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Building, understanding and controlling the possible usages of nanoobjects or stackings of nanoobjects, those found in nature or made by man using high-precision nanometric scalpels, is a key scientific project at the dawn of the 21st century.

At the end of the nineties CNRS the French National Center for Scientific Research introduced a research program called *Individual Nanoobjects* and was thus able to act as an incubator for the *Nanoscience Concerted Action* program developed jointly by the French Ministry of Research, CNRS, the Atomic Energy Commission (CEA) and the General Armament Directorate (DGA). The scale and framework given to this priority action enabled CNRS to assume the role of coordinator of a Consortium, initiated by the French Ministry of Research and recognized and supported as an Eranet by the European Commission, bringing together the nanoscience programs of ten countries.

In 2005, according to a survey by the European Consortium, the French national effort is being carried out in 190 laboratories, 166 of which are associated with CNRS, and involves 1.700 full-time researchers and academics, 1.250 Ph.D. students and post-doctoral fellows, as well as 500 engineers and technicians. This involvement is implemented within a context in which Europe as a whole devotes approximately 1 billion Euros to this field of research.

The nanosciences open up new channels for interdisciplinary work, from quantum information to nanobiosciences, strongly underpinned by nanoelectronics, nanomagnetics, nanophotonics and nanochemistry, new fields for solid and fluid mechanics, new metrologies and instrumentation and, lastly, new fields for theoreticians, often only too pleased to restrict the size of the object of study. Ethics is also significant in this area of research.

Within this framework, CNRS, along with universities and other research organizations, is fully aware of the extent of the effort required and acts as an integrator in accordance with its multidisciplinary mission and its European calling.

Bernard Larrouturou
CNRS Director General

September 2005

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The Nanosciences: a Twenty-First Century Challenge New Scientific and Technological Perspectives at the Heart of the Infinitely Small

In all the industrialized nations we are witnessing a considerable expansion in the nanosciences from fundamental research to technological innovations. Building, understanding and controlling the possible usages of nanoobjects or stackings of nanoobjects, those found in nature or made by man using high-precision nanometric scalpels, is a key scientific project at the dawn of the twenty-first century. Both the United States (National Nanotechnology Initiative) and France (*Agence Nationale de la Recherche*) have made it clear that the nanosciences are one of the major keys to tomorrow's economic successes. The nanosciences are also one of CNRS' essential priorities.

In introducing this *Focus The nanosciences*, an idea and an image spring to mind that have taken almost forty years to converge.

"*There is plenty of room at the bottom*" - this statement, part of a seminal speech by Richard Feynman (1965 Physics Nobel Prize) at the 1959 annual meeting of the American Physics Society, is finally becoming a reality. It reflects his solid conviction that a handful of atoms or molecules, sub-divided at will with almost surgical precision or assembled piece by piece, will give rise to extraordinary new properties, defined by concepts from quantum mechanics but nonetheless going against common sense. Such properties and concepts differ hugely from those that metals, sand, glass, or polymers have as macroscopic objects made of several million billion atoms or molecules. The collective effect predominates in those situations, whereas in a tiny cluster, the "functional signature" is a result of small size, shape and basic building blocks.

"*Small is beautiful and should be kept clean down to an extreme level*". The clean room, so extremely clean that humans must work in space-suits, is like a sanctuary in which the fabrication technologies and the metrologies of the world of the small are kept isolated from the tiniest speck of dust or the smallest disturbance.

Innovation in the nanoworld requires breaking down barriers and bottlenecks in the fields of materials and processes, architectures, distributed and consumed energy, connector technology and mechanical strength for each element of a device. Significant breakthroughs will allow us to propose fruitful new directions to overcome the "quantum wall" of extreme miniaturization.

A Considerable Commitment of Human and Financial Resources

The diversity of nanotechnology applications has called for investments measured in billions of Euros in the United States, Europe and Japan. In May 2005, the American *National Nanotechnology Initiative* (NNI) program estimated worldwide investment at around 9 billion dollars.

In the United States, in 2004, the federal government allocated 1 billion dollars to this field of research, 65% of which went to academic research. This government investment, initiated three or four years ago, was essentially tripled by funds from state governments and industry. Eleven funding agencies in addition to the NSF are joining forces for stronger coordination of the effort.

In Japan, the annual investment in the national *Nanosciences* program is of the order of 850 million Euros, an amount that is tripled by contributions from industry, the regions and universities.

In Europe, in 2005, the annual budget dedicated to research in nanoscience is approximately 1 billion Euros, 700 million of which correspond to national contributions from member states of the European Union and 300 million approximately come from the 6^{th} European Union Framework Program for Research and Technological Development (FP6), for which "Nanosciences and Nanotechnologies" is a priority theme. Overall, Europe has allocated 1.3 billion Euros to this priority area over the five years of FP6.

In France, the new *Agence nationale de la recherche* (National Research Agency or ANR) has named "Nanosciences and Nanotechnologies" one of its four priority sectors and has created a special program, known as *PNano*, to coordinate funding of this field. *PNano* supercedes an earlier support program by the French Ministry of Research. Beyond the contributions of research organizations and regional authorities, this earlier program consisted, on the one hand, of support from the Technology Directorate for capital equipment in the major nanotechnology center facilities and for the Micro- and Nanotechnologies Research Network (RMNT) and, on the other hand, of direct financial support by the Research Directorate, in conjunction with CNRS, the CEA-DSM and the General Armament Directorate (DGA), for research teams responding to calls for proposals as well as for regional facility centers, which are flexible technology platforms, more versatile in terms of wafer size and open to a wide range of materials.

Remarkably cohesive French dynamism

The French effort is extended by the activity of a Consortium bringing together the Nanoscience programs of ten European nations. This Consortium was initiated by the French Ministry of Research and is coordinated by CNRS and financed by the European Commission within the framework of the *Eranet* programs. The partners in the Consortium will open their domestic calls for proposals to transnational collaboration and common evaluation.

The cohesion in the effort of the French partners and the need for Europe-wide coordination were well received by the ANR. On the ground, the creation of Centers of Competence, known as *C'Nano*, one per major region, ensures networking among the regional facility centers and allows a clear, consolidated information base to be established, available for sponsorship, regional authorities and industrial partners. *The C'Nano* centers, set up in 2004 and 2005, are the optimizing and coordinating tools needed by French laboratories (of which 190 have been identified) engaged in the rapid development of the nanosciences.

Nanosciences, the Source of Tomorrow's Consumer Products

The nanosciences are already at the heart of many consumer goods. Several tens of billions of hard drive read heads are produced annually, almost all using tunnel magnetoresistance (TMR), an advanced quantum form of giant magnetoresistance discovered by Albert Fert (2003 CNRS gold medal) and Peter Grünberg. Another example is nanolasers, which are already in DVD drive read heads.

It is therefore only natural to envisage a pivotal role for the nanosciences in the development of small and large computers, flat screens – stimulated by an "electron gun" matrix made of carbon nanotubes – or in the management of communicating systems, from cell phones (combining sound and image) to product labeling. The impact on this sector is beyond question, whether for devices at the heart of functions or new approaches to connectics, where speed and temperature factors could necessitate the use of nanolasers and nanometric optical waveguides.

Beyond these applications in electronics, computer science and telecommunications, the nanosciences will lead to revolutions in a wide range of fields, such as medicine and health, safety and transportation, the environment and energy, the prevention of seismic risks, biotechnology and agriculture, etc. The night vision of car drivers will be enhanced by the combined use of nanodiodes and matrix sensors restoring an image free of the fuzziness due to scattered light.

In 1965 lasers required a threshold current of 100.000 A/cm^2. In 1970 that threshold was ten times lower, and in 2005 lasers based on nanometric "quantum dots" reduced that threshold to 6 A/cm^2. These long-life light sources will find applications in new "nomadic" products and will also be useful as energy-saving sources in fields labeled as low-tech. Savings of at least 50% are foreseen in public lighting, with robust nanodiode matrices requiring greatly reduced maintenance. Domestic lighting will only require low voltage (12 V instead of 220 V), increasing safety. In the near future, it will become possible to build sensors so precise as to be able to detect a sugar cube thrown into a lake, or to design new devices for pollution management or energy storage.

Other spin-offs of nanosciences and nanotechnologies are at the heart of new avenues that are ambitious both scientifically and technologically. Examples are light sources that emit photons one-by-one, electron gas confined in a single 60-nanometer-wide layer, single electron transistors and quantum communications. Theory and simulations are as important as the new forms of instrumentation and experimental methods in approaching these extremely rich fields, opened up by nanoobjects.

Ethics and Societal Preoccupations in the Face of the Advances and the Potential Risks of Nanoscience

Our sense of ethics, reflecting man's desire to enable various generations to live together harmoniously and decently, drives us to analyze the moral foundations of discoveries through open debate, turning the scientist back into a concerned citizen.

In the field of nanoscience, the perspective of mastering complexity at a tiny scale is used sometimes as a fallacious argument based on fear. Even if ill-founded, such negative attitudes must be taken into account: engaging in public debate about ethics is a moral obligation for scientists. A first step in this debate is undoubtedly measuring and recognizing the huge gap between our understanding of a few functions at the nanometric scale and the complexity of life. This complexity involves a highly specific overlaying of billions of elementary functions, in which energy, thermal and chemical inputs operate with a selectivity that is unattainable by man in any foreseeable future. In the nanosciences, the complexity of the products that can be envisaged in a well-founded and realistic approach is closer to that of a therapeutic molecule, with one or two functions, rather than to a robot that could take possession of the human brain.

CNRS, at the Forefront of this Priority Action

CNRS, a multidisciplinary institution present in every major region of France, partner of numerous European and international institutions and universities, is at the heart of developing research in the various fields of the nanosciences and nanotechnologies. Indeed, these fields make up one of the five areas of focus chosen by CNRS.

CNRS, incubator of innovative scientific themes, is also creative in providing the research community with collaborative structures and research networks open to all institutions and universities. It is through the use of such tools that reactive and fluid collaborations can be supported, while remaining open and flexible.

It should be stressed, however, that research strategies are all developed inside the laboratories: CNRS has strongly encouraged them to engage in this priority direction, assigning to it both human resources and collaborative platforms for sharing equipment, thus significantly amplifying their means for action.

This *Focus The Nanosciences* provides a non-exhaustive description of the extent and diversity of the themes studied in the nanosciences in CNRS' own laboratories as well as in joint laboratories between CNRS and the universities or other research organizations.

Research in the Nanosciences

CNRS is the principal public player in the fields covered by the nanosciences. In addition to implementing its own scientific policy, it also contributes to the definition of a consistent national policy for structuring research communities and deploying the necessary infrastructures.

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The National *Nanosciences* Program

The national *Nanosciences* program was launched in 2003 in order to support, structure and develop fundamental research in this key area. This program is jointly coordinated by the French Ministry of Research, CNRS, the Atomic Energy Commission (*Commissariat à l'énergie atomique* or CEA) and the General Armament Directorate (Délégation générale pour l'armement or DGA), via a coordinating committee. Its principal activities include launching annual calls for proposals to fund the best scientific projects, supporting training activities, leading and structuring the scientific community as well as assisting in networking local technological facilities. CNRS' departments have actively participated in managing this program and CNRS contributes to its financing via the Nanosciences-Nanotechnologies interdisciplinary research program. The ANR, since its very first year of operation, included the *PNano* program (National nanosciences and nanotechnologies program) among its priorities, and its 2005 call for proposals continues to emphasize work in this area.

Femto: Franche-Comté electronics, mechanics, thermal engineering and optics.

IEF: Institute of fundamental electronics.

IEMN: Institute of electronics, microelectronics and nanotechnology.

Laas: Systems analysis and architecture laboratory.

Léti: Laboratory for electronics and information technology.

LPN: Laboratory for photonics and nanostructures.

The Network of Central Technology Facilities

In 2003, the French Ministry of Research established a network of major technology centers involving CNRS, the CEA and the universities. This network, which organizes French technological resources in micro- and nanotechnologies, is to provide France with a new public infrastructure of state-of-the-art facilities, enabling it to meet the global challenges of nanotechnologies. In addition to local facilities, the network's five major central facilities are located in Grenoble around the CEA-Léti/Minatec, in Besançon around Femto, in Lille around the IEMN, in Toulouse around Laas and in the Paris region around the IEF and LPN. The central facilities in the latter four regions are housed in CNRS-owned or CNRS-associated laboratories. The creation of this network supplements the national nanosciences research structure, which also includes, for upstream research, the research organizations (CNRS, CEA, universities, engineering schools), the national *Nanosciences* program, while for research-industry partnerships it involves the Micro- and NanoTechnologies Research Network (RMNT) as well as industrial research structures, such as the Eureka Medea +, Pidea and Eurimus clusters.

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The *C'Nano* Centers of Competence

Regional Centers of Competence, known as *C'Nano*, have been in place since 2004. These structures associate at the regional level teams and laboratories from various disciplines and research organizations active in the field of nanoscience. They help promote contacts between researchers, pool resources, strengthen synergies and instigate ambitious projects. Each center takes the lead in several research fields identified as federating thematic areas at the regional level. Three centers have been operational since 2004 (Île-de-France, Rhône-Alpes and Grand-Est) and will be followed in 2005 by two additional centers (Nord-Ouest and Sud-Ouest). Most laboratories associated with CNRS and engaged in nanoscience research are, or will be, part of these regional Centers of Competence.

International Involvement

Among the many international activities in which CNRS is involved, its insertion in the European Research Area is a priority.

CNRS in Europe

For the last 20 years, the European Commission has encouraged European competitiveness and transnational cooperation. In order to support research and innovation, it has launched a succession of framework programs for research and technological development. These programs lead to the development of a very high level, truly European, scientific community. Economic growth is increasingly dependent on research, while many of the current challenges facing industry and society can no longer be met simply at national level. The skills and experience of CNRS in the nanosciences make it a major player in the construction and structuring of the global research area. Its position in international collaborative projects is an illustration of its strength in the field.

The Fifth Framework Program (1998-2002)

In 2002 the EU's fifth Framework Program for Research and Technological Development (FP5) came to an end. In this program, the nanosciences were not identified specifically as a priority. Nevertheless, many nanoscience projects were supported, principally within the thematic programs "The user-friendly information society" and "Sustainable competitive growth". Over 117 European research projects involving various aspects of the nanosciences were funded, with a budget of 150 million Euros. Among these projects, 35 involved CNRS laboratories. Each project brought together five or six research laboratories from different European countries working together in close collaboration on a wide variety of subjects, such as the development of instruments for nanofabrication using focused ion beams (FIB), or the study of magnetic molecules.

The Sixth Framework Program, FP6, (2002-2006) and the European Research Area

Strengthened by their experience, CNRS teams responded in large numbers to the first call for proposals of the "Nanosciences" priority of FP6. Considerably broader than the projects of FP5, the Networks of Excellence (NoE) and the Integrated Projects (IP) are new tools which the European Commission has developed to structure the European Research Area in a sustainable way. The budget allocated to the "Nanosciences" priority is 1.3 billion Euros. Of the 31 proposals selected for discussion following the initial call, CNRS is involved in 11 of the 17 Networks of Excellence and 4 of the 14 Integrated Projects. The *Complex Metallic Alloys* (CMA) project, for example, coordinated by CNRS, plans to organize a community in the field of new metallic materials and their development in technological applications. Its eventual aim is the creation an integrated European center for the development of metallurgy and materials physics (Idea). The *Expanding membrane macroscale applications by exploring nanoscale material properties* (Nanomempro) NoE, also coordinated by a CNRS laboratory, will allow 122 researchers and 57 Ph.D. students in the field of membrane technology and nanotechnologies to form a structured European network which will give them international visibility and permit them to exercise leadership in this field at the world level.

Working at the Nanometric Scale

Context and Issues

The reduction of the size of objects, making it possible to explore and exploit new properties of matter, requires the design and use of new tools. One of the fundamental challenges in this booming scientific field is the mastery of the means of viewing, analyzing, measuring and operating at all the scales involved, down to the very smallest: the atom and its immediate environment.

Man is naturally blind when plunged into this world of the infinitesimally small, and needs ever-more powerful magnifiers. The regular successes of CNRS in improving the performance and extending the field of application of microscopes and various radiation sources make a major contribution to the development of our spatial and spectral vision at this scale.

Our outlook has also been transformed by the revolution brought about by the introduction of novel techniques relying on ultra fine tips as local measurement probes or for manipulating nanoobjects. These tips constitute "blind man's sticks" enabling today's researchers to move about and work at the nanometric scale.

These new tools offer researchers the possibility of acting at the very heart of matter. The exploitation of this new dimension permits them to imagine and prepare to implement numerous innovations such as nanolaboratories in which several observations under constraints will be carried out in parallel. Applications in the fields of nanoobjects, nanosystems or materials are already envisaged.

The construction of appropriate observation and manipulation tools is a pre-requisite for the exploration and exploitation of the new properties of matter at the nanometric scale. CNRS' teams are dynamic in this field which promises to bear fruit in the form of numerous future advances.

Tools for Observing and Manipulating

Thanks to a constantly diversifying arsenal of tools, it is now possible to obtain images and analyze the local properties of materials and nanoobjects at the nanometric scale. CNRS teams are deeply involved in the development of these new tools, often in collaboration with teams abroad. They play a pivotal role in the establishment and leadership of European networks for the construction of state-of-the-art instruments.

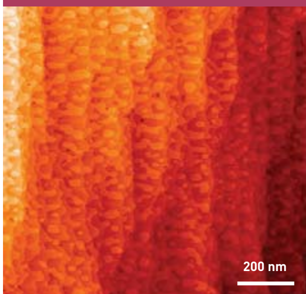
Very High Resolution Electron Microscopy

Recent developments in electron microscopy make it into an essential tool in the exploration of the nanoworld, capable of analyzing and measuring the properties of individual nanoobjects. The tenth-of-a-nanometer barrier has been broken in spatial resolution, making it possible to observe and understand the three-dimensional organization of atoms and study possible defects in its regularity. Electron energy loss spectroscopy allows chemical analysis to be carried out locally, to such a point that researchers are able to identify a single isolated atom. The energy resolution obtainable (0.2 electronvolt) makes it possible to analyze the electronic properties of an individual nanostructure with a resolution approaching that of a synchrotron. The extent of the studies dedicated to single or composite carbon nanotubes and to solid nanophases in the environment demonstrates the stakes involved in the development of such instruments.

Image of titanium oxide nanotubes using very high resolution electronic microscopy.

Scanning Tunneling Microscopy

The invention of the scanning tunneling microscope (STM) marked the entry of science into the nanoworld and the launching of nanotechnologies. For the first time, it was possible to observe the atoms of a surface, to manipulate and to organize them using a simple metal tip. Using an STM, it is possible to construct, atom-by-atom, nanoobjects controlled at the nanometric scale: molecules of biological interest, atomic wires, nanotransistors, magnetic nanoclusters etc. Thanks to scanning tunneling spectroscopy (STS), a recent development of the STM, we are able to go beyond the fabrication of nanodevices and probe their new and unexpected electronic properties, based often on quantum concepts. This method, which consists of measuring the tunnel conductance at all points of the nanostructure, may be extended to different types of metal tips capable of analyzing, for example, the local magnetic properties. STM and STS are a booming new field of activity.



Single crystal of gold observed using scanning tunneling microscopy (STM).

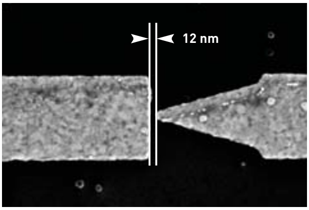
Electrostatic Force Microscopy

The electrostatic force microscope is a tool derived from the atomic force microscope. By means of a mechanical oscillator (an oscillating tip that scans the surface to be observed), this microscope measures the local electrostatic properties of a material with a spatial resolution in the ten nanometer range. It makes it possible to establish a nanoscale map of electrical charges or electric potentials with resolution of the order of the charge of a single electron. Using the microscope tip, it is possible to inject charges to probe and manipulate the electronic states of individual nanostructures. Researchers can thereby access the electronic properties of thin dielectric layers and nanoobjects (nanocrystals, carbon nanotubes), as well as the electrostatic analysis of nanodevices.

**Left: atomic force microscopy image of a carbon nanotube.
Right: electrostatic force microscopy image after a charge injection experiment.
Charge emission can be seen at the extremity of the nanotube.**

Nanofabrication Tools

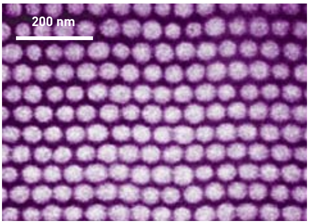
The fabrication of nanometric-sized objects and structures is essential to the advancement of the nanosciences. One possible approach, the so-called "top down" approach, consists of obtaining nanometric objects from massive systems. There are numerous techniques that make this structuring possible and constant improvements make them even more effective, as the three examples below demonstrate.



Nanoelectrodes obtained by electron nanolithography.

Electronic Nanolithography

Electron beam lithography techniques are essential in the fabrication of artificial nanostructures. An electron beam, directed at a sensitive surface and controlled by a computer, draws a pattern following a pre-programmed track. The material to be processed is usually covered by a thin layer of polymer. The areas irradiated by the beam are damaged and then become more soluble than the intact areas. The latter form a protective mask whose pattern can be transferred, for example by etching, to the original material. The resolution achieved currently makes it possible to produce patterns with a line width of approximately 50 nm but, by optimizing the tool, certain teams, notably at CNRS, have achieved sizes of less than 10 nm. This technology can be miniaturized and adapted to an atomic force microscope.



Lattice of nickel with 50 nm a diameter and 60 nm period , produced by nanoimprint

Nanoimprint

Nanoimprint is a new lithographic technique for duplicating, rapidly and at low cost, patterns of a few nanometers in size on a large surface. It consists of shaping a thin layer of polymer deposited on the substrate to be structured. A mould is applied to the polymer layer, which then takes on the shape that the researchers wish to print on the substrate. As in the case of electron beam nanolithography, the areas still covered by the polymer are protected. The patterns on the polymer layer can thus be transferred to the substrate by reactive ion etching. Combined with current microfabrication techniques, nanoimprint makes it possible to produce high-performance nanocomponents. Surfaces covered with evenly distributed nanometric patterns are useful for high-density magnetic recording. They can also be used as etching masks for photonic, electronic or biological nanostructures.

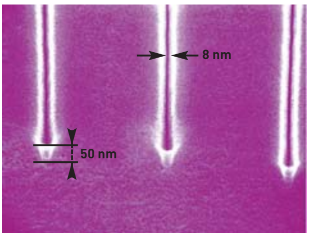


Image of a series of lines etched by FIB, achieving a duplicable record width of 8 nm.

FIB (*Focused Ion Beam*)

The FIB system makes it possible to sculpt nanometric shapes directly into conducting samples using a focused ion beam. A material can thus be structured without having to deposit an intermediate sensitive layer, essential in conventional nanolithography. The structuring can be carried out as required, either by creating defects in the structure of a crystal, by implanting ions, or by direct etching. The experience of CNRS researchers in this field has made it possible to develop an innovative FIB system using gallium ions (40 kiloelectronvolts) on a very small area (5 to 8 nm). CNRS thus established the world record for writing by FIB etching at 8 nm and opened up new horizons for this technology.

Large-Scale Facilities

CNRS is contributing to the construction of the European Research Area by participating, with its French, European and international counterparts, in the construction and operation of major research facilities. Researchers from all scientific fields (biologists, physicists, chemists...) thus have access to state-of-the-art equipment to explore matter at the nanometric scale.

ESRF

Financed by eighteen countries, the ESRF (*European Synchrotron Radiation Facility*) in Grenoble is the most powerful synchrotron light source in Europe. Its extremely bright X-ray beams are essential to a large community of researchers (5.000 visits annually) for the study of matter at the atomic scale, as much in the field of physics as in chemistry, biology, medicine, the life sciences and for the study of materials. This research, both fundamental and applied, concerns in particular the extraction of data on the structure of micro- and nanoobjects inaccessible by other techniques. The synergy between the expertise of CNRS in the fabrication of nanostructures and the exceptional power of the ESRF's analytical methods, is particularly conducive to the advancement of research in the nanosciences.

***European Synchrotron Radiation Facility* (ESRF) in Grenoble.**

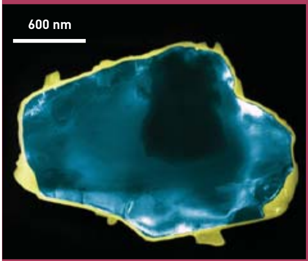
Soleil

When setting up the *Soleil* project, particular care was taken to develop high grade tools for analyzing and characterizing micro- and nanoobjects. An X-PEEM (X-ray Photoelectron Emission Microscopy) spectromicroscopic line is currently under development. Thanks to the detection and analysis of electrons emitted by a sample when excited by X-rays, researchers will be able to visualize in real time changes to the surface of nanometric objects and to their chemical composition, at the ten-nanometer scale. Moreover, the use of polarized light and of magnetic dichroism will make it possible to obtain images of magnetic domains, a feature that will open up new research potential in high-capacity data storage media. Also under study are the techniques of deep lithography (LIGA) and analysis of strains in microprocessor circuits by microdiffraction.

Future *Soleil* site in Saclay. *Soleil* is a particle accelerator that produces synchrotron radiation.

Nanosims 50

CNRS and the French National Museum of Natural History will soon take possession of the latest generation of ion probes: Nanosims 50. This instrument makes it possible to analyze the chemical and isotopic composition of solids with a spatial resolution of 50 nm. At this scale, molecules can be visualized. Nanosims 50 makes it possible to gather a great deal of data concerning the natural composition of geomaterials thanks to the acquisition of quantitative images. Understanding the detailed composition of solids is an aim common to many disciplines, such as cosmochemistry, with the study of meteorites and interplanetary dust, paleontology, which strives to understand our past thanks to fossils of micro-organisms several billion years old, or mineralogy. Nanosims 50 could also throw light on the operation of biological molecules and on the composition of aerosols.



Thanks to Nanosims 50, it is possible to deduce the ionic composition of solar wind from the study of this grain of lunar soil covered with a layer of amorphous silicates.

Producing and Understanding Nanoobjects

Context and Issues

Magnetism and light have always captured the imagination of man, who has written fiction inspired by these concepts. In these fields, nanoobjects are becoming a reality, simple to define but difficult to understand, as is the quantum world at the core of nanoscience. Transmitters, sensors and actuators are used, either alone or integrated with millions of similar ones into computers or more mundane objects, such as traffic lights. Thus, everyday life gets progressively steeped in this highly complex, reliable, robust and more energy-efficient technology.

Organized into networks, magnetized nanoscale objects, each carrying a binary "0" or "1", increase the power of memories, also making them far more energy-efficient. While the magnetization of bulk magnetic material is dominated by defects and their interactions, it is the intrinsic properties of the fundamental interactions of "exchange" and "anisotropy" that dominate in small magnetic particles.

Microcavities, which are like nanometric cages for light, give rise to nanolasers and lead to a new approach for electrical connections on microchips. The two-dimensional electron gas, confined to a size of less than 100 nm, can resonate like a flute at frequencies of around a terahertz. This as yet little known frequency range, at the boundary between light and radio waves, will be strategic, among other reasons, for monitoring the freshness of food.

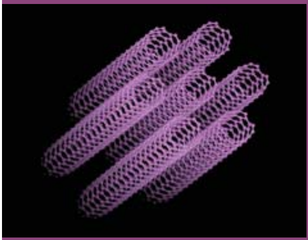
At the boundary between the organic and inorganic worlds, carbon is a major supplier of nanoobjects. After the fullerene, the nanometric football, the nanotube has come to enrich the toolkit that will give birth both to new bio-inspired materials and to efficient electron emitters for the flat screen displays of the future. The carbon nanotube has been a source of inspiration in the creation of even more exotic nanotubes, made from the III-V semiconductors of optoelectronics.

Carbon Nanoobjects

Produced with ever-improving yields, carbon nanoobjects are at the heart of numerous fields of research. While some are present in the interstellar medium, their exceptional properties are giving researchers a glimpse at their numerous applications.

Carbon Nanotubes and Fullerenes

Fullerenes and carbon nanotubes are tiny molecules formed exclusively of carbon atoms. Fullerenes are spherical. The most common fullerene consists of 60 atoms and has a diameter of 0.7 nm, whereas carbon nanotubes take the form of extended tubes, ranging from 1 nm to several hundred micrometers in length. The bonds between the carbon atoms are very similar to that of graphite. Associated with the effect of size, they give nanotubes cohesion and exceptional mechanical, electronic and thermal properties. Ever since their discovery, CNRS has invested a considerable amount of effort into these new objects. Several research networks have been formed and interdisciplinary studies have been initiated to answer the many questions raised by these nanoobjects. How can they be synthesized and organized? What are their possible applications in electronics and in field emission or in the development of new materials? How can their chemical reactivity or energy storage capacity be used? The rapid advance of research has made it possible to finalize the creation of a start-up company, *Nanoledge*, focused on the production of nanotube-based systems. Very recently, CNRS set up a European joint unit, based on four priorities: controlling the growth and managing the characteristics of components for nanoelectronics and field emission, functionalization and dispersability, environmental impact and interaction with the living. This unit will certainly be the driving force behind major advances in the field.



Carbon nanotubes.

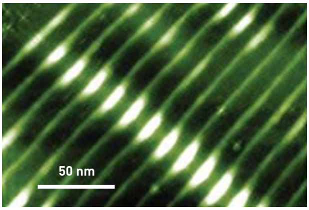
Stellar and Interstellar Nanoparticles

Numerous nanoobjects are present in interstellar matter. They consist of nanometric sized particles (between 1 and 20 nm) produced at the end of a star's life or on completion of a cascade of chemical processes in interstellar clouds. For astrophysicists, it is essential to characterize these particles and to establish their role in physico-chemical processes, such as those that govern the formation of stars and planetary systems. Several research teams are trying to clarify their composition by analyzing infrared data provided by space observatories. These particles can be aromatic macromolecular aggregates, nanodiamonds, or nanoparticles of silicates or metal. Other CNRS teams are trying to extract nanoparticles directly from meteorites or particles of extraterrestrial interplanetary dust. Finally, complex experimental devices make it possible to reproduce the conditions of the interstellar medium and thus study the formation of these nanoobjects, their reaction to ultraviolet radiation and their catalytic properties during the formation of complex or even pre-biotic molecules (existing before the appearance of life). These areas of research are developing within an interdisciplinary context that is strongly encouraged by CNRS and involves astrophysicists, physicists, geochemists and chemists.

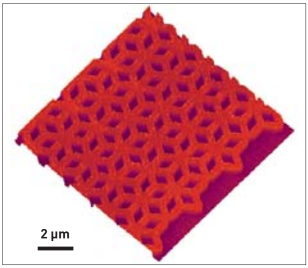
PIRENEA experiment dedicated to the study of the physico-chemical properties of nanoobjects of astrophysical interest.

Semiconductor Nanostructures

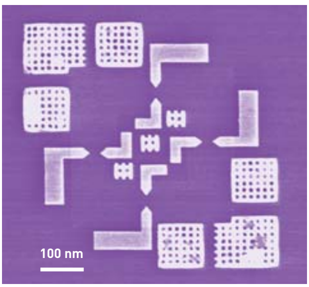
The recent development of nanofabrication techniques makes it possible to create artificial systems in which certain fundamental physical phenomena, previously only observed in atomic physics, can be studied now also in solids. These systems are eliciting a lot of interest in fundamental physics, as they embody theoretical physical situations and involve the exploration of interactions in ideal situations, thus leading to the introduction of novel concepts. The structures fabricated today are likely to have important applications in quantum computers and in nanoelectronics.



Sectional view using tunneling microscopy of an assembly of quantum dots.



Lattice etched in a structure that induces localization of electrons by quantum interference effects.



Electron microscope view of an experimental device composed of ohmic contacts and grids for measuring quantum correlations of electrons confined within a ring.

Semiconductor Quantum Dots

Optoelectronic devices (including laser diodes) presently use a very thin semiconductor layer or "quantum well" as an active medium. CNRS is developing quantum dots consisting of nanometric sized inclusions of one semiconductor inside another. These nanoobjects confine electrons strongly in the three spatial directions and thus, like atoms, present discrete electronic states and very narrow spectral emission lines. Furthermore, the emission wavelength of a quantum dot depends on the number of electrons that it contains, due to the strong Coulomb interaction among the trapped electrons. CNRS researchers have recently taken advantage of these two very specific properties to produce the first single-mode source of single photons. This device, capable of emitting photons one-by-one, in a perfectly controlled manner, will make it possible, in particular, to develop perfectly secure communication systems based on quantum cryptography.

Quantum Transport in Semiconductors

When an electron moves inside matter, there is interference among all the possible trajectories: this is the result of the superposition principle in quantum physics. To study these phenomena, CNRS researchers observe them in a micrometric size, nanostructured material, at very low temperatures (–271 °C). The use of semiconductors also makes it possible to alter the geometry of the nanostructured material and its characteristics using electrostatic grids. Numerous theoretical predictions in the field of quantum mechanics have thus been confirmed, such as oscillations in resistance depending on the magnetic flux in a ring (Aharonov-Bohm effect), the presence of a permanent current in a non superconducting ring or the quantification of conductance through a constriction.

Ballistic Transport

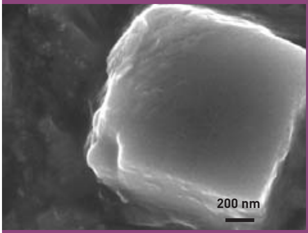
Progress in nanostructure growth techniques makes it possible to obtain high-mobility two-dimensional electron gases. This has permitted a new electron gas state to be identified: the fractional quantum Hall effect. In nanostructures it is also possible to achieve a regime in which electrons propagate without colliding other than with the edges of the sample: this is the ballistic regime. By constructing structures very similar to the model systems used by theoreticians, researchers can confirm theoretical predictions. Thus, they have observed the localization induced by the geometry of a topologically complex lattice. It is also possible to produce microbilliards into which ballistic electrons are injected. The quantum nature of these particles brings in a wealth of phenomena, for example, in quantum chaos theories.

Magnetic Nanoobjects

Magnetic nanoobjects or networks of magnetic nanoobjects constitute important areas of research for CNRS. Mastering their fabrication is a pre-requisite, not only for discovering physical effects but also for the production of materials with specific properties that could, for example, make it possible to create more efficient recording systems.

Synthesis of Magnetic Nanoobjects

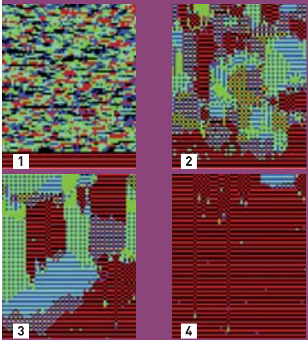
A CNRS-Insa-Motorola SPS team has developed an original method for synthesizing magnetic nanoobjects, making it possible to choose the shape and size of the nanoobject by preventing surface oxidation of magnetic particles of iron or cobalt. An organometallic molecule is decomposed under hydrogen into very small spherical metal particles (1.5 to 5 nm) with original structure and excess magnetization with respect to bulk metal. These nanoparticles compact together to form, in the case of cobalt, ferromagnetic nanowires at room temperature and, in the case of iron, nanocubes that organize themselves into superstructures (cubes of cubes). The future of these magnetic nanoobjects is extremely promising both in magnetic recording and in mobile telephony.



Scanning electronic microscopic view of nanocubes of iron organized in a superlattice (cube made of smaller cubes).

Magnetic Nanostructuring

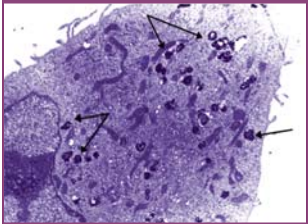
One major challenge for multidisciplinary fundamental research which is mobilizing CNRS physicists and chemists is knowing how to design dense networks of magnetic nanostructures on surfaces of a few square centimeters simply and economically, with perfectly controlled properties. The many techniques currently developed will make it possible to keep up the growth rate of magnetic recording density, which has doubled every year since 1998. In addition to self-organization, already producing convincing results, the irradiation of magnetic multilayers or alloys using ion beams is very promising. Direct irradiation or through a mask allows modification of the magnetic properties with extreme precision. For example, it can be used to transform a disordered alloy into an ordered structure at moderate temperatures, making it compatible with industrial processes.



Progressive ordering under irradiation of an iron and platinum alloy.

Nanomagnetism at the Scale of a Living Cell

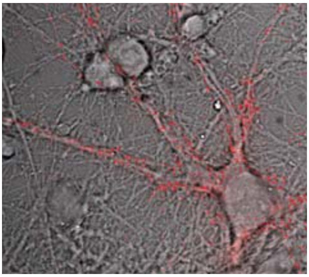
The use of magnetic nanoobjects in living cells is an example of their possible applications. These nanoobjects can be very efficiently inserted into cells thanks to electrostatic adsorption on the membrane followed by internalization through spontaneous endocystosis. Researchers then have "magnetic cells". The new properties of these cells make it possible either to sort them magnetically according to type, or to guide them to a precise location within the organism, in the case of cells of therapeutic interest. Moreover, these magnetic cells can be monitored in real-time using MRI, a major advance for the emergence of new techniques in cell therapy.



Magnetic cell observed under an electron microscope: each small sphere (arrows) is filled with magnetic nanoparticles. This marking does not alter either the cell's viability or its functional capacities.

Nanoobjects in Biology

Nanosciences and biology are intrinsically linked, if only because of the nanometric size of biological macromolecules. New research tools derived from nanoscience open the possibility of monitoring the operation of living cells in ways unequalled by conventional approaches. Moreover, the living cell itself is rich in nanoobjects that can be studied through nanoscience techniques, leading to a novel and more precise description of cellular mechanisms. CNRS teams are well-advanced in such directions of research and have produced remarkable results.



Observation of proteins in the nervous system using semiconducting nanocrystals (shown here in red).

Semiconductor Nanocrystals

In order to better understand how cells work, it is essential to determine the dynamics of the biological processes involved. In this respect, recent progress in nanomaterials opens up completely new perspectives. In particular, biological molecules can be easily attached to some semiconductor nanocrystals that are remarkable light emitters and can be monitored individually. Using this technique, CNRS and INSERM researchers have been able to observe the movement of proteins involved in the transmission of nerve signals with unprecedented clarity. Eventually, by making ultra sensitive cellular imagery possible, these nanoprobes will allow us to shed new light on numerous biological processes.

Magnetic microballs, anchored by a DNA molecule to the surface of a capillary tube, are observed using an inverted microscope.

Study of DNA/Protein Interactions at the Single Molecule Level

CNRS has developed an original technique for studying the interaction between a single enzyme molecule and a DNA molecule. This molecular-scale detection avoids the inevitable loss of resolution inherent in conventional bulk observation techniques, where it is the average behavior of an enzyme population that is observed. By associating a DNA molecule fixed on a support with a magnetic microball, researchers have been able to stretch and twist the DNA using tweezers made of tiny magnets. Initially, this technique allowed comparison of the elastic properties of DNA predicted by theoretical modeling with the observations. Now, by using these elastic properties, it is becoming possible to identify even a minimal change in the extension of a DNA molecule caused, for example, by its interaction with a single enzyme. This technique has made possible the study of the dynamics and led to a better understanding of the mechanism of the action of numerous enzymes (topoisomerases, helicases and polymerase DNA and RNA) whose dysfunction often accompanies cancerous or genetic pathologies.

Nanotube network from a giant vesicle under fluorescent microscopy.

Membrane Nanotubes

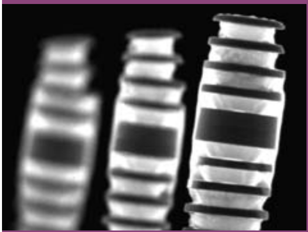
Communication between the various compartments inside the cell is essential to its operation. This function is fulfilled in part by fine tubes of membrane that allow targeted transporting of molecules and, thus, of information. In order to establish the essential mechanisms and important physical parameters that control this phenomenon, biologists and physicists in CNRS laboratories at the Institut Curie have reconstituted, *in vitro*, a model system of membrane nanotubes pulled by molecular motors. This biomimetic system not only makes it possible to better understand the mechanisms of intracellular transport, but also, understanding the formation and dynamics of membrane nanotubes makes it possible to imagine applications of particular interest for nanoscience. Long membrane nanotubes could, for example, form networks to transport fluids to microreactors.

Nanoobjects for Photonics

Optical systems are widely used in the fields of information processing and optical communication. However, the miniaturization of conventional optical devices is reaching its limits. In order to overcome this technological barrier, CNRS is formulating new concepts which may produce technological breakthroughs in the future and thus arouse great interest for their scientific and applicative spin-offs.

Microcavities

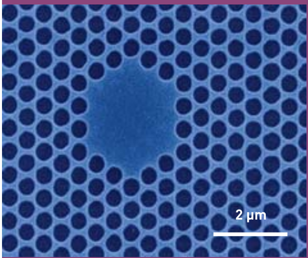
Optical microcavities are tiny light cages bounded by reflecting sidewalls, measuring a few hundred nanometers. When a light emitter is placed in a microcavity, new optical phenomena appear that make it possible to control the rate and the direction of light emission. Several CNRS laboratories are exploring the phenomena involved in these structures and fabricating microcavities from semiconductors, polymers, or other materials, using nanotechnology processes. Innovative spin-offs are expected in the production of extremely efficient light nanosources (nanolasers) that could be integrated into photonic nanocircuits.



Semiconductor microcavities. The alternation of two materials in the same vertical direction forms the mirror and confines the light within the "body" of the cavity located in the center.

Photonic Crystals

A photonic crystal is a material on which periodic patterns are etched, making it possible to guide, trap or filter light. The idea of using two- or even three-dimensional periodic patterns to trap light was first proposed in 1987, triggering a worldwide race in many promising directions such as the realization of periodic arrays of extremely fine holes, or stackings of nanospheres or "nanologs". The goal was to produce ultraminiaturized architectures for telecommunication devices or biological sensors. Housing light sources at the very heart of these structures will make it possible to give them many functions. The applications of these future optical microcomponents range from heating by radiation to super light-emitting diodes (LEDs), those tiny indicators that are to be found on all our portable gadgets and which could well replace conventional Edison lamps or fluorescent tubes for lighting.



Hexagonal "defect" in a photonic crystal.

Metallic Nanostructures for Optics

Under certain conditions, known as "surface plasmon resonance conditions", metallic micro- and nanostructures greatly confine the electromagnetic fields of visible or near infrared light. Operating as plasmon guides, these metallic structures allow the propagation not only of light but also of electrical signals. The combination of these two properties on the same material support makes it possible to envisage the design of microsystems with novel characteristics, combining light-guiding components and numerous electrical connections. These structures could be particularly useful for developing components for telecommunications and new types of biological sensors. On these themes, the researchers of a Université de Bourgogne/CNRS team are coordinating the European "Plasmo-Nano-Devices" Network of Excellence.

Optical functionality of a 40 nm thick gold strip.

Constructing Nanosystems

Context and Issues

Within the context of inter-disciplinary research, CNRS researchers are exploiting new possibilities for making and manipulating nanoobjects by organizing them into original architectures, called nanosystems. The structure of these nanosystems and related phenomena enable researchers to endow them with new functions.

The design of a nanosystem requires a mixed bottom-up/top-down methodology whereas usually a system is designed using a top-down approach. This difference, which may at first appear insignificant, is in fact a veritable scientific revolution. It requires a new approach to systems, which consists of developing architectures that are not the result of the association of pre-established blocks. This mixed bottom-up/top-down methodology makes it possible to increase the degrees of freedom available to designers and will thus result in numerous major innovations.

Nanosystems will enable scientists to probe hitherto unknown fields, such as the exploitation of molecular interactions in mechanical, chemical and electrical processes. In the field of life sciences, they will make it possible to develop new types of sensors or even new characterization methods at the molecular scale, which will have both scientific and societal repercussions. In the field of information processing, sensors with improved resolution and new storage system architectures will be developed based on new concepts for devices that take advantage of quantum interactions between electrons and matter or between light and matter. Finally, increasing the density of integration is one of the principal challenges of the next few years. It will become possible, on an ever-smaller chip, comparable to smart dust or a veritable "lab-on-chip", to associate several functions of information processing, energy management and communication.

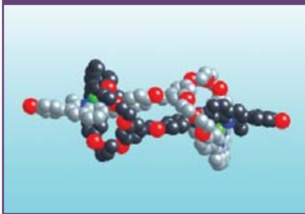
The fabrication of these nanosystems requires a series of complex technological steps, a "technological process architecture" that calls for fundamental research into technology and for the development of true technological systems. Moreover, the two strategic directions of design and characterization of nanosystems are themes developed by CNRS for the extensive exploration of this phenomenal field of research.

Molecular Machines

No law of physics or chemistry requires machines to be macroscopic in size. Thanks to the discovery of a method of manipulating single atoms or molecules using the tip of a tunneling microscope, at the beginning of the 90's, chemists and physicists have been able to push back the frontiers of miniaturization by designing, synthesizing and studying machines the size of a single molecule. These molecule-machines will perhaps be the computers, memories, robots or transducers of the future.

Molecular Motors

Biological processes use "natural" molecular motors. These motors consist of proteins that are most often set into motion by ATP hydrolysis (the "biological fuel"). For synthetic chemists, the production of totally artificial molecules whose behavior echoes that of biological systems, but are smaller in size, is a formidable challenge. It requires being able to set into motion part of a component or an assembly of molecules by means of a signal transmitted from the outside, whilst other parts remain immobile. At CNRS, teams of chemists have synthesized tiny rotary motors, linear motors set into motion by an electronic signal or synthetic molecular "muscles", capable of contracting or extending under the action of an external stimulus.



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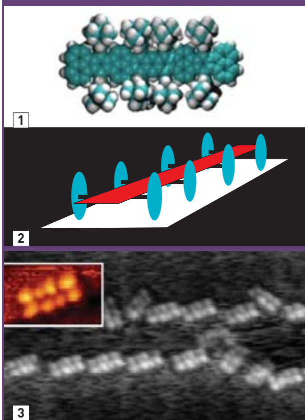
Structure of a molecular "muscle", obtained by X-rays

Molecular Nanotrucks

The family of molecules called *Landers* (or molecular trucks) has recently been synthesized at CNRS. These molecules are used in surface studies using scanning tunneling microscopy (STM). They consist of a rigid central frame (the active part of the molecule, in red on figure 2) and 4 to 8 legs (or wheels) separating this frame from the surface so it retains its properties and movement. Each time a component of the circuit is at the right height above the substrate, the nanotruck attaches itself there. The manipulation of individual nanotrucks by an STM tip has made it possible to monitor to a high degree of precision the intramolecular mechanics. Nanotrucks also have the particularity of reconstructing the surface of certain metals by stabilizing metallic nanowires under their frame, between their wheels. These are the first steps in the development of an atomic technique for molecular electronics.



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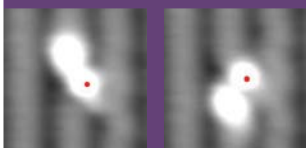
1 Model of a molecular nanotruck.
2 Concept.
3 STM image of molecular trucks with 8 legs parked along mono-atomic steps on the surface of copper.

Surface Monomolecular Switch

The extreme spatial resolution of a low temperature STM, less than 10 picometers (0.01 nanometer), allows experiments to be conducted inside a single molecule and to produce completely new molecular devices based on a single molecule. CNRS has thus been able to make a molecular switch out of a biphenyl molecule adsorbed on a silicon surface. The switching action can be triggered by electronic excitation using an STM tip. Researchers, working with submolecular spatial precision, can control the position within the molecule where the electronic excitation is administered and thus control the switching dynamics.



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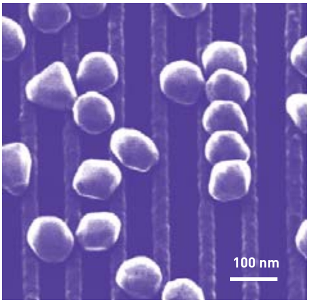
Tripping of the switch on the silicon surface after its excitation by a tunnel current.

Nanosystems for Biology

The new nanometric sensors are the best tools for tackling one of biology's current challenges: obtaining systems that, thanks to their size, offer the possibility of carrying out a large number of ultra-sensitive detections simultaneously, at the molecular scale. The development of these massively parallel methods represents a major challenge for upstream research, since they underlie major economic issues, particularly in the field of genomics. In order to achieve these objectives, CNRS has been active for several years in investigating the applicability of this research and this has led to several important patents.



30 nm wide nanoelectrodes bridged by 90 nm diameter gold nanoballs.

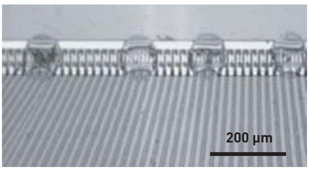
Electrical Detection Using Nanoballs

Detecting the interaction between biomolecules using an ultra sensitive nanosystem that can be integrated on a microchip is a major challenge for the development of miniaturized instruments capable of carrying out biological assaying, screening of medicines and sensors for the environment or for food safety. CNRS is developing a nanosystem capable of converting the specific affinity between two proteins into an electrical signal. The technological feat is to obtain intermeshed nanoelectrodes of a size comparable to that of biomolecules, thus making it possible to achieve single molecule sensitivity. Grafting these electrodes metal nanoballs onto proteins makes it possible to enhance their electrical response. Thanks to this miniaturization, early diagnosis of cancers can become extremely sensitive.

Piezoresistive nanolevers.

Nanolevers for Biological Detection

The detection of molecules that are present, even in very small quantities, in a volume of liquid of less than a nanoliter, is possible thanks to the use of nanolevers: if a molecule is present, it attaches itself to the nanolever, causing a vibration or a change in its resonance frequency. A CNRS team has succeeded in considerably increasing the sensitivity of this technique by structuring the surface of nanolevers with nanoparticles or layers of active biomolecules. It has also developed integrated methods that make it easier to achieve the same result by eliminating conventional external optical detection stages. The emergence of large-scale fabrication techniques for nanoobjects makes it possible to reduce the cost of these nanodetectors and to use them for medical diagnosis. This biotechnology has been emerging rapidly for several years now, with three patents currently being extended internationally.



Deposition of microdroplets containing DNA onto a network of field effect transistors.

Electronic Detection of DNA on a Network of Transistors

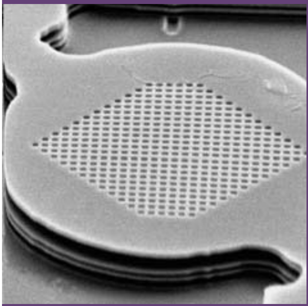
A team of CNRS physicists from the École normale supérieure and université Paris 6 and 7 has made it possible to detect DNA purely by electronic means, using a network of a hundred silicon transistors, each with an active area of a few micrometers. When the transistors are in contact with a biomolecule, their electronic characteristics vary with the electric charge of the biomolecule. Together with biologists from the Institut Pasteur, the researchers have thus been able to develop a test for detecting one of the most common pathogenic mutations of the human genome, responsible for hereditary deafness in children. This technique has numerous other potential applications: the detection of biomolecules without marking, miniaturization at the micrometric scale, analysis of a very large number of samples in parallel, development of "lab-on-chip" type devices, etc.

Photonic Nanocircuits

Current optical communication systems are still a ways off from taking full advantage of the potential of optical technology. Yet using photonic circuits would lead to a considerable improvement in the performance of these networks. CNRS is exploring every channel likely to allow researchers to by-pass the technological hurdles that prevent the advance of integrated nanooptics.

Towards Photonic Integrated Circuits

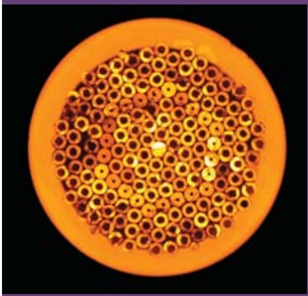
Producing a circuit based entirely on optical processing could lead to more reliable circuits and is a promising alternative to electronic circuits, subject to numerous limitations. However, the integration of an optical system into a single microchip remains a challenge that seemed unachievable in the absence of generic concepts and fabrication processes. The emergence of photonic crystals and their use in structuring vertically-confined waveguides in two dimensions offer a new route to achieving photonic integrated circuits made of wavelength scale components and tailored using optical mode engineering. The availability of low-consumption nanosources that can be integrated remains the final barrier to this objective.



Photonic structure: stacking of semiconductor membranes containing a network of holes and slits with sub-micron periods.

Photonic Crystal Fibers

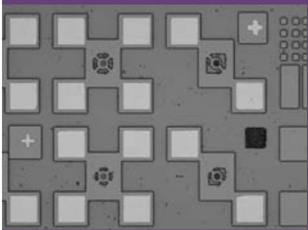
Photonic fibers make it possible to guide light and, thus, to transmit signals and data. A new generation of fibers, photonic crystal fibers, can guide light thanks to their geometric properties. Air channels run along a fiber and their periodic distribution determines the wavelengths for which light propagation is allowed. The arrangement of these channels and the introduction of breaks in their periodicity give access to new as yet unexploited properties, such as guiding light through a core of air. Such fibers make it possible to compensate for the dispersion of conventional fibers and push back the threshold of non-linear effects. They are thus of particular relevance for high-speed transmission systems and, at the same time, open up a vast area of potential innovation: transport of high-power beams, propagation of femtosecond pulses over long distances, supercontinuum generation, guiding of atoms and molecules by radiation pressure.



Optical fiber preform.

Emergence of Revolutionary Optical Functions

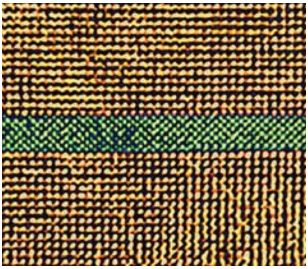
Mastering optical nanostructure fabrication processes can lead to new materials with physical properties as yet unknown in nature which could revolutionize optical instrumentation and imagery. CNRS researchers are trying to demonstrate the existence of “left-hand” materials in which light is not refracted in the direction imposed by the conventional laws of refraction. These materials could lead to the fabrication of flat lenses producing an image with a resolution undistorted by diffraction.
Similarly, light sources based on silicon nanocrystals could lead to the emergence of silicon photonic circuits and allow considerable advances to be made in the convergence of microelectronics and nanophotonics. Beyond their advantages in optical interconnects and in all-optical routing, associating photonic nanostructures with other materials, for example organic or biological materials, could revolutionize whole application sectors in medical techniques and in biosensors.



Photonic structures for optical generation and processing, resolved spectrally and angularly.

Spintronics

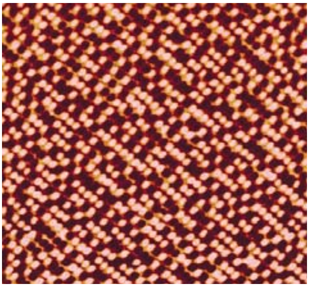
Spin electronics make use of a quantum property of the electron, the spin. Spin can be thought of as a magnetic moment (tiny magnet) associated with the permanent rotation of the electron. Whereas conventional electronics exert a force on the charge of electrons, thus causing them to move, spintronics acts on their spin. This additional lever produces new effects and new potential, already used in current technologies (computer hard drive read heads, etc.).



Cross-sectional view of a magnetorestrictive tunnel junction using high-resolution electronic microscopy.

Giant Magnetoresistances (GMR)

The discovery of the GMR effect in France in 1988 has led to a new generation of extremely sensitive magnetic sensors. This effect, observed in sandwich structures consisting of two ultra-thin magnetic layers separated by a non-magnetic layer, produces a very large variation of the electrical resistance when the magnetic configuration of the two magnetizations (parallel or antiparallel) is modified by the application of a magnetic field. Since 1997, all hard disk drives use GMR to detect, with high sensitivity, the small magnetic fields generated by writing on a hard disk or tape. This led to a considerable increase in the density of data stored (130 gigabits/inch^2 in 2004). In the automobile and aeronautical industries, GMR sensors have also been adapted to the detection of position and speed and to the counting of magnetic objects.



Network of magnetic contacts for ultra-high-density recording.

Magnetic Memory and New Spintronic Architectures

In new Magnetic Random Access Memories (MRAM), researchers have made use of the TMR effect (Tunnel Magneto Resistance). As for GMR, the resistance of the tunnel junction depends on the orientation of the electron magnetization in the two magnetic layers that compose the junction. Binary data can thus be encoded in a tunnel junction. Unlike conventional random access memories (RAM) in which all data are erased as soon as the power supply is switched off, MRAM can preserve the data they contain without consuming any power and with excellent speed and miniaturization potential. These memories are produced in France by ST Microelectronics and Altis, with whom CNRS is collaborating closely to adapt to the needs of industry and pioneer worldwide the design of the next generation of MRAM: new junction materials (oxides, semiconductors), sub nanosecond magnetization dynamics, new memory cell architectures for very high densities.

Submicron magnetic tunnel junctions.

New Spintronic Phenomena

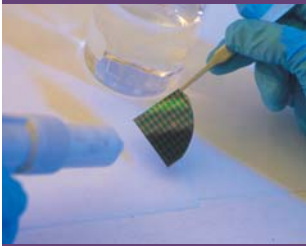
Spintronic effects, GMR or TMR, are currently used to transform the magnetic data on a hard disk or an MRAM cell into an electrical signal. A decisive turning point was recently reached with the new concept of spin transfer which, conversely, makes it possible to write magnetic data by transfusing the spins carried by an electric current. This concept should allow purely electronic encoding of ever-smaller magnetic cells in the next generations of memories. Another possible use is in logic circuits, with the unique possibility of being able to reconfigure the circuit by switching the magnetization of its components. Indeed, spintronics is advancing towards a fusion with conventional electronics and this produces the need for semiconductor/magnetic material heterostructures.

Spintronics

Promising studies into the problem of injecting or manipulating spin polarized electrons in a semiconductor and research into higher performance hybrid materials announce the emergence of new functionalities for computer technologies and, in the longer term, for quantum computing...

Future Materials for Spintronics

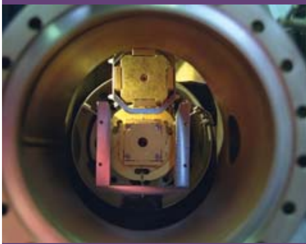
Current spintronic devices use cobalt and iron alloys for polarizing spins. The polarization obtained is modest, typically less than 50% in the junctions of MRAM memories. The discovery of conductors with polarization approaching 100% would make it possible to considerably improve the performance of these devices. A manganese oxide has shown almost total polarization and junctions using this oxide achieve record magnetoresistances of 2.000%. This performance, achieved at low temperature, is, however, too strongly degraded at room temperature to be considered for applications. Nevertheless, this avenue remains open, as other promising oxides are currently under study. A new concept, that of spin filtering by tunneling through a magnetic insulator, should also lead to very high performance levels.



Fabrication of magnetic tunnel junctions by optical lithography.

Magnetic Semiconductors

Data are currently recorded and processed using two very different types of materials: ferromagnetics and semiconductors. In mass storage, data are recorded in ferromagnetic metals that get magnetized when placed in a magnetic field and retain part of this magnetization when the field is removed. Data processing relies on components derived from microelectronics and semi-conductor based optoelectronics, capable of controlling current transport and light emission. Spin electronics aims to integrate these two functions. The ultimate integration would consist of making the semiconductor itself ferromagnetic and associating it with a normal semiconductor in nanostructures. Such ferromagnetic semiconductors already exist at low temperatures: CNRS laboratories are making such semiconductors, seeking to improve their performance, and studying the new perspectives they open. We already know how to modulate their magnetization using an electrical voltage (rather than a current, which is energy-consuming) or by illuminating them, a feature that would permit direct image recording.



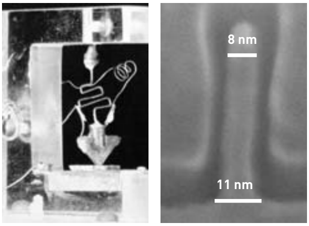
Polarized electron source (upper gold plate) in a high-vacuum chamber and device for collection and analysis of emitted electrons (center).

Polarized Electron Emission

One of the challenges posed by spintronics is the use of highly spin-polarized currents in conducting materials. Free electron beams in vacuum, almost 100% polarized, are already available. To obtain such beams, researchers illuminate a semiconductor at room temperature using circularly polarized light. Photons are then absorbed and cause the excitation of electrons while transferring their rotational characteristics to them. This is known as optical pumping. This phenomenon produces a spin-polarized free electron gas. Even if these optical pumping techniques are not likely to give consumer applications in the short-term, they are nevertheless very useful in various fundamental research fields, particularly for studying the injection of spin polarized electrons in spintronic devices.

Nanoelectronics

The future of electronics depends on its ability to reduce the dimensions of basic electronic components. The critical dimensions of these components, such as transistors, are no longer measured in microns but in tens of nanometers. Two complementary approaches are underway at CNRS: the adaptation of existing technologies to the nanometric scale and the construction of components from nanostructures, molecules or even atoms.

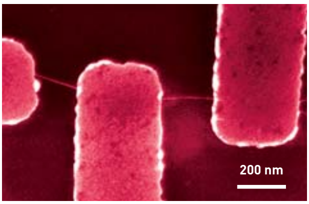


DR. © LTM/CNRS-CEA-Léti.

Left: first point contact transistor (1947). Right: CMOS technology transistor.

Nanoelectronics in Silicon Technology

Silicon microelectronics is governed by the frantic rush to miniaturize the characteristic dimensions of CMOS components, an essential technology in the integrated circuit industry. This reduction of the dimensions predicted by what is known as Moore's Law, will lead to the fabrication of transistors not exceeding ten nanometers or so by the 2010s. The development of CMOS technology on silicon is coming up against the unavoidable problem of quantum phenomena that require the development of new architectures. Miniaturization techniques that use the top-down approach are also becoming difficult to master. This is the reason why the replacement of CMOS components must be envisaged, either by non-planar devices on bulk substrates (SOI) or by components derived from nanoelectronics. Audacious technological innovations involving the introduction of new materials are under study at CNRS (SOI substrates, constrained SiGe alloys, metal grid/high K), proposing original solutions in terms of materials, technological processes or architectures for devices that will make it possible to push back the limits of integration.



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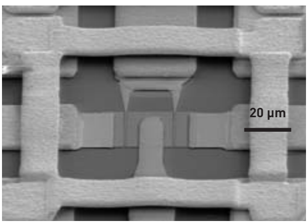
Carbon nanotube based transistor, self-assembled and electrically connected during its synthesis.

Carbon Nanotube Nanocomponents

CNRS is using the exceptional properties of carbon nanotubes to devise nanometric electronic components. One of these properties is the ability of electrons to propagate within a carbon nanotube as far as the junction with the metal without experiencing any electrical resistance (the resistance occurs from the junction). By applying an electrostatic field to an electrode close to these contacts, it is possible to modulate this resistance in the case of a semiconducting nanotube. These junctions then become ultraminiaturized field effect transistors. By functionalizing these contact surfaces by chemical means, sensors of unrivalled sensitivity can also be produced. Another particularly interesting property is that carbon nanotubes are very efficient electron sources. They open up new possibilities for field emission devices such as, for example, the production of flat screens.



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Coplanar integrated circuit on a III-V heterostructure (in this case indium phosphide).

III-V Nanoelectronics

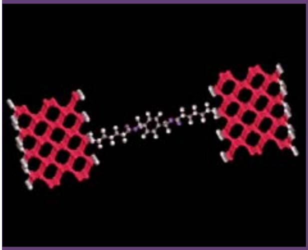
The reduction in the dimensions of electrical circuits and the excellent electron transport properties of III-V heterostructures (consisting of two elements from columns IIIb and Vb in the Periodic Table), make it possible to envisage the design and fabrication of devices operating in the "terahertz/picosecond" range. The growth of these heterostructures is now fully mastered. As early as the end of the 70's it was demonstrated that the use of these materials would greatly improve the performance (speed, power and consumption) of field effect transistors or bipolar transistors. Thanks to modern lithographic processes, it is possible to fabricate III-V heterostructure transistors whose working frequency approaches the terahertz (1.000 gigahertz) range. III-V nanocomponents have many industrial applications in the field of ultra high-speed communications.

Nanoelectronics

Molecular electronics is a subject of increasing interest. It offers the possibility of building low-cost high-density electronic circuits and proposing new functionalities that are difficult to produce using traditional semiconductor based technology. A molecule can fulfill two roles in the field of nanosciences and nanotechnologies. It can be an active component or a "tool box" for the programmed fabrication of nanoobjects and nanocomponents.

Electrical Conduction in Metal-Molecule-Metal Junctions

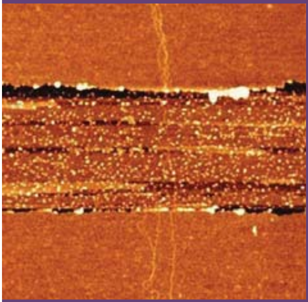
It is now possible to connect a molecule to two metal wires thanks to tunneling microscopy or electronic lithography techniques. Researchers can thus measure the electronic conduction of the metal-molecule-metal junction. At this scale, the conduction phenomena are quantum mechanical. Thus, before using molecules as electrical conductors, it is necessary to understand their nature and the link between the structure of the molecule and the transport properties. Research conducted in collaboration with the CEA has highlighted the importance of the chemical bond that is created between the molecule and the metal. These experiments make it possible to conceive of electronic components that take advantage of the richness of chemistry and could integrate computation functions in a single molecule.



Example of a metal–molecule–metal junction.

DNA Conduction, Myth or Reality?

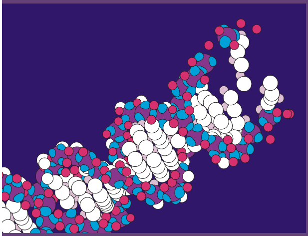
In the search for nanometric conductors, DNA molecules are of very special interest. They are easy to manipulate, can be spread across a surface and offer self-assembly properties that can be used to design self-organized nanocircuits. However, experiments on electrical conduction in the DNA molecule have produced highly contradictory conclusions since some have shown that DNA is a conductor, while others indicate that it is a semiconductor or a perfect insulator. A group of CNRS researchers has measured an electrical resistance of DNA on the order of 100 kilo-ohms per molecule at room temperature, which corresponds to the best conduction currently observed for DNA. They demonstrated that, in these experiments, not only is DNA a conductor down to low temperatures, but also that transport is then consistent from a quantum point of view over a distance of a hundred nanometers. However, the debate continues, and CNRS is now seeking to characterize and control the environment and structure of the molecules studied, in order to understand the reasons for these divergences.



Strands of DNA laid on platinum contacts separated by an insulating slot.

DNA, a Tool Box for Nanosciences

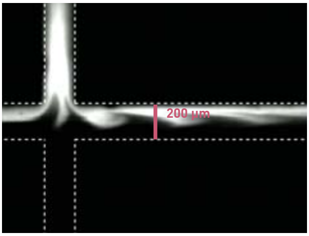
Since Watson and Crick, we have known that DNA consists of two strands linked in a double helix. Each strand consists of a sequence of molecules that can only associate itself with its complementary sequence. This unequivocal molecular recognition is used by several CNRS teams to link, associate and position nanoobjects in a programmed manner. In this case the DNA is not used for its electrical properties, which are controversial, but as an aid to constructing nanoobjects (programmed nanofabrication) or as a molecular template. By attaching a nanoobject on a DNA sequence, researchers are able to hook this nanoobject precisely onto the complementary sequence and in this way produce numerous nanometric scale constructions.



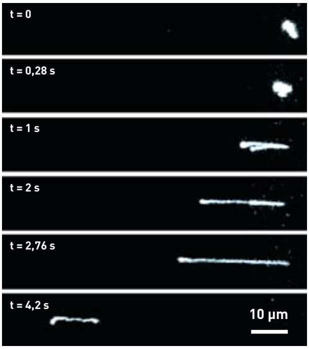
Structure of a DNA molecule.

The Advantages of Nanotechnologies for Microfluidics

New technologies are currently used to fabricate micrometric and nanometric sized systems. The nanosciences make it possible to create miniaturized multifunctional systems with spectacular uses in many fields, such as biology, analytical chemistry and chemical engineering.



Flow in a cross-shaped mixer.



Conformation changes in a DNA molecule colliding with a nanocolumn of magnetic particles during electrophoretic separation.

Nanosciences for Microfluidics

Microfluidics have been designated by MIT (Massachusetts Institute of Technology) as one of the ten technologies likely to revolutionize the twenty-first century. The control of material and heat flow in microsystems may make it possible to produce very complex systems, comparable with those produced by nature. Such systems may be capable of many new tasks, not only in reducing consumption of chemical products, energy and space, but also in optimizing efficiency and allowing mobility of experimental setups. This is the key issue in "labs-on-chips", destined to generate major economic activity in the years to come.

Two processes for producing microfluidic devices are under development at CNRS. The first is micromachining, an offshoot of the microelectronics industry, in which microfluidic components are etched into a silicon or a glass wafer. The second consists of sculpting the components of a device out of polymer or elastomer. The choice of technique depends on whether fast prototyping or high-density nanostructures are required. Finally, it is often necessary to cover sidewalls using molecular self-organization. The boundary between the nanometric and micrometric scales remains extremely porous in the field of microfluidics.

Artificial Gels

One of the major challenges in microfluidics is the development of analytic microsystems for biology and medicine. Nanotechnologies make it possible to produce nanoscopic structures, within micrometric devices, that are adapted to the scale of the molecules to be analyzed. Thus, two CNRS teams, one affiliated with the Institut Curie, have developed artificial gels, created by reversible self-organization of magnetic nanoparticles. In these media, it is possible to separate large molecules of DNA in a few minutes, compared with twelve hours or so using traditional methods. The teams are now extending this approach to cell sorting.

Other types of artificial gels based on self-assembled polymers have also been developed and applied to the detection of mutations causing predisposition to cancer, in collaboration with the Institute's hospital.

Nanotechnologies and Microfluidics

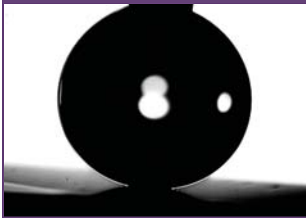
Thanks to microfluidics, researchers can integrate systems capable of analyzing, modifying or synthesizing products onto a glass, silicon or plastic chip. This is the "fluidic" equivalent of electronic microchips that carry out numerous operations on streams of electrons.

The Magic Carpet Effect: Carbon Nanotubes for the Walls of Microchannels

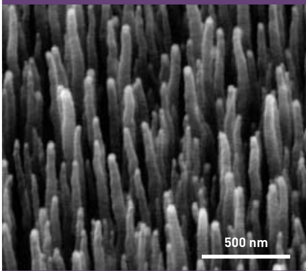
Nature is a constant source of inspiration in the quest for innovative technological solutions. Many plants have developed remarkable surface properties, such as super-hydrophobicity, which prevents water drops from spreading across their surface. These properties have their origin in complex micro- and nanostructures on the surface of the leaves: the liquid is unable to penetrate the crevices and surface tension forces hold the liquid suspended, as if on a magic carpet of nails! Using this observation and its technological facilities, CNRS is producing super-hydrophobic surfaces structured at the nanometric scale, in collaboration with the Université Lyon 1. These surfaces have a considerable number of applications in microfluidics, where one of the major challenges is the design of innovative solutions for moving and manipulating small quantities of liquid for use in chemical and biological analysis. The interdisciplinary approach encouraged at CNRS, at the interface between nanotechnologies, microfluidics and surface physics, has led to an innovative and original solution to the problem of large-scale production of nanostructured surfaces. It consists of using directional catalysis to grow carpets of carbon nanotubes directly on a support. When treated chemically, these surfaces become super-hydrophobic and make it possible to transfer and displace fluids in microchannels.

Microreactors and Nanosciences: Reciprocal and Complementary Development

Microreactors are micrometric cavities that harbor chemical reactions. Their size makes it possible to produce and monitor a large number of chemical reactions simultaneously on a small surface. These microreactors are essential elements of a "lab-on-chip". Nanosciences have brought many improvements to the field of microreactors, in particular by covering the inside of microchannels with catalytic molecules. Conversely, these chemical reactors have become the preferred tools in the nanosciences. They allow flows to be controlled locally and mixtures to be closely monitored, which are the essential conditions for the synthesis of new nanomaterials by precipitation, crystallization or supramolecular chemistry. New devices, known as microstructured reactors, are beginning to emerge. They are integrated microfluidic macrosystems for industrial production. The move from the laboratory to production generates new multi-scale research, necessary to the industrial future of these nanotechnologies.



Drop of water deposited on a super-hydrophobic surface. It does not spread out and thus retains its spherical shape. The surface consists of a carpet of carbon nanotubes.



Electron beam microscope image of a nanotube carpet.

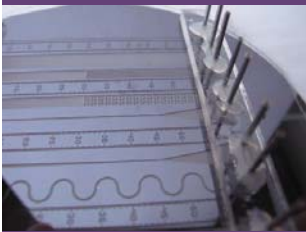


Plate with microchannels of different geometries for studying the separation of gaseous and liquid phases during the confined boiling of a liquid.

Inventing Nanomaterials

Context and Issues

The commitment of CNRS chemists to the development of new methods for synthesizing materials or objects structured at the nanometric scale is resulting in a veritable revolution in their way of thinking and working.

By generalizing from the methods of supramolecular chemistry, the first area of chemistry to reach the nanometric scale, researchers are producing new materials by acting directly on their innermost structures. While they already knew how to synthesize single nanometric molecules and produce organic materials at macroscopic scale, they are now able to construct materials molecule-by-molecule and even atom-by-atom. In these nanosynthesis processes, it is possible to control precisely the structure of the products. This level of control makes it possible to obtain "zero-defect" or even "controlled defect" objects, when the presence of defects is at the origin of desired properties. Certain three-dimensional structures, such as spheres, tubes, complex geometrical volumes, which were hitherto impossible to construct reproducibly and at large scale, are now being produced at CNRS. Nanovolumes of this type are already used as decontaminants for complex media, as transporters for directing medicines to precise targets, and even as microreactors allowing products to be prepared in a clean, pollution-free and with very little energy consumption.

The new methods of synthesis, such as metallurgical or self-organization processes, make it possible to assemble and organize a large number of nanostructures and thus obtain nanomaterials with astonishing macroscopic properties. Their nanometric scale structure gives rise to new properties that can be explained through increasingly powerful modeling and simulation procedures.

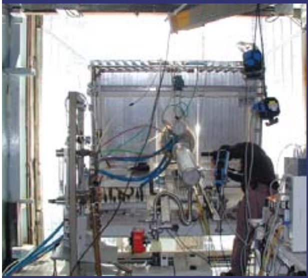
The production of nanomaterials and nanoobjects, thus, is clearly a new field of exploration for science, a factor for progress for humanity and within an optimistic vision of the future of mankind guided by sustainable development.

Synthesis of Nanoobjects

Certain nanoobjects have exceptional properties that enable researchers to invent the materials of tomorrow. However, their production still remains small in volume. CNRS is investing in the development of methods of large-scale, efficient synthesis of these key components for nanomaterials.

Synthesis of Carbon Nanotubes

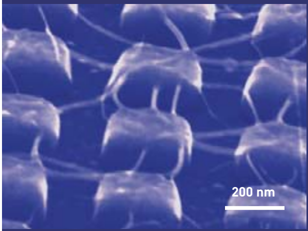
The low weight and solidity of carbon nanotubes make it possible to increase the strength of materials without increasing their weight. As individual molecules, carbon nanotubes will be extremely valuable in nanoelectronics. It will, however, be necessary to produce them in sufficient quantity and quality. CNRS is exploring several channels for synthesizing nanotubes to make mass production possible: by arc discharge between two graphite electrodes, by graphite evaporation under laser irradiation and by chemical reaction of a carbon-containing vapor using a metal catalyst. This latter method makes it possible to place a semiconductor nanotube in very precise contact with electrodes. It is therefore particularly well-suited to nanoelectronics and is already used to produce flat screens. Another original process for synthesizing molecules containing carbon uses concentrated solar energy. Carbon nanotubes are obtained from vaporizing graphite mixed with metals at high temperatures (over 3.000°C). This technique also makes it possible to obtain closed carbon molecules out of graphite, some of which are spherical in shape, namely fullerenes.



Carbon nanotube synthesis reactor in the large solar furnace in Odeillo, during an experiment (viewed from the focus cabin).

Dendrimers: Modular Nanoobjects

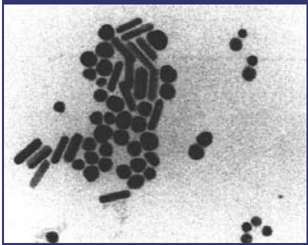
A dendrimer is a giant tree-structured molecule prepared by repeating a sequence of reactions that allow successive layers to be constructed (called generations) around a central core. Once a certain number of generations has been reached, the dendrimer generally takes on a spherical shape with a large number of branches and various chemical functions in its periphery. The synthesis strategies, particularly those developed at CNRS, allow numerous functional groups to be grafted on. This tailor-made preparation uses clean chemistry, with no toxic by-products. It allows a large number of innovations in the fields of biology, medicine and catalysis. In particular, it allows new nanomaterials to be produced and surfaces to be modified. Thanks to the support of CNRS, several French teams are pioneering in this field.



Carbon nanotubes self-assembled by growth around silicon towers.

Synthesis by the Colloidal Method

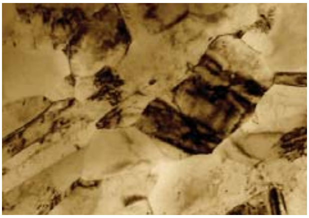
A CNRS team has developed a simple physico-chemical method for synthesizing nanoobjects. In a non-polar solution such as oil, certain so-called surface-active molecules have the ability to form droplets or interconnected cylinders several nanometers in length. These droplets, or colloids, protect the macromolecules (enzymes, proteins...) that they contain from solvents liable to denature them. Subject to Brownian motion, they move around randomly within the solution. When two colloids collide, their contents mix together and a nanoobject is formed. They are thus used as nanoreactors capable of controlling the size and shape of the nanoobjects synthesized within them. A wide variety of organic or inorganic materials of various shapes can be synthesized in this way (nanotubes, silver nanodisks etc.)



Interconnected cylinders.

Production of Nanostructured Materials

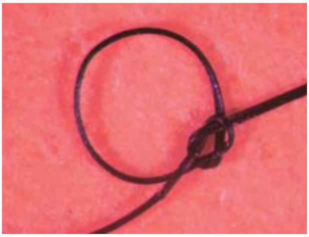
The new tools of nanoscience make the composition and internal structure of materials accessible to researchers, who are now able to structure matter at nanometric scale.



Grains of nanostructured copper measuring approximately 100 nm observed with transmission electron microscopy.

Nanometals, the Example of Nanocrystalline Copper

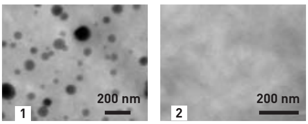
Nanocrystalline copper is used in microelectronics but is also a reference for the study of nanometals. It is produced by assembling nanoparticles of copper synthesized by the vapor condensation technique. Its fabrication requires compaction, heat treatment and pressurized densification stages developed by pooling scientific and technical expertise from the fields of chemistry, physics and process engineering. This nanomaterial displays astonishing mechanical properties: not only is it three times harder than conventional copper, it is also highly susceptible to plastic deformation. The production of materials from nanometric particles opens up new possibilities for highly interesting applications in the shaping of materials at room temperature.



Nanotube wire.

Carbon Nanotube Wires

CNRS is working on a wide range of methods for producing individual nanotubes. However, their exploitation for materials composed solely of nanotubes for highly innovative applications, such as ultraresistant materials, sensors and electromechanical actuators, remains a technological bottleneck. CNRS is developing various lines of research to meet this challenge. Among these studies: a process for manufacturing continuous nanotube wires that are aligned and, thus, ideally organized to take advantage of their electrical and mechanical properties. These wires are much stronger than existing high-performance fibers. They can also be used as microelectrodes for biosensors or as electromechanical actuators with highly promising properties for use in robotics and medicine.



1 EVA/Si(OR)^4 reticulation-free hydrolysis; 2 Hybrid organic-inorganic material. Transmission electron microscopy images (4% silica by mass after full hydrolysis of the precursor).

Nanostructured Polymers

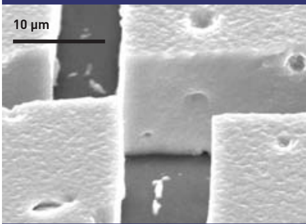
Researchers in a CNRS-Université Lyon 1 laboratory have developed a new way of synthesizing hybrid organic-inorganic materials that is pollution-free, as it requires no solvents. It is thus possible to generate, in a polymer network, an inorganic phase consisting of 5 nm diameter silica particles, instead of the usual hundred nanometers. The production of these materials is not limited to thin films; it is also possible to obtain large objects. This new technique can also be used to synthesize isolated particles a few tens of nanometers in diameter. These nanostructured materials open up countless possibilities. It is easy to imagine processes that will make it possible to obtain transparent and fireproof or conducting materials whose consistency (flexibility, rigidity etc.) may be defined at will.

Production of Nanostructured Materials

Under appropriate conditions, certain nanoobjects can structure themselves spontaneously into large networks: this process is known as self-organization. This is a particularly promising field of research for producing macroscopic materials from elementary nanoobjects. Understanding and controlling the mechanisms of self-organization are therefore essential challenges for the nanosciences.

Self-organization of Inorganic Nanocrystals

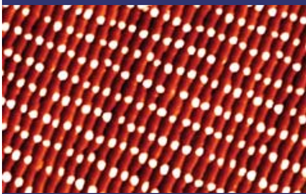
Nanocrystals are crystals whose grain size is of the order of a nanometer. This small size gives them a very large contact surface with their medium. The resulting specific properties, particularly their high level of chemical reactivity, are of both fundamental and practical interest. Under various conditions, the nanocrystals can self-organize, leading to artificial solids (supercrystals) whose physical properties are neither those of the individual objects nor those of the bulk material. Each nanocrystal influences its neighbors and the assembly has characteristics that are said to be collective. The organization of nanocrystals into a supercrystal influences their electron transport properties. Also, they can vibrate coherently and the dipolar interactions between the particles induce specific optical and magnetic properties. Supercrystals can coalesce into large single crystals at low temperatures, thus opening up a new avenue for crystal growth. Moreover, organized nanocrystal patterns, such as rings and lines, are resistant to etching and can be transferred to a silicon support, where they are useful for nanolithography.



Supercrystals of 5 mm diameter silver nanocrystals, organized over a long distance in a face centered cubic lattice.

Self-organization on Crystal Surfaces

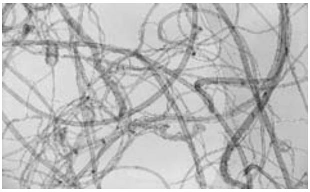
In the race to produce ever-higher data storage densities, a revolutionary approach would consist of recording a magnetic bit on a magnetic nanostructure. In order to do that, regularly-distributed nanostructure lattices are required. The self-organization of nanostructures on naturally pre-structured materials is a simple and economical nanofabrication technique. Instead of etching thin layers by lithographic techniques, individual atoms are deposited on a material with periodically-distributed receiving sites. A network of nanomesas with a surprising level of regularity in size and spacing can thus be produced in a single step. A CNRS team has obtained, for example, a system of cobalt atoms deposited on a reconstructed surface of gold, thus realizing an assembly of high-density (26 terabits/inch^2) magnetic nanoparticles several nanometers in diameter (0.4 nm high), without interaction and presenting a narrow magnetic energy distribution. This massively parallel bottom-up approach, opens the way to new investigations of the physical properties of structures at the nanometric scale.



Self-organized growth of cobalt (in white) on a gold surface, viewed using a tunneling microscope.

Mechanical Properties of Nanostructured Materials

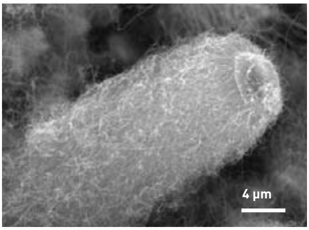
The nanometric dimensions of the components of a material give rise to new properties while still obeying the laws of conventional chemistry. This is an open door to the discovery of as yet unexplored properties.



Carbon nanotubes seen using a transmission electron microscope.

Nanomaterials and Particle Nanoreinforcements for Composites

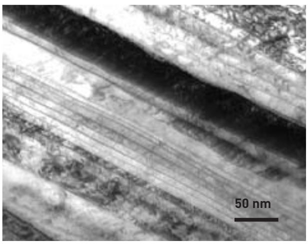
Polymer-based composites are generally reinforced using fibers with a diameter of around 10 µm. Using certain nanometric-size reinforcements, multi-functional composites can be obtained with original mechanical, electrical, optical (transparency) or surface properties. The reinforcements can be spherical (silica, carbon black), in slabs (clays) or fibrous (cellulosic nanofibrils, carbon nanotubes). In these materials, the typical distance between reinforcements is comparable with the dimensions of the macromolecules in the matrix, and this gives them remarkable mechanical properties: they become more rigid. In certain cases, they achieve considerably higher rigidity than conventional materials.



Carbon nanotubes grafted on to micrometric reinforcements.

Carbon Nanotubes for Reinforcing Polymer Matrices

Carbon nanotubes have 100 times the tensile strength of steel and are good electrical and thermal conductors. These extraordinary properties have given rise to the idea of reinforcing polymer-based materials to alter their mechanical, electrical, optical or thermal properties. The selective production of nanotubes and their integration into composites are problems on which CNRS is currently working. While paying particular attention to safety when handling them, researchers are working at combining reinforcements of various dimensions. The resulting reinforcing effects are achieved by associating phenomena at different scales. A major CNRS contribution to improving the safety and performance of composites consists of grafting carbon nanotubes onto micrometric reinforcements. The assembly becomes much less volatile and easier to use for reinforcing polymers.



Transmission electron microscope view of the microstructure of strongly wiredrawn steel.

Strongly Wiredrawn Steel Wires

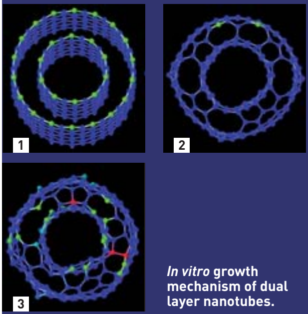
Very strongly wiredrawn steel wires (wiredrawn by passing through a wiredrawing die) can achieve exceptional levels of mechanical strength (around 5.000 MPa), better than those of carbon fibers. They can then be used for the fabrication of cables as well as for synthesizing composite materials. Understanding the origin of these mechanical properties is a major challenge, as it is recognized that one of the main reasons for their appearance is the nanostructuring of the material during wiredrawing. Some of the research undertaken by CNRS is centered on the study of the mechanism involved in the plasticity of these fibers. Thanks to various physical techniques (transmission or scanning electron microscopy), mechanical tests and digital models, researchers can now describe the microstructure of these fibers at nanometric and micrometric scales and thus can better understand the origin of their very high strength.

Modeling and Simulation

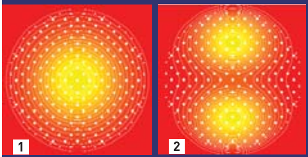
Understanding phenomena observed experimentally relies on theoretical modeling. The nanosciences employ a whole range of numerical and theoretical methods, not only to describe nanoobjects or molecules within a quantum framework, but also to account for their macroscopic behavior. Relying on new advances both in theoretical physical chemistry and on the exponential growth in computer power, CNRS laboratories are deeply involved in the development of these methods.

Simulation of the Structure and Growth of Nanoparticles

The characteristic size of nanoobjects makes it possible to simulate directly the individual movements of the atoms that compose them. It has thus been possible to predict the formation, structure and composition of existing or imagined nanoobjects using modeling. Even before it is measured, the effect of size on the mechanical and thermal properties of nanostructures can be calculated and the main microscopic mechanisms can be identified. Concerning thermal properties, this work has already been used, particularly at CNRS, to increase the density of memories, to improve the thermoelectrical conversion power in the cooling of microprocessors, as well as to produce the most thermally insulating materials in existence.
Another important example of the benefits of numerical simulations is the understanding of the growth mechanisms in nanoparticles, nanowires and nanotubes. As their morphology (size, symmetry etc.) has a radical effect on their properties, it is crucial to understand which factors (temperature, catalysts etc.) influence the growth of nanoobjects and favor a specific shape. Experimentally, it is often impossible to observe *in situ* the dynamic mechanism involved in their formation. By simulating the growth of nanoparticles with a computer, it is possible to visualize these mechanisms at the atomic scale and understand the reasons for the formation of materials with specific properties. This information is also very valuable for inventing new synthesis strategies.



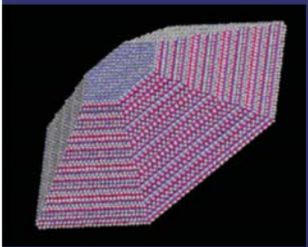
***In vitro* growth mechanism of dual layer nanotubes.**



Wave function of an electron in a nanocrystal of indium arsenide.
1. Ground state.
2. Excited state.

Calculation of the Electronic Properties of Nanoobjects and Nanomaterials

Numerical simulations are also essential for searching for new applications for the physical properties (electronic, optical, mechanical or chemical) of nanoobjects. Their nanometric size makes it possible to solve their basic quantum mechanical equations and thus to simulate directly the system's electrons. These equations can be solved either using *ab initio* methods based on the elementary principles of physics with no adjustable parameters, or by semi-empirical methods based on simplified physical models with a few adjustable parameters. These tools make it possible to study the response of nanomaterials to external excitations (electric field, optical excitation). Their integration into complex device simulations is meant to result in the direct simulation of an entire system starting from its description at the atomic scale.



Modeling of quantum dots of gallium nitride (GaN).

Context and Issues

After the great controversies that have shaken our societies in the last twenty years, such as the issue of genetically modified organisms, the nanosciences are beginning to invade the public forum through new high-profile debates. The globalization of trade, the proliferation of new literary fiction, alliances between science, industry and defense, and social movements with humanist aspirations, all contribute to the emergence of major debates about likely and desirable visions of the future. Research institutions, companies and governments may become embroiled in these immense controversies.

Research into the nanosciences will lead to the emergence of technologies endowed with capacities for learning, communicating and storing data as well as a greater energy self-reliance. Societies will soon have to come to terms with these new objects from the legal, ethical and political point of view. These technological innovations, though sources of progress, will also be sources of apprehension. How can these burgeoning controversies be handled? Their entry into our daily life will lead to the transformation of important aspects of life in society, to the development of new practices and to the creation of new sociotechnical networks. What legislative, professional and economic changes are needed to be ready to take advantage of these nanoresources?

A source of fear for some, of hope for others, sometimes a bit of both, this new field requires a free and open ethical reflection at the very heart of CNRS. In 2004, the CNRS Science Ethics Committee (Comets) promoted reflection on the ethics of nanosciences. By interviewing personalities involved in nanoscience research and by considering the ethical aspects of nanoscience, the Comets is forming its own ethical vision of the field and, through dialogue and listening, is fostering awareness among both CNRS personnel and members of the National Committee that evaluates research.

Nanosciences in Society

CNRS sociologists, political scientists and economists are deciphering the nanosciences, their organization, their possible risks and how they are perceived by the various social players.

Nanosciences and Macrorisks?

Should we be afraid of what "nano" represents? We have been living with nanoobjects for thousands of years, without knowing it, for example in inks, dyes and other pigments. Yet the emergence of new technologies always raises questions that sometimes take on a dramatic appearance. This is also the case with nanotechnologies, when they are exploited to make up catastrophic scenarios that spell out the end of life on earth. The philosophical and ethical questions raised (among others, respect of privacy and defense of the environment) must be studied calmly, without unwarranted alarm. There are always risks associated with new technologies introduced by man. Scientists involved in nanoscience, aware of these fears, have already begun studies to quantify some of these risks (toxicity, carcinogenic and mutagenic aspects, environmental pollution etc.) CNRS sociologists and political scientists have already developed expertise on the emerging risks and major controversies. This research is directed towards the regulatory mechanisms called for by these social concerns. CNRS participates in national and international structures (national ethics committee etc.), and the reflection carried out by these bodies aims to provide clear and objective answers to these questions.

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A Great Upheaval in our Way of Life

Rejection or apprehension of objects derived from the nanosciences is not only based on their perceived risks or novelty. Very specific new questions are raised. The nanosciences will soon make it possible to miniaturize everyday objects, so that some objects may even become invisible to the naked eye. This disruption of our traditional perception of the world may be accompanied by questioning. How can we optimize the man-machine interface? How can we trust an object that is going to affect us, but over which we have no direct control? Another vital question: nanometric monitoring systems could improve the traceability of products, but will they not also be a potential threat to personal freedom? For all these reasons, CNRS is paying particular attention to encouraging upstream reflection and debate between the various social, scientific and political players and the general public.

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The Dynamics of Knowledge Production and of Innovation

What is happening in the field of nanotechnologies is an example of a dual phenomenon of territorial concentration and networking of scientific and technological expertise. It is a major phenomenon in the history of science and technology: after the age of large equipment and major technological programs, then the emergence of scientific cooperative networks, comes the age of scientific and technical districts. Researchers at CNRS, sociologists, economists, political scientists, but also managers and geographers, are trying to understand this phenomenon of territorialization of the sciences and the corresponding economic dynamics.

Nanosciences and the Training-Research-Innovation-Industrial Transfer Continuum

The International Year of Physics, in 2005, is an opportunity to show young people, tomorrow's work force, the benefits of science. An important fact: universities, schools and, above all, laboratories are deeply involved in dispensing appropriate training to young scientists, future researchers, engineers, technicians and teachers, and giving them access to the sanctuary of the clean room, which was for so long reserved only to microelectronics professionals. In this field as in others, this commitment is vital for the development of scientific jobs. The supply of highly-qualified human resources is a determining factor for major companies when they decide whether to be spread out into various regions of France (like Alliance Motorola, Philips, STMicroelectronics, Altis) or to remain in a single location. In parallel, the development of the academic research network, *C'Nano*, should be strengthened, since *C'Nano* will become an integrating instrument capable of responding to regional and industrial decision-makers, while maintaining national coordination.

Is the explosion in the nanosciences due solely to the enthusiasm of researchers, who see in them a new frontier to explore? The answer is no. The San Francisco conference (1-3 June 2005, *1st Int Nano. Conf.*) highlighted the American, Japanese and European convergence, expressed both by the initiators of academic programs (NSF etc.) and by the microelectronics industrial associations. Investments in the nanosciences concern two thirds of American companies listed on the stock exchange and more than 600 start-up firms.

Are we still in an exploratory research phase with its share of uncertainties? The answer is uncertain. For the most part, yes, but with major breakthroughs in microelectronics, such as spintronics. The discovery by Albert Fert (CNRS gold medal in 2003) at the end of the 80's of giant magnetoresistance, the fertile cradle for spintronics and for its more advanced and quantum form, TMR (*Tunnel Magnetoresistance*), has made it possible, 15 years later, to produce some tens of billions of hard disk drives annually.

The training-research-innovation-transfer continuum, highly visible in the field of micro- and nanoelectronics, a leading field for accepting rapid technological transfers as soon as they become compatible with existing heavy technologies, will find other application sectors, taking longer to implement, but less dependent on the technological substrate. Health, particularly the fields of diagnosis and medicine delivery; safety, with sensors deployed just as easily in automobiles as in the other tools of human life; transportation; nomadic power (distribution or creation). These are all fields in which the demand is potentially high. The nanodevice, essentially passive today, active tomorrow and in interactive stackings the day after tomorrow will be produced through a massively parallel approach, like the transistor, and thus be reliable and cheap. The social acceptability of the nanosciences will, of course, depend on the cultural substrate, but also on their intrinsic force of innovation, as is the case today with cell phones, which are in the hands of over 2 billion men, women and adolescents.

CNRS pays particularly close attention to the development of scientific collaborations with European laboratories of international reputation. The pursuit of this objective takes several forms. Firstly, the support given by CNRS to the formation of an Eranet on nanoscience: this novel network concept, created by the European Commission to promote the coordination of national programs, aims at launching common calls for transnational collaborative proposals, in ten or so European countries, and evaluating them by a European panel of experts. The role of CNRS within the "Nanoscience Concerted Action" program of the French Ministry of Research was a determining factor in the implementation of this innovative instrument within the European scientific community, despite the difficulties arising from the wide variety of support procedures for nanoscience in the countries participating in the Eranet.

Of more immediate concern is the creation of Associated European Laboratories (LEA) such as the one between the "Institut d'électronique, de microélectronique et de nanotechnologie" (IEMN, CNRS-Université Lille 1-Université de Valenciennes-ISEN) and the Université catholique de Louvain (UCL). The aim of this laboratory, called the European Microelectronics and Microsystems Laboratory (LEMM), is to develop a strong collaboration in microtechnologies and microsystems as well as in advanced components and materials for use in nanoelectronics. Nanomagnetism is the subject of another LEA between the Laboratory Louis Néel (LLN, CNRS) in Grenoble and its counterpart at the *Max-Planck Gesellschaft* in Halle.

At an intermediate scale, the *C'Nanos*, established in 2004 and 2005, are the optimization and coordination tools needed by the French laboratories and constitute partners of choice for the other European regions at the forefront of nanoscience.

According to all estimates, particularly those coming from the other side of the Atlantic, the economic stakes of nanoscience are very high and varied. The experimental and theoretical know-how, the technologies involved, the coordination with and among companies, start-ups or microelectronics consortia, determine the extent to which sharing and pooling will take place in these new sectors of knowledge. In order to have the development of knowledge in the nanosciences bear fruit rapidly and in various forms, CNRS is determined to be a driving force in creating new channels for exchange and new spaces for sharing scientific and technological knowledge with other European scientific organizations.

A Few Indicators

- Worldwide investment*: 9 billion dollars annually.
- U.S. budget: 3 billion dollars per year, including 1 billion dollars from the federal government, of which 65% is earmarked for academic research (14% from the National Institutes of Health, 31% from the National Science Foundation, 24% from the Department of Defense).
- Total European effort: approximately 1 billion Euros per year, of which 700 million Euros from European national budgets and approximately 300 million Euros from the 6th Framework Program of the EU.
- Overall, the budget of FP6 for the "Nanosciences and Nanotechnologies" priority is 1.3 billion Euros over 5 years.
- 166 laboratories associated with CNRS are working in the field of nanosciences, out of a total of 190 French laboratories identified by the Eranet.
- Consolidated budget: 150 million Euros annually for CNRS-associated laboratories.
- Personnel: 3.500 researchers, engineers, technicians, academic staff and Ph.D. students active in these laboratories, including 1.000 full-time CNRS researchers, engineers and technicians.
- Total area of clean rooms in the national facilities: 6.000 m^2.

*according to the American National Nanotechnology Initiative program

Pour en savoir plus :

Visit the French Ministry of Research website on nanosciences:
www.nanomicro.recherche.gouv.fr/uk index.html

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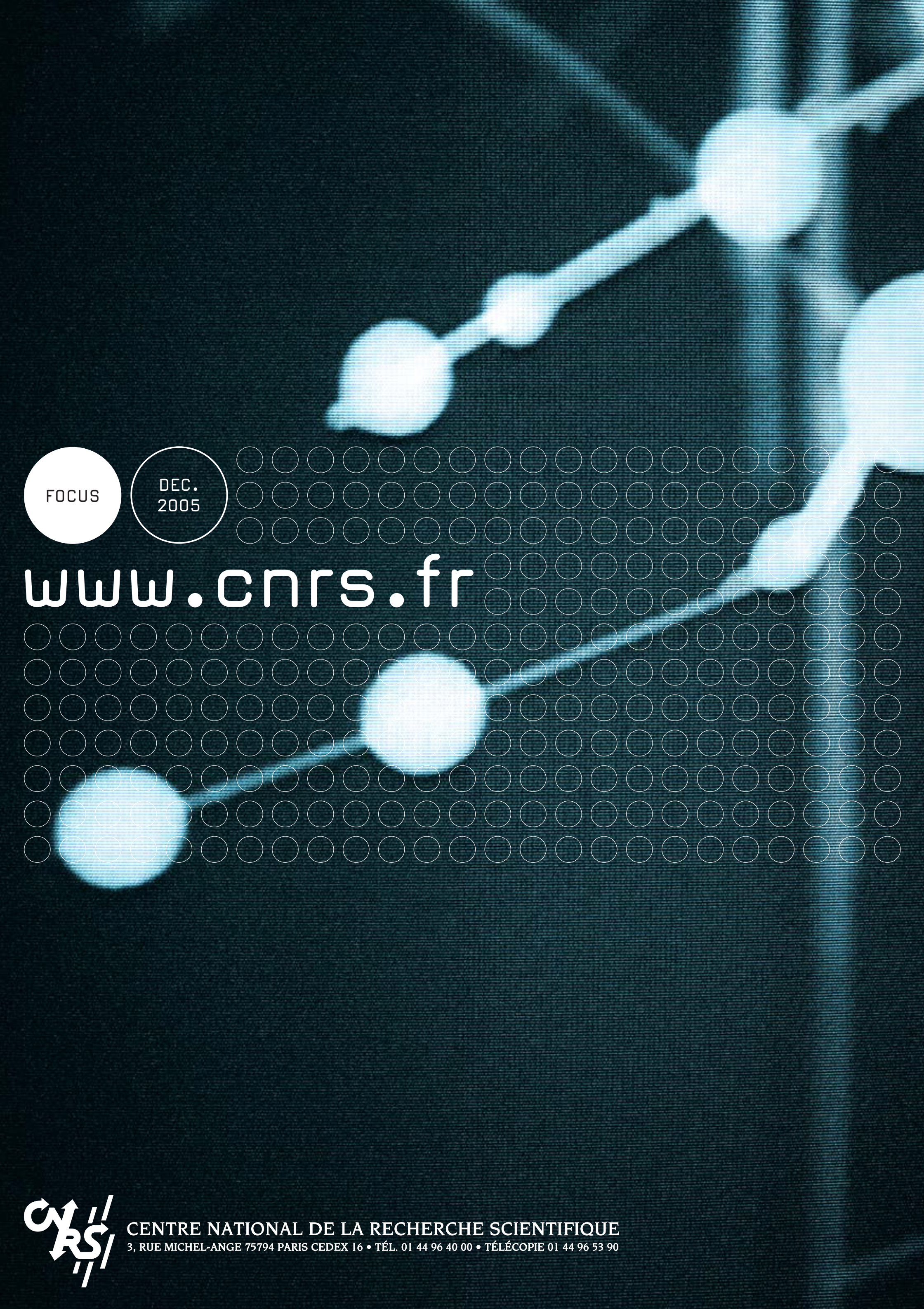

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