mica is very smooth, allowing full dispersion of the oxide pigment particles, and makes it an easy-to use-product where fully dispersed colour is required.

Mica platelets coated with oxide particles of titanium, iron and other metals also serve as pearlescent pigments for plastics, cosmetics, shampoo, etc. Their effect depends critically upon the thickness of the oxide layers, typically in the 60-240nm region.

For some products, multilayers of oxides with differing refractive indices are used to broaden the spectrum of colours obtainable. A closely controllable industrial process enables layer thickness to be adjusted within tight limits to give the desired effects. These materials are produced at volumes of more than 10 ktonnes/year, for use in applications such as automotive finishes.

Silica flakes 100-500nm thick form another base material for pearlescent pigments. The platelets are manufactured by a web-coating process from sodium silicate, which gives very homogeneous results. Here, the thickness of the platelets is very important, because the silica itself is optically active in the end products.

Silica spheres

Silica spheres with particle sizes ranging from 50nm to 3µm (Ronasphere®) improve the skin feel of cosmetics. The spheres are also used as light-diffusing pigments that optically hide wrinkles on the skin – here they are coated with titanium and iron oxide particles less than 60nm in diameter. While the skin surface normally reflects 5-7% of incident light, the light diffusing pigment increases this to around 30%, making wrinkles are less visible.

For absorption pigments, silica spheres coated with metal oxide particles of 60nm diameter or less are particularly effective – the particles are almost perfectly mono-dispersed, thus producing a high degree of colour purity. Coating silica spheres with diameters of 50 nm or less with titanium oxide gives a very effective UV-absorbing sunscreen agent.

Highly ordered structures of monodispersed spherical materials form opal-like materials. These structures can be used as opalescent pigments and are currently of great interest as photonic band gap materials which, to a photon, are the same as semiconductor materials to an electron. Applications envisaged include, for example, threshholdless lasers and optical computers in integrated optics.

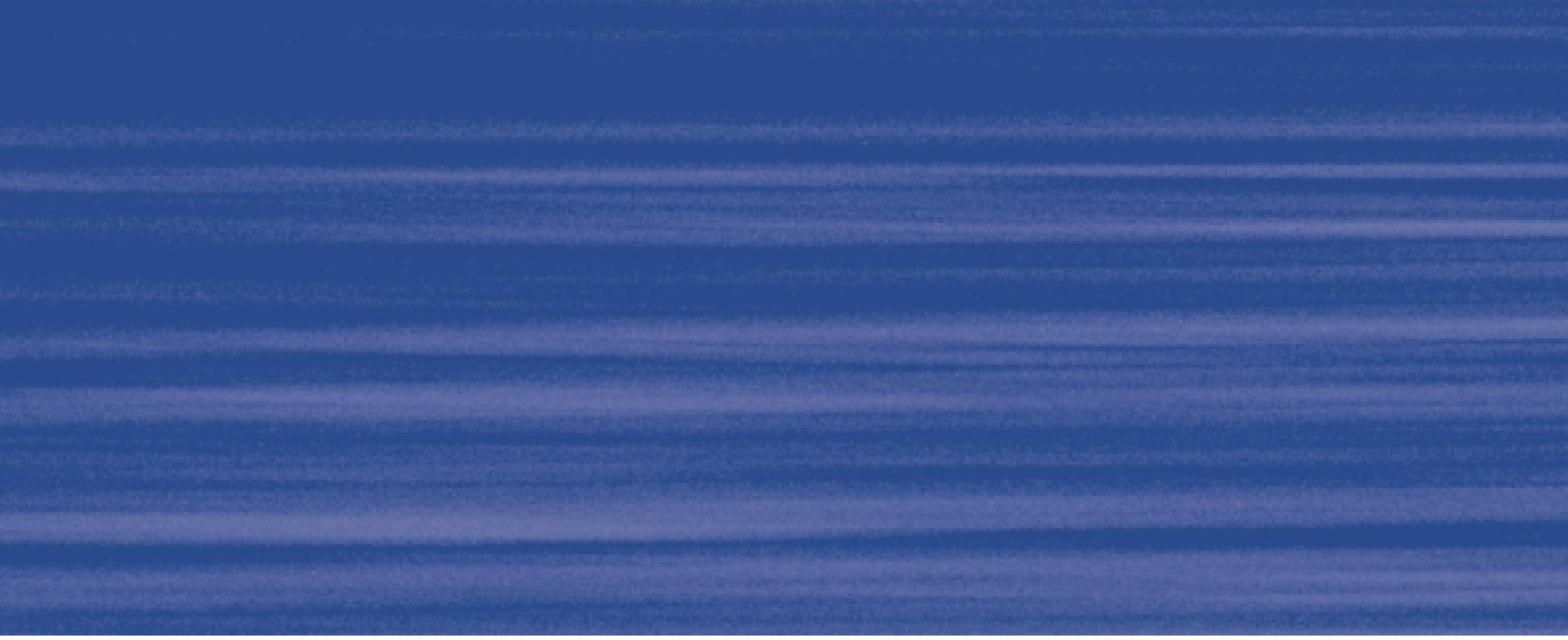
Aqueous suspensions

Electrolytic methods produce homogeneous titanium and zirconium oxide particles in 1-15nm sizes. The resulting aqueous sol can be applied as a coating material by inkjet spraying, followed by laser sintering to produce 3D structures or coatings that reduce friction and extend the life of cutting tools.

Another application concerns the production of anti-reflective films on glass. This process is fully industrialised, and is applied on a large scale to glazing in buildings.

Carbon nano-structures

Carbon nano-structures are produced by laser methods and arc discharge, although these are not yet in large-scale production. The techniques give mixtures of materials that need to be separated – high-pressure liquid chromatography is currently being tested as a means of separating fullerenes and nano-tubes. ⇨



Ever-decreasing dimensions

| *Prof. M. Greenblatt, Dept. Chemistry, Rutgers University, USA*

The ways in which atoms form into 3D networks make for a fascinating field of study. For many years people have been looking at porous nanomaterials such as zeolites. These have usually been produced on a meso-scale as the available tools have largely determined our abilities.

As the tools improve, researchers can work at decreasing dimensions. With high-resolution electron microscopes and scanning probe microscopes, we are reaching a level of tens of nanometres. Now there is talk of moving from proteins to organs, from molecules to logic circuits, from genome to bio-algorithms, and from polymers to optical switching networks.

Source: National Science Foundation, USA

Carbon nanotubes

Growing fields of study

Gas separation: great strides are being made in the use of meso-membranes for gas separation. Using templated methods, pore sizes can now be controlled from around 300nm down to 1nm. The essential requirements are to avoid cracks and pinholes in the membranes, while maximising volume fraction porosity and minimising membrane thickness. With such materials it is possible, for example, to separate carbon dioxide from methane, recover hydrogen at 90% purity and to selectively extract NO_x.

Electronic devices: pores can also be used to prepare nano-wires – it is relatively simple to obtain wires with diameters of 2-3nm, from all kinds of metals.

High-density magnetic memory storage is another potential application. Using platinum and ferrous organometallics with templating materials, densities can be controlled to give 3-10 nm nanocrystals and superlattices, which could lead to a 100-fold increase in storage density.

Looking beyond porous materials, there are several other areas of interest. We have been hearing about semiconductor quantum dots for about 20 years – scientists are still doing interesting things, but this is a mature field for the II-VI and III-V compound semiconductor families.

Nano-crystal polymeric composites with useful photovoltaic properties are now emerging. We find excellent separation of the charge in a device where a polymer is used as a hole conductor and nano-crystal quantum dots as electronic conductors. Single electron transistors are also built from these quantum dot materials; more recently, there have been reports of ZnO lasers.

Lighting and displays: further applications of quantum dots are found in LEDs and diodes based on nano-crystal and polymer layers. Electrons can be injected into the nano-crystal layers and holes into the polymer layers, to control the colour of the emissions by voltage and the choice of layer thickness.

Nano-rods and nano-wires: topics of special interest lie in the areas of nano-tubes, nano-rods and nano-wires. Recently reported gold rods 2-3nm in diameter exhibiting fluorescence – where the wavelength of the emission increases with length, and the intensity with the square of the length – open up a completely new field of tuneable emission from nanomaterials.

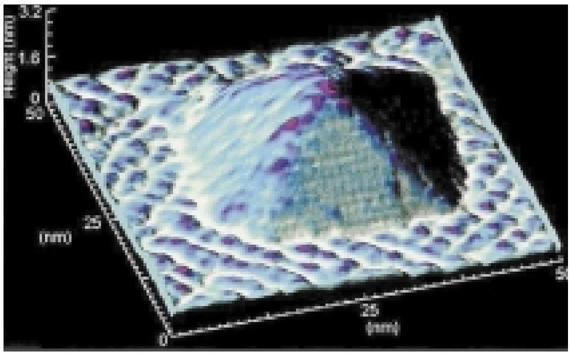
Researchers are trying to prepare carbon nano-tubes in a controlled way, with 2-3nm diameter and of any length. These can form one-dimensional electronic conductors or semiconductors, depending on the turn of the helices in the tubes. While bulk materials are quasi one-dimensional, these are truly one-dimensional, and it will be exciting to discover what properties they will exhibit.

One fascinating potential application of nano-tubes is as connecting materials for computers. When laid down on a dielectric SiO_2 layer on top of a conducting (doped silicon) layer; non-conducting towers support the nano-tube wires, with 'on' contacting and 'off' open junctions between them forming computer devices. Bundles of 20-50nm wires have been observed, indicating that 10^{12} devices could be placed on a 1 cm^2 chip area (compared with 10^{7-8} in a current Pentium).

Elsewhere, work is focusing on quantum wires which can be produced from almost any silicon and metallic materials by following the pioneering catalytic/colloid techniques. These will be very important in realising the wiring of nano-systems. A key process parameter is the size of nano-cluster of catalyst which enables the diameter of the wires to be controlled at sizes from 30nm downwards. It can be shown thermodynamically that catalyst clusters cannot be larger than about 0.2µm, although this problem has been overcome by using laser ablation.

Where next?

Nanotechnology came about because of new advanced tools/techniques, such as the scanning tunnelling microscope, the atomic force microscope, the magnetic force



Source: National Science Foundation, USA

A quantum dot

microscope and very powerful computers that enable us to see atomic-scale structures. So which materials are worthy of study? Here are just a few suggestions:

- quantum dots other than II-VI and III-V semiconductors
- quantum wires in all kinds of material
- new synthetic materials, such as charge-density-wave bronzes, which can be driven to superconductivity
- energy-related materials – for use as nano-electrodes, sensors, and electrolytes for batteries and fuel cells

We have heard about bio-mineralisation: how do complex inorganic materials such as calcium phosphate hydroxide form in teeth, bones and tendons – and can we mimic this phenomenon? Interfaces are also very important in bio-mineralisation and other cell-reactions, as well as in many other aspects of science and technology. A greater understanding of interface phenomena on the nanoscale could lead to applications in computers and electronics.

Equally interesting are the colossal magneto-resistance materials, where again we see intriguing phenomena that may be useful for computational purposes.

Finally, there are the nano-tubes: extremely strong, yet bendable and allowing the passage of huge amounts of current.

4. MANUFACTURING AT THE NANOSCALE

Tools of the nano-trade

Prof. M. E. Welland, Nanoscale Laboratory, Dept. of Engineering, University of Cambridge, UK

This presentation considers the tools of nanotechnology, the ways in which they can be used to create new structures, and how structures may be controlled to give functionality not otherwise obtained.

Powerful tool

The scanning probe microscope (SPM) uniquely combines the ability to image, characterise and manipulate single atoms and molecules. This combination means that it is the most powerful tool nanotechnologists have at their disposal.

To make structures that comprise just a few molecules, yet which could be the functional elements of a future nanoelectronics circuit, it is necessary to create very small gaps in metallic wires into which the molecules can be fitted. This can be done by taking a 25nm metal wire and causing it to break by electromigration. Molecules can then be placed into the gap, and differences in current/voltage characteristics observed before and after the insertion.

From this it can be demonstrated that the molecules themselves can alter the conductivity in a manner similar to a conventional solid-state diode. Given that the size of the molecular junction is only a few nanometres, there is tremendous potential to shrink the size of electronic devices by using a few molecules as the functional elements. The fact that molecules can be synthesised with specific electronic or optical functionality means that molecular nanotechnology is one of the most promising areas from which new types of device will emerge.

Creating new structures

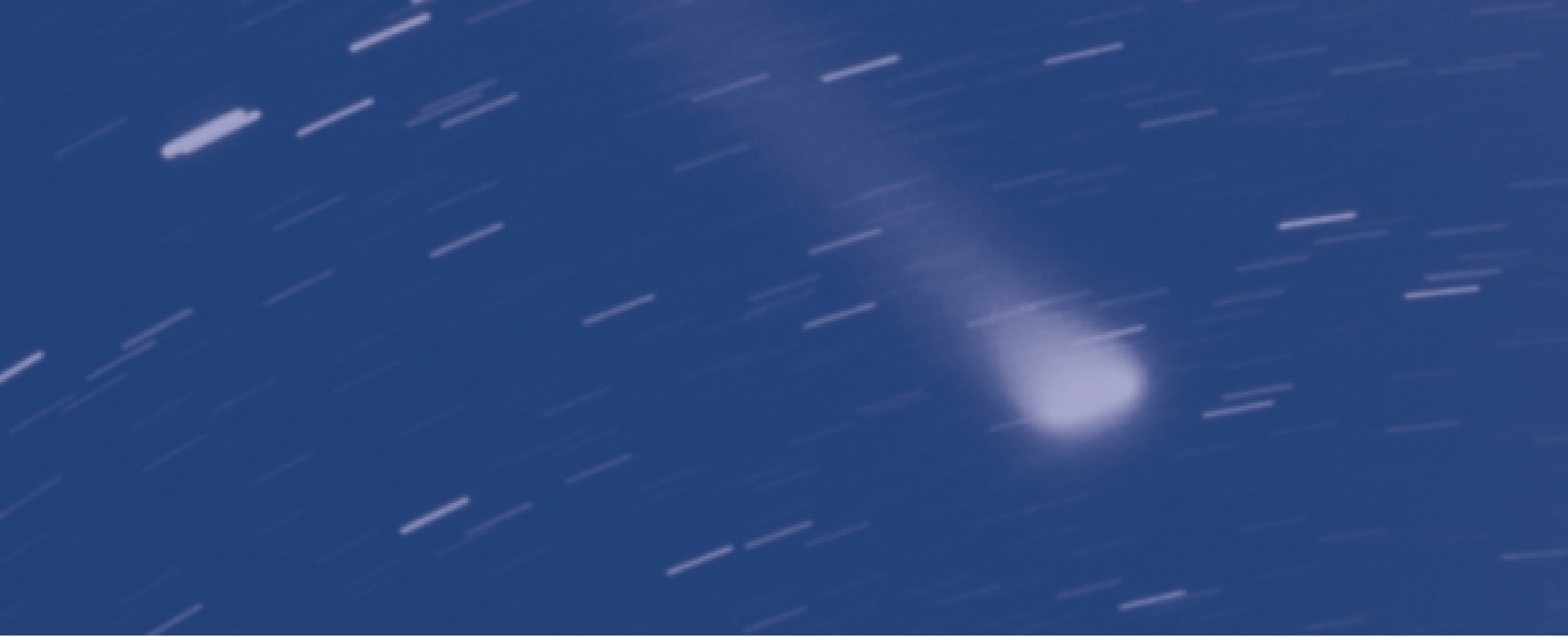
Recent work has explored different way of growing carbon nano-tubes in specific locations on surfaces. While various catalytic methods are available to effect the growth of nanotubes over large areas, a radically different route was chosen which relied upon the precise positioning of chemical precursors on a surface. This involves evaporating mixtures of metal and C_{60} molecules, to form arrays of 300nm-sized 'pockets' on a surface. Upon heating, crystals of single-wall nano-tubes are formed exhibiting an almost perfect internal structure. The fact that such unique structures can be fabricated using nanometre-scale methods opens up the possibility of growing a whole new range of material structures that are impossible to produce using bulk methods.

Controlled functionality

The physical properties of nano-structures are not entirely determined by bulk physical properties, but rather depend on the shape and size of the structure. This is a consequence of the fact that, once an object is smaller than some characteristic length – such as electron scattering length, plasmon wavelength, magnetic domain size or electron coherence length – the relationship between shape, size and characteristic length becomes important.

To illustrate this, consider the magnetic properties of magnets smaller than the critical domain nucleation size. Figure 1 (see page 36) depicts the properties of three nanomagnets with sizes up to around 800nm, in the form of a triangle, a square and a pentagon. The colour coding is a measure of the hardness of the magnetic properties in different directions. It is immediately apparent that the magnetic properties have symmetry related to the physical symmetry of the magnet. This would not happen if the magnets were significantly larger. In other words, these magnetic properties are unique to the nanometre scale. Such properties can be exploited for both data storage and computing, the latter using the coupling of adjacent nano-magnets to effect information flows.

Given that a whole range of characteristic lengths are in the nanometre range, we can expect further exploitation of the interplay between size, shape and characteristic length in a range of applications.



Coupling bottom-up and top-down

| *Prof. J. Heath, Chemistry Dept., UCLA, USA*

Modern technologies originated largely from an understanding of the very large (bulk materials) and the very small (atoms, small molecules). In the 21^{st} century, technologies will come from a fundamental understanding of how to manufacture at intermediate scale.

Moore's second Law relates the cost of electric devices in relation to their feature size. The top-down techniques of lithographic manufacture are now becoming mature. However, if feature sizes could approach the molecular scale, the Law suggests that device cost would be around $\text{US}\$10^{16}$ – equivalent to weight of the earth in US$100 bills!

Bottom-up manufacturing, on the other hand, is relatively immature. Many people think it will work because biology offers a proof principle. This presentation examines some approaches that are bio-inspired, and considers how they can be applied to information technology.

We can improve the efficiency of research by coupling theory/modelling and structure/function relationships to generate new synthetic approaches. In addition, we can increase the potential for success by coupling bio-inspired bottom-up manufacturing with traditional top-down silicon processing.

Naturally occurring protein dimers and trimers can be combined in rational ways to produce artificial protein dimers for the construction of superstructures based on the angles at which they come together. By programming particles into building blocks, it could be possible to produce a protein wire, or even a drug-delivery agent.

Surface adsorbates: harnessing the use of surface adsorbates is a remarkable technology based on viral coatings, which could lead in a number of directions. The aim is to develop molecules that bind on to particular types of semiconductor, e.g. GaAs 220.

So far, we have produced some 109 different peptides and, for any given surface, we have found at least one or two that would bind – indicating great potential as a separation technique.

To replicate the complex silicate structures of nature it will be necessary to isolate the bio-regulatory pathway and identify the active building protein. This knowledge could then be used as a basis for the manufacture of biomimetic materials such as quantum lasers.

Bottom-up approaches will have a large impact in all of the areas involved in building computers – i.e. in logic and interconnects, timing and memory, visualisation, etc. The easiest to make is memory. Solid-state devices improve in efficiency as dimensions reduce.

One of the big challenges we face in quantum wires is to fabricate wires with single atom dopants. This is probably well beyond lithography, but may be achievable by manipulating proteins or similar structures. We can then begin making spin-based devices. The simplest of these, apart from the already existing giant magneto-resistance read head for hard disks, is memory.

Interconnects: one of the significant opportunities for a biomimetic approach is to take Si-based device such as xyz-translatable MEMs mirror, and couple on to it a non-Newtonian optical mirror. We can use photonic band-gap materials made with a top-down approach, but to a large extent are limited to two-dimensional materials – which are not as interesting as 3D materials made from the bottom up. One could make very complex, more optically powerful band-gap materials could also be made, but this will only become possible by using biomimetic techniques.

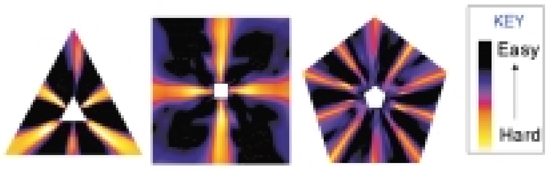


Figure 1: Symmetries in nano-magnetism

Logic: logic is probably the most complicated part of a computer to make. This is a fantastic approach to logic from the bottom up. A quantum dot placed in the 'stadium' is positioned so that all reflections go to one point. If we move the focal point, the resonant image disappears. This is bottom-up, but not really what could be called chemical assembly. The problem for manufacturing is that if we take a simple chemical approach, we obtain uniform crystalline structures. For logic, however, more complex structures are needed, and this poses a very serious challenge.

Visualisation: returning to the topic of memory, we use strain growth methods to create heteroepitaxial structures – 3D is less efficient than 2D, 2D than 1D, the most efficient being 0D. There are now a number of ways of growing highly ordered arrays in 0D which present the opportunity to make highly efficient luminescers – for example, producing white light with gallium nitride. These are very competitive with other types of lighting, offering twice the efficiency of halogen lamps, and are already in operation on big displays in Times Square, New York, and elsewhere. In a few years time we can expect solid-state light bulbs that will never need changing and will cut our energy consumption by half.

CONCLUSIONS

Introduction

The workshop was organised by the European Commission (Directorate Competitive and Sustainable Growth I) and the National Science Foundation (Directorate for Mathematical and Physical Sciences and Directorate for Engineering), and focused on nanotechnology, which is an area of intense and promising research both in Europe and in the USA. The workshop was held under the umbrella of the agreement on scientific and technical co-operation between the European Community and the United States of America, within the scope of the implementing arrangement for co-operation in materials sciences between the Research Directorate-General of the European Commission (EC) and the National Science Foundation (NSF).

The workshop brought together **37 participants** (20 from Europe and 17 from the USA), representing a broad spectrum of scientific specialisation and professional backgrounds, covering all areas of nanotechnology and combining expertise as diverse as protein structure analysis and industrial nanopowder processing.

Several eminent personalities attended the meeting:
P. Busquin - European Commissioner for Research
E. Andreta - Director, Directorate Competitive and Sustainable Growth I
H. Stormer - Nobel prizewinner for physics in 1998 and
P. Laggner - Member of the Austrian Academy of Science.
The National Science Foundation was represented by
T. Weber - Director, Division of Material Research, and
M. Roco - Programme Director NSF and Chair Interagency Working Group NNI.

Objectives and scientific/technical topics addressed

The main objectives of the workshop were:

- to strengthen mutual awareness of activities in nanoscale science and engineering;
- to promote scientific/technical co-operation, joint RTD projects and networks between the EU and the USA;
- to better understand the state of the art in nanoscale science and engineering in the EU and the USA; and
- to identify areas on nanoscale science and engineering where EC/NSF co-operative initiatives could have high impact and provide mutual benefits.

Four broad topics were addressed. Each was introduced by two speakers: one from the EU and one from the USA. The topics around which the discussion was structured were:

Topic 1: Nanomaterials for the information society;

Topic 2: Nanobiotechnology and interfaces to biology;

Topic 3: Nanomaterials for structural and chemical functions;

Topic 4: Manufacturing at the nanoscale.

The first three subjects correspond to those areas where nanotechnology is expected to have major societal impacts, whilst the fourth, nanomanufacturing, can be considered as a 'precondition' for the development of nanotechnology as a whole.

The presentations covered a wide range of research aspects and provided valuable insight into leading-edge developments, for example: magnetic random access memories and related topics; simplification and use of biological molecular functionalities; nano-wires, crystals, carbon nano-tubes, and quantum effects; industrial production of nano-coatings on silicon-oxide powders; protein building blocks for nano-scale assembly; epitaxial self-assembly. Metrology at the nanoscale was also addressed as an area of mutual interest and possible synergy.

Summary conclusions

The workshop **contributed very effectively to**:

- confirming that RTD in the field of nanotechnology must now be considered as an 'urgent priority';

- raising **awareness** of the potential of nanotechnology in a future knowledge-based and sustainable society;
- promoting **visibility** of the existing and possible future initiatives in nanotechnology;
- giving evidence of some **strengths and weaknesses** of research in the EU and the USA throughout the various nanotechnology areas;
- identifying some strategic **RTD domains** that had not been given sufficient emphasis in the initial agenda of the workshop, such as simulation, modelling, metrology and working conditions;
- highlighting the need to stimulate the **science-society** dialogue which appears to be a sensitive issue in the USA already;
- demonstrating the **multi-disciplinary** character of nanotechnology, highlighting the need to rethink some of the traditional approaches to technical/scientific careers and mobility; and
- confirming that the very **long-term research** objectives of nanotechnology and the associated **high-risk** element have, until now, prevented industry from taking a more active role, in spite of its great interest. This clearly justifies the need for **public support**.

The workshop represented the first step in identifying:

- complementary expertise in the EU and the USA; and
- possible domains for co-operative RTD projects with both high impact and mutual benefits for the EU and the USA.

It provided evidence of the high degree of novelty and scientific discovery in nanotechnology, as well as the novel forms of organisation of multi-disciplinary work and the tremendous range of potential applications. Participants also showed a willingness to co-operate and emphasised the need to strengthen this co-operation, particularly in the following cases:

- where scientific/technical challenges exist at a global level, such as for environment or energy;
- where scientific/technical challenges are so large that a multi-party approach is warranted, such as for self-assembly; and
- where it is important to have or to develop common methods and standards, such as for metrology, reference of materials or exchange of samples.

Some obstacles to co-operation were also identified, such as intellectual property rights (IPR). In fact, IPR provisions are seen as a practical deterrent for carrying out joint projects, and further clarification will be needed to enhance co-operation between the EC and NSF. Meanwhile, it was emphasised that mutual participation in networks is less hindered by IPR issues.

Immediate actions that may stimulate future joint projects were identified:

- enhanced mobility of students and/or researchers between the EU and USA, with more extended stay periods;
- mutual participation in research networks; and
- joint efforts to set up databases of activities.

Although it was not possible to identify specific scientific/technical subjects for co-operation, **the way opened by the EC/NSF implementing arrangement was considered to be effective and promising**. Further initiatives should be undertaken during the coming months to consolidate and better tune the operational functioning of this co-operation (e.g. regarding research projects, networks, training and mobility, etc.) and to identify areas for further EC/NSF joint initiatives.

The development of a **common strategy** to reinforce transatlantic co-operation in the field of nanotechnology will also be the subject of future discussions and possible joint actions.

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