3rd Joint EC-NSF Workshop on Nanotechnology

Nanotechnology

Revolutionary Opportunities & Societal Implications

Lecce (Italy), 31 January - 1 February 2002

The Workshop has been hosted by the Regione Puglia and the National Nanotechnology Laboratory of the Istituto Nazionale per la Fisica della Materia (INFM)

EUROPEAN COMMISSION

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Research Directorate-General

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Preface

The early 21st century may come to be seen as the start of the nanotechnology revolution. While we must beware of hype and oversell, it is clear that nanotechnology is already beginning to have an impact on everyday life, and its impact is likely to grow very rapidly in the near future. Public interest in ‘nano’ and its societal implications is strong. In a recent New York Times article, reporter Barnaby Feder describes the rising commercial and industrial stake in nanotechnology[1]. Feder notes that a global report on nano released in March 2002 by CMP Cientifica, a Spanish research company, is “a snapshot of an explosion” according to the chief executive of CMP. While current sales of nanocomponents are estimated at a modest $ 30 million (€ 34 million) a year or so, Feder reports an estimate from Nanomat, a European nanotechnology consortium, that products using nanomaterials generated sales of € 30 billion ($ 26.5 billion) world-wide last year. These numbers are rising quickly.

Materials research is a global activity. The need for international co-operation in pre-competitive materials research, and in nanoscale science and engineering research in particular, is also becoming increasingly apparent. No one country or region of the world has a monopoly on the cutting-edge research capabilities necessary to advance materials science and nanotechnology. Research groups in different countries and regions can bring complementary expertise to solve common problems for the ultimate benefit of society as a whole. The experience gained by students and senior investigators working together across national boundaries will be invaluable for advancing materials and nanoscale science and technology in the future.

The European Community and the National Science Foundation have a common interest in encouraging and fostering international co-operation in science and engineering generally, and in materials research and ‘nano’ in particular. Consequently they are sponsoring a series of workshops addressing key themes in nanoscale science, engineering and technology. This report summarises the outcomes of the third of these workshops, hosted in Lecce, Italy, by the Regione Puglia and the National Nanotechnology Laboratory of the INFM (Istituto Nazionale per la Fisica della Materia). Participants in the workshop - an eclectic mix that included scientists, engineers, sociologists, philosophers, journalists and managers from academia, industry, business and government in both the United States and Europe - explored the technical, educational and ethical implications of nanotechnology for both European and American society. The results open a fascinating window onto the societal implications of nanotechnology, and they provide a rich source of ideas for co-operative US-European efforts as well as guidance for further co-operative international activities in this critical area of science and technology.

W. Lance Haworth, National Science Foundation
Ezio Andreta, European Commission

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[1] Tiny Technologies Slip Unseen Into Daily Life (New York Times, March 11th 2002)

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SUMMARY

Approximately 70 participants from the EC and US attended the workshop, which comprised three technical sessions and a poster session. An introductory session laid the foundation for the workshop. In the US, the National Nanotechnology Initiative (NNI) has provided a mechanism for various funding agencies to collaborate in nucleating and enhancing research efforts across a broad spectrum of technical, educational and social issues related to nanotechnology. A comparable level of vitality characterizes nanotechnology in the EC, supported through government initiatives in many focus areas, such as electronics and photonics. Efforts in both the EC and US increasingly involve extensive collaborations across traditional disciplines and embrace academe, industry, and government. Summarized below are some of the highlights of the technical and poster sessions. The summary is meant to be illustrative rather than exhaustive. More detailed information may be found in the summaries prepared by individual speakers and poster presenters.

Future Technical Opportunities in Nanotechnology

Increasingly, materials can routinely be prepared with control at the atomic level, leading, in many cases, to novel properties. Furthermore, an expanding array of tools has become accessible for characterizing nanoscale materials. Examples presented at the workshop demonstrated the importance of defects, the appearance of quantum effects, and the limitations of bulk scaling laws and physicochemical descriptions that define nanoscale science and technology. Nanoparticles, for example, can exhibit very different physical properties, such as melting point and magnetization, compared to bulk forms of the same material. Layered nanostructures can be exploited to create more efficient light sources that have already impacted lighting and display industries on a global scale. Nanoscale alloys, nanocomposites and nanoporous membranes may lead to better catalysts and separation methods. Such advances could have an enormous impact on energy conversion, storage, and utilization. Carbon nanotubes provide an example of the challenges and opportunities associated with nanoscale materials. While these materials show great promise for creating, e.g. new types of field emission displays and supercapacitors, the ability to make particular nanotube structures and thus to determine structure-property relationships has not yet been achieved.

The interface of nanotechnology with life sciences has the potential to revolutionize medicine and healthcare. A new era in biotechnology and biomedical engineering is emerging with use of nanoscale structures for diagnosis, gene sequencing, and drug delivery. Biocompatible nanomaterials may afford more robust artificial tissues and organs. Nanotechnology holds promise for enabling us to learn about the detailed operation of individual cells and neurons, which could enable us to re-engineer living systems.

Exciting opportunities exist in the construction of nanomachines. Single-molecule devices that facilitate motion, computation, transduction, and communication have the potential to create entirely new nanoscale infrastructures. Likewise, nanoscale electronics coupled with information technology can fundamentally change our society. As far as we have come in information technology since the days of ENIAC, a comparable leap remains to be made to the ultimate computational limits achievable through nanotechnology. Such advances could have societal impact that transcends what we have experienced thus far.

Educational Implications of Nanotechnology

Its multidisciplinary nature makes nanotechnology a challenging field for recruiting and training the technical workforce that is needed and for educating the public as to its significance. Recruitment of students to careers in nanotechnology underscores the importance of presenting the exciting advances that characterize this field. Results and images from cutting-edge nanoscale science and technology, and new demonstration and laboratory experiments, kits, software and websites based on nanotechnology are examples of mechanisms for attracting students to this field. These instructional materials can be introduced into the curriculum even at the earliest stages of schooling.

Traditional, disciplinary-based education will continue to be of great value in supporting nanotechnology, but both EC and US educational systems are adapting to promote educational opportunities in this field. Efforts to eliminate barriers between traditional disciplines in academe, caused by differences in terminology and culture, are underway at many universities in the EC and US. Graduate students and postdoctorals have effectively served as bridges to link faculty across disciplines. Partnerships of academe, industry and government around nanotechnology educational initiatives are also being developed. Re-training programs for current members of the technical workforce have been initiated.

Reaching the public is another important aspect of nanotechnology education. Mechanisms for working with the print and electronic media to provide accurate descriptions of nanotechnology are needed. Informal nanotechnology education can be accomplished through websites and through community presentations and museum partnerships, to name a few examples.

Societal Implications of Nanotechnology

A broad, burgeoning field like nanotechnology invariably raises new issues of concern to society. Of particular concern to the public will be nanotechnology's impact on life sciences and on the environment. Nanobiotechnology could dramatically improve public health, but there is already considerable concern that technical developments could cause adverse effects that are unforeseen. "The revenge of unintended consequences" is a common feature of new technologies, whose inventors are not always able to predict how a change in one system can affect other systems. Better models for the coupling of complex systems are needed so that harmful consequences can be anticipated and avoided. In a similar vein, as large-scale manufacturing of nanomaterials occurs, the environmental impact of these materials needs to be determined. Advantages associated with nanoscale manufacturing include use of less material and energy and production of less waste. However, evidence for transport and uptake into living systems of nanomaterials has been obtained, and early studies suggest that there may be harmful effects on living organisms. Studies are needed to determine what environmental and health risks are associated with nanomaterials.

Ethical issues associated with nanotechnology represent another area of concern to society. The invisible nature of nanoscale materials has already fed fears that nanotechnology will lead to a significant invasion of privacy. Prospects of microlocomotion, autonomous operation, and self-replication have fueled additional concerns that such a technology could spin out of control with dire consequences for society. Mechanisms to address these concerns and to sort out what is real from what is imaginary are needed. Promising strategies that have been implemented in the EC are scientific cafes and consensus conferences. In these venues, scientists meet with citizen groups to discuss implications of new scientific discoveries. Such meetings have the potential to build communication and trust between the public, policymakers, the media, and the technical community.

Conclusions and Recommendations

The workshop revealed that the EC and US nanotechnology communities face common technical, educational, and societal challenges that would benefit from enhanced collaborations. Some specific recommendations that were noted during the workshop:

- Mechanisms for exchange of personnel should be expanded, as this can benefit both EC and US communities by sharing technical skills and unique instrumentation.
- Models for technical workforce recruitment and training that are compatible with the US and EC educational systems are needed, as are models for professional development. These could be developed collaboratively.
- There are opportunities in the application of nanotechnology to energy usage, protection of the environment, information technology, and biotechnology that can be promoted through EC-US technical partnerships. Moreover, the connection of these applications to commercial opportunities and public policy is an area that is ripe for joint exploration with industry and government.
- New collaborations should be developed in education. Joint development of instructional materials based on cutting-edge nanotechnology that could be used in both the EC and US, throughout the educational system, could be facilitated through visits by graduate students, postdoctorals, and faculty.
- Support for new initiatives that bring the technical community in contact with the media and other deliverers of informal science education such as museums and science centers should be promoted.
- Expansion of mechanisms that encourage a dialogue with community groups should be supported and evaluated to determine how this can be accomplished most effectively.

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SYNOPSIS OF THE DISCUSSION

Background

In this Workshop, seventy scientists in various disciplines, educators, communicators, sociologists, philosophers, journalists, and public administrators from the EU and the USA met and discussed scientific/technical challenges and societal implications of nanotechnology. Participants had a high degree of specialisation in their respective fields, but the debate was structured following a holistic approach.

In particular the objectives for this Workshop were:

- examination of the developments in nanotechnology and the perspectives in the next decades, as well as the interface of nanotechnology with the environmental technologies, energy, information technologies, materials science, and biotechnology;
- consideration of social, ethical and political issues associated with nanotechnology;
- integration of nanotechnology into the education and into outreach activities;
- similarities and differences in the structures of the American and European societies with respect to the development and impact of nanotechnology.

Nanotechnology presents itself as a “revolution” that will shake industry and society, inducing major changes during the next decades. Indeed, nanotechnology is identified as one of the mega-trends for science, technology, research and education in the new century. Information for the public as well as perspectives for future development are needed to understand where we are going and, in particular, where the allocation of public funds is concerned.

The Workshop did not aim at drawing conclusions, but rather to contribute to the development of a debate and a methodology, and to analyse the role for the EC-NSF co-operation that can have relevance and impact, the EU and USA being major players in nanotechnology at the world level.

Scientific and Technical Issues

The present ability to understand, operate and control matter by humans has greatly progressed, but it is still limited. Nanotechnology offers the possibility of making a major "jump" in this sense. The scientific and technical challenges connected with nanotechnology are huge. They cross at the same time: materials, (inorganic, organic, biological, hybrid), architectures, concepts and processes.

Nanotechnology will allow much better comprehension of Nature, opening a new world of products with enormous market possibilities. In fact nanotechnology is not a new discipline, but a new approach, based on well-established scientific disciplines (e.g. physics, chemistry, and biology) and applied sciences (e.g. engineering and mechanics) and can permeate, enter and re-orient virtually all domains.

Working at the nano-scale will enable us to approach the ultimate in miniaturisation, which is of interest to achieve materials, products, components, devices, systems, and processes that are characterised by: less space, less material, less energy, less impact on the environment, and should also be more effective, faster and safer than today’s solutions.

Scientific and technical roadmaps are needed to better focus research and development efforts targeting major social demands and avoid any possible barriers. However, it is difficult at present to define a single roadmap for nanotechnology. The possible applications in different areas can originate from developments that are unexpected today.

More knowledge on fundamental phenomena is still needed. The field has not yet matured to initiate detailed roadmaps, since they would be of little reliability. Nevertheless, we already know enough to have macroscopic predictions, and it would be not be wise to leave all development to chance.

As with some other technologies, nanotechnology may grow exponentially and may reach a point of saturation and/or meet its physical (or other) limits. Whatever the ultimate outcome, there is no doubt we are presently on the growth side of the curve.

When looking at the past decade of research and development, electronics emerges as probably the field where nanotechnology has progressed the most, as well as the world of nanoparticles. Health, medicine, drug delivery, and structural materials are of particular interest to society. Biocomputing and molecular motors are highly challenging and promising. Sensors are highly demanded for everyday practical use (security, safety, etc.).

"Information" is a physical quantity and follows the laws of physics. At the same time, this indicates the dimensions for improvements and limitations. It is possible to build computing devices that would be billion times more efficient than those that we have today. We do not know yet how to do that, but we know that making things smaller helps a lot. The perspective is that nano(10^{-9})-level can allow reaching the peta(10^{15})-bites level of operations per second in tomorrow's computers.

A frame of reference for the level of control that we have today comes from observing Nature. Indeed, the most powerful computers can nowadays reach the number of operation per unit of time that characterise an insect; that is orders of magnitude inferior to those, e.g. done by a warm-blooded intelligent being such as a mouse, and more orders of magnitude less than a human being.

Two great challenges for nanoelectronics are to develop new switching devices and to develop new fabrication processes. More innovation can come when looking at the architecture: we may need to reinvent the computer, not the transistor. Self-assembling wires of 2 nm width and 9 nm distance separation are already a reality. The combination of silicon structures and molecular electronics may open the way for solutions of impressive potential.

In general, a much higher integration and new levels of compatibility can be achieved to have a new type of user-friendly intelligent facilities/goods in an environment where people can interact and have much richer communication and benefits. Facilities of common use such as houses, cars, shoes, spectacles and so on can be re-conceived to obtain beneficial interactions that will increase enormously the level of “service” that they offer today.

The potential of nanotechnology applied to catalysis and local reactions (lab-on-a-chip) is one of the fields of development that directly comes to mind. Applications in sensing are a particularly important field of use, e.g. for high sensitivity detectors to improve security, check quality of food, improve health, and protect us from accidents and terrorists' attacks.

The drive toward a sustainable development, and, in particular, toward the conversion/storage/production of energy from renewable sources can receive a new start from nanotechnology and nanostructured materials. This may occur first of all for marginal improvements (e.g. for solar cells, fuel cells and the use of hydrogen), but also for substantial innovations thanks to the opportunity to reconceptualise products and processes. Nanotubes are, for instance, one of the most fascinating fields of research with many potential applications, even though these materials still require solutions to significant technical problems and lowering of their high cost.

Nanobiotechnology, drug delivery systems and biomedical engineering can be highlighted as main fields of research and development. With a touch of paradox, one may argue that biology itself is a natural nanotechnology, characterised by atomic/molecular precision, self-assembling, etc. Consequently, medicine and health are privileged fields for research, development and applications, first of all for, e.g. novel biological building blocks, self-assembling properties, functional nanostructures, consolidated materials and hybrid systems. Nanotechnology could also play a central role in treating diseases much earlier thanks to specific sensors and devices.

Biomolecular analogues offer challenging perspectives with huge potential, such as molecular computation, optoelectronic devices and bioelectronics. Electrophysiology and anatomy on single cells combined with nanotechnology can allow identification and exploitation of functions. Single cell analysis and treatments can be imagined. Genomics, proteomics, transcriptomics and metabolomics can have a powerful impetus. Physicophysics is another fascinating field of application that would allow, e.g. images to be processed and seen by blind people.

Enabling technologies to move detection and manipulation to the single atom/molecule are indispensable. Instrumentation and metrology are thus priority fields of development. Research and development effort should address microscopy and other powerful techniques, such as mass spectrometry.

Molecular motors are among the most fascinating areas opened. Proteins allow building of complex, functionalised molecular structures. Can we operate single-molecule machines? If so, for what purposes? How do we supply energy to them? Generally or locally? How do we control their energy supply? Research will have to encompass computation, organic chemistry, multi-step organic techniques, sublimation, analytical techniques, molecular manipulation, control and many other ancillary techniques.

Better performing goods and services and improved communication can greatly contribute to quality of life, to personal satisfaction, to development of business as well as to democracy. Generalising from electronics, one can say that hardware is making big jumps, while software is at present not being improved at the same speed, perhaps because software has to interface with people.

Constant attention and appropriate priority should be granted to metrology and instrumentation. The tragedy of September 11th has obviously brought up security issues.

More Knowledge, More Power, More Responsibility

History teaches us that a reflection on new technologies is a wise pre-requisite for their use since it helps avoid unexpected negative consequences, which have characterised the introduction of many new technologies (“unintended consequences”).

Moving into the nano-world will allow virtually total, absolute control of matter, i.e. control at the level of the single atom or the single molecule. Novel properties, phenomena, and processes will be made possible. Countless domains may be influenced with improved performance to better people’s lives.

But does nanotechnology present risks? In particular, is there any additional or special risk in comparison with the usual impact of any new technology? Substantially, no. The possible potential negative effects that could be irreversible within the time required for developing a countermeasures was debated, but no particular negative features were identified.

The debate is ongoing. In the USA a dedicated workshop has been held on initiative by NSF and its proceedings issued in the book "Societal Implication of Nanoscience and Nanotechnology"[1]. In the EU, discussions about the ethical implications of nanotechnology have also started, e.g. in Germany and Denmark. Future initiatives will allow a better understanding of implications that may arise from nanotechnology (basically in the bio-medical fields) toward the ethical values embodied in documents, such as the Bioethics Convention of the Council of Europe and the European Charter of Fundamental Rights.

Nanotechnology by itself does not affect human dignity and integrity. However, some of its applications can present some risks, as for all technologies. More attentive monitoring and control has to be enforced in the fields where technology meets the human body, such as in biomedical applications.

Is there a problem of fairness and technocratic power? As a matter of fact, nanotechnology requires advanced infrastructures and scientific/technical background. In reality, big human tragedies have mostly not been caused by advancing technology. It is, however, true that a lot of science is needed "to make the thing", but very little technology is needed "to push the button". Information, communication and education play a major role in applying scientific advances to address societal needs.

In his first book of ethics, Aristotle indicated that through knowledge people can possess truth. Then, for making good and evil, people's intentions are determinant: if we want to help or harass neighbours, we will use any possible instrument that accordingly becomes a tool or a weapon. Public understanding with regard to nanotechnology is needed for nanotechnology to achieve its full potential. In view of the intellectual challenges originated with nanotechnology, mechanisms for enhancing science literacy have to be explored at all levels of education, from primary school to secondary school and university and for continuous training of the workforce concerned.

There should be a focus on fundamental research, on a policy of inclusions and partnership, recognising the importance of vision, preparing the workforce for nanotechnology, addressing broad humanitarian goals, and transforming strategies.

As for any technology, risks of inappropriate or even dangerous development may exist. Adequate transparency in research is needed and a safe set of rules has to be set in place. The absence of control may result in irresponsible or even dangerous results, but unmotivated prohibitions would be counterproductive. Researchers might flee and constitute "technological paradises" in countries where less or no controls are enforced. Indeed, unlike nuclear energy, nanotechnology (as well as electronics, biotechnology, genetics, etc.) are developed by private companies, substantially outside direct public control. Public power, through politicians and public opinion, should have the cultural instruments and access to appropriate qualified expertise to assess, steer and -where appropriate- control developments.

[1] Kluwer Academic Publ., 2001; the report is posted on http://nano.gov/nsetrpts.htm.

The risk and the perception of risk may also not be aligned. Speculative scenarios and even science fiction situations could be studied as models for hypothetical developments or as tests for public reactions, but should be distinguished from predictable developments.

During the Workshop, it was elaborated that negative projections or worries that nanotechnology may stimulate very often derive from the possible combination of the following characteristics:

- invisibility of nano-entities,
- autonomous locomotion,
- self-replication.

None of this exists. Literature reports new theoretically possible lifeforms, autonomous and self-replicating, but this is only science fiction. However, sociologists warn that even if the construction of such entities/machines/beings might be impossible, from a sociological perspective they already "exist". Indeed, the perception of risk can exist even if the risk itself does not, and vice versa. Consequently, analysis and communication based on rationality are indispensable.

Moreover, the three above-mentioned characteristics above refer to carbon-based chemistry, being e.g. relevant to viruses and studied under genomics. Thus, nanotechnology tools and approaches may be adopted, but substantially these aspects stay outside the development of nanotechnology as we intend it. In fact, we may regard life itself (first of all the viruses) as "natural nanotechnology"…

Another fear debated was: What happens if computers become intelligent? We have to think about this and probably we just do not know enough yet. However, maybe the problem is that we still do not understand enough about the human brain and we may need to agree about the definition of "intelligence".

Many other possible problems will have to be addressed, e.g. filtering the nanoparticles. Will nanomaterials released in the environment be inert? Many nanoparticles are not biodegradable and colloid-mediated transport can lead the nanomaterials to unforeseen environments. What about their lifecycle? What will be their behaviour, e.g. upon sorption/desorption, biotic uptake, and aggregation? What about toxicity, catalysis, and their accumulation in nature, especially in higher organisms? What about inhalation risks? Is there a possibility of respiratory problems? Would ingestion cause concentration in the liver? Would there be inflammation and tissue damage? Would there be any auto-immune diseases?

"Earlier is better". At present we can just speculate that nanomaterials will not be inert. Dedicated research would be beneficial and requires a highly interdisciplinary research environment, including environmental engineers and medical doctors. And the public should constantly be informed.

An improved dialogue has to be stimulated between scientists and groups of stakeholders, opinion-makers and interested people in broad sense. The public should be given factual elements to differentiate between science and science fiction. The fear of risks should not impede progress and prevent benefits from being generated. But the search for quick commercial benefits should also not hide the realistic risks that should be considered. Rigorous and systematic studies are indispensable. Transparency and the possibility of a broad debate are also a must.

Science fiction can exert a positive effect as a way to gauge people's possible reactions to nanotechnology. Science fiction can thus play a role in communication between the public and scientists in their joint development of technologies that will shape our common future.

The scientist is a citizen and science is one of the most powerful instruments that people have to improve their quality of life. An example can come from the demand after September 11th: more security is required. Will this additional security reduce personal freedoms? If so, to what extent should this happen?

Nanotechnology will generate positive and negative effects: new industrial opportunities, but also decline and even extinction of some industries. More knowledge of nature will result, but also a possible “nanodivide” will occur, a distinction between those who understand the new technological approach and those who do not. This “nanodivide” could be exacerbated if considered at a global level, as a separation between countries or geo-economic areas.

Attitudes toward science are mixed: there is confidence that science and technology are progressing quite rapidly, but uncertainty about “where are we going”. Both optimistic and pessimistic visions exist. Indeed, there are many examples in which technologies generated benefits to society, but at the same time created accidents or serious disadvantages. For instance, controlled adjustment of nanostructured materials and their properties is promising to reach improved properties, but at the same time this has to be carefully investigated, since modifications induced may also have unexpected negative effects. Transparency, research and surveillance will ensure our ability to recognise negative outcomes before they occur.

Nanotechnology is a new frontier with few sheriffs. Transparency and systematic studies are needed. Support for social and economic research studies on nanotechnology should become a priority. New legal problems may also arise, e.g. concerning the ownership of successful generations of nano-systems and devices.

Scientists have been described as a “tribal culture” that is largely unknown to the public. Surveys shows public interest in science and technology, and a substantially optimistic view of them, but with a broad degree of variations. There is also a wish for scientists to listen to the public and to work for their benefit, not only for the economic benefit of a restricted number of industrial or financial operators. The relationship between scientists and the media could also be improved. The scientific community considers sensationalism as a main source of distrust of the media. Informing the media is an important need. Appropriate initiatives should be launched in this respect. Co-ordinated or joint initiatives by the EC and NSF could be particularly effective.

Panels of citizens and panels of experts can establish a dialogue in interactions with a dedicated advisory group and eventually create reports of value to governments and the public. This would greatly facilitate listening to citizens and creating a consensus. The fact that topics can be technically complex should not deter discussions about social and ethical implications of the technology.

Both *élites* and the general public should be addressed with appropriate communication vehicles. There is not “one public”, but “many publics” with various expectations, feelings and priorities. There is a call for a Socratic model of science and technology: all voices should be heard.

As recalled before, nanotechnology has the specific characteristic of working at the first level of organisation of atoms and molecules, and the nano-approach is able to interpret phenomena at micro- and macro-level in the human-scale world. Experts can make nanotechnology accessible to the public through a variety of hands-on demonstrations and analogies.

Creating the "Nanotechnologist"

Physics, chemistry, biology, engineering and even sociology are the rivers that shall feed the *mare magnum* of the nanotechnologist's education and skill. A different education system seems needed. There is a need to develop and scale up models that promote interactions across traditional academic disciplines.

Virtually in every discipline and research and development program there can be -where appropriate- a "nano" approach that can embrace nanoscience and nanoengineering.

Observation, analysis, interpretation, abstraction and prediction skills can be developed in primary and secondary schools to stimulate future interest for the intellectual challenges of science and research. Nanotechnology awareness should be introduced throughout the scholar education enterprise at all levels. Kits and other instructional materials could greatly help students develop interest and confidence in nano-science and technology.

As noted above, the new generation of workforce of scientists, engineers and technicians must have a broad background in physics, chemistry, biology and engineering as well as in the basic principles of manufacturing and control. Specialists need to reach beyond their immediate expertise and develop a common language and modes of interaction for making possible an integrated exploration of nanotechnology.

Nobody can become a specialist in everything, of course. Moreover, to prepare individuals who are specialists in all disciplines would take too much time, cost too much and probably even destroy the creativity that scientists need to have. Valuable inputs come from specialists, but a multi-disciplinary, inter-disciplinary environment is indispensable and all have to understand each other. This affects thus both the background education of the single researcher and the team building or networking of the groups.

Putting together scientists of different background is not *per se* a solution. To be able to work together, they will have to share concepts and languages with a new common approach: "nano". There is an "activation energy" associated with this process, but successful experiences have already occurred.

At present, there is not only a problem of "quality" of the nanotechnologists, but also of their "quantity". In proportion of the penetration and impact of nanotechnology into industry and society expected during the next years, the quantity of available skilled operators is by far too limited. An adequate workforce is required.

Equipment for nanomanipulation is also expensive and relatively scarce. Sharing equipment as well as non-competitive knowledge seems in the short term an appropriate solution to be realised through stronger interactions (e.g. within the EC-NSF co-operation), sharing of information, and developing models to create the required multidisciplinary culture. Scientific hubs are needed to share knowledge and technological hubs to share equipment. Networking and virtual teams can be a successful mechanism. Co-operative or joint multi-disciplinary research centres are another possible way. As a metaphor, one can say that the molecules are there, but we need the architecture and more interactions. One can assume that Ph.D. students still define the most appropriate training level. An easy way of interacting still needs to be developed, but problem/project-based learning has proved to be very effective and motivating. Mobility, also involving foreign students, is obviously of paramount importance.

Who leads now? The university more than industry. However, there are collaborations that occur, such as situations where the industry provides facilities and the university carries out experimental work.

It can be said that nowadays, nanotechnology is fashionable and may be a powerful attraction element to reverse the decline of students in science and technology in the Western world. The scientific and technological challenges of nanotechnology can stimulate the taste for science and research in youth. The first nanotechnology diploma programs have been launched, and we can assume that these will attract high quality young scientists. The next few years will hopefully validate this assumption.

Apart from recruiting young people, continuous training should be considered. For the older existing workforce, reorientation, summer schools, and workshops could be launched. Mid-career post-doctorates could be a powerful tool. For all the above, the EC-NSF co-operation could be an important incubator.

However, in providing support for nanoscale science and engineering, funds for international co-operation should not receive special priority over competing projects. International, overseas co-operative proposals should compete on a “level playing field” with all others. Quality and potential impact of research should always prevail.

EC, NSF and NNI

Beneficial critical mass can be reached in co-operation between the EU and the USA. Co-operation is now facilitated by co-ordination: in Europe by the European Commission (EC) and in the USA by the National Science Foundation (NSF) through the National Nanotechnology Initiative (NNI).

The EU and USA are leaders in nanotechnology. For research, the EU and USA budgets represent the majority share of the total R&D investment in nanotechnology world-wide.

The NNI counts 15 agencies and federal departments, with a total federal public funding of 604 M$ in fiscal year 2002 and a request to Congress of 710 M$ for fiscal year 2003. Research funds are focused on fundamental research and several long-term science and technology “grand challenges” (see the overview of NNI in the proceedings). The announcement of NNI in USA in 2000 has stimulated nanoscale research world-wide.

In the EU one can estimate some 200 M€ public funding in 2001 and a rise to 300-350 M€/year in the next years. The proposals for the Community 6th framework program (currently in its inter-institutional debate) give high priority to nanotechnology and can mobilise funds of the order of magnitude of 1 billion € to be devoted to nanotechnology over the period 2003-2006. These funds will complement the financial means that are set available by the European States under national research and education programs.

EC programs will give priority to funding long-term research projects that are oriented toward more knowledge-based materials, products, components, devices, systems or processes. One thematic priority area addresses specifically nanotechnology with four broad themes: nanoscience, instrumentation/nano-manipulation, nano-manufacturing, and applications. New instruments will also be introduced, such as integrated projects and networks of excellence. Research projects could include education as well as activities addressing societal aspects and diffusion of information.

There is room for important, effective co-operation between EC and NSF through existing schemes, with the adjustments needed to facilitate joint initiatives and actions in the common interest. There should be scheme of actions and measures to address possible unforeseeable, undesirable consequences.

In particular, it would be ideal to have co-operative or parallel projects in critical areas, according to the nature and progress of the development: research, education, communication, and interaction with public. A two-way communication is needed, with democratic modes of interaction and the involvement of *rerum naturae* and social scientists.

Particular attention should be paid to nomenclature. Many terms come from various established disciplines and it is important to find unequivocal terms and meanings. Simplicity should be kept as a goal in order to avoid creating confusion. There was general agreement that there is no need to create new words, apart from exceptions to be analysed on a case-by-case basis. The prefix "nano-" before the usual terms is normally enough. A new jargon is not needed and would complicate communication, increasing the nano-divide.

Websites

In Europe www.cordis.lu/nanotechnology
In the USA www.nano.gov & www.nsf.gov/nano

Note

This synopsis does not necessarily represent a consensus of the visions and opinions of all participants in the workshop. The two-day discussion led to various positions that could not be reported in their entirety in this short text.

EC-NSF Co-operation in the Field of Materials Science Research

3rd EC-NSF Workshop on Nanotechnology

Nanotechnology:

Revolutionary Opportunities

and Societal Implications

KEYNOTES

The Action Plan of the U.S. National Nanotechnology Initiative

Mr Mihail C. Roco, Chair, U.S. Nanoscale Science, Engineering and Technology Subcommittee, NSTC, White House and NSF Senior Advisor (USA)

Towards a European roadmap for nanotechnology

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THE ACTION PLAN OF THE U.S. NATIONAL NANOTECHNOLOGY INITIATIVE

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ABSTRACT

The vision of novel phenomena, unity in nature, and promise of the most efficient manufacturing length scale has been essential in establishing the multidisciplinary National Nanotechnology Initiative (NNI). The research opportunities and projections of their societal outcomes have been integrated into a transforming strategy to yield the program announced in January 2000. This paper briefly outlines the motivation of this major investment, its systematic preparation since 1996, current activities in 2001, and key challenges for the future. Societal and educational implications play a key role in the initiative. Virtually all industrialized countries have initiated or have in advanced planning stages a national activity on nanoscale science and engineering stimulated by the NNI since 2000. This transforms nanotechnology into a field of broad international interest, increasing collaboration and stimulating competition.

Keywords: Nanoscience, nanotechnology, R&D strategy, societal implications, international perspective.

1 THE VISION

We know most about single atoms and molecules at one end, and on bulk behavior of materials and systems at the other end. We know less about the intermediate length scale - the nanoscale, which is the natural threshold where all living systems and man-made systems work. This is the scale where the first level of organization of molecules and atoms in nanocrystals, nanotubes, nanobiomotors, etc. is established. Here, the basic properties and functions of material structures and systems are defined, and even more importantly can be changed as a function of organization of matter via 'weak' molecular interactions.

We are beginning not only to see and touch matter at the nanoscale, but also to uncover new phenomena and envision manufacturing processes. Developing a strategy for a research and development (R&D) program of national and international relevance must be treated with at least the same rigor as the investigation of an individual research project. There are two main reasons why nanotechnology has received increased attention in the last few years:

a. The intellectual drive toward smaller dimensions, which was essentially enhanced by the discovery of new phenomena, properties and the manipulation capabilities at the nanoscale.

b. The promise of significant societal implications, which include better understanding of nature, efficient manufacturing techniques for almost every human-made object, a new world of products beyond what has been possible with other technologies, molecular medicine, and sustainable development leading to a cleaner environment. It is projected that $1 trillion products worldwide will be affected by nanotechnology in 10-15 years [1].

2 TIMELINE OF NNI

A planning activity at the national level to advance nanoscale science and engineering has been underway in the U.S. since November 1996 through an ad-hoc interagency Nanotechnology Group.

Nanotechnology was perceived as a dormant opportunity with immense potential. We felt that there is a tremendous potential for scientific and technological progress, as well as a generality and a unity in concepts among disciplines and areas of relevance that would stimulate intellectual advancement and economic developments. First, we have established a vision that is focused on the novel system behavior and manufacturability at the nanoscale and less on the advantages of smallness itself. This vision is applicable to all disciplines, involves potential contributors from all areas of relevance, and aims for long-term objectives.

Seed research funding limited to specific objectives or areas of relevance has been provided on a continuous basis at NSF starting with the Nanoparticle Synthesis and Processing initiative (focus on chemical processing, 1991- 2001, $3-4 million per year) and the National Nanofabrication User Network (with the original focus on miniaturization in microelectronics, 1994-2003, $4-5 million per year). In 1997-1998, NSF sponsored a multidisciplinary program entitled "Partnership in Nanotechnology: Functional Nanostructures" and in 1999-2000 the program on "Modeling and Simulation at the Nanoscale" (see http://www.nsf.gov/nano). The purpose of this program was to develop a knowledge base of the interplay of multiphenomena at multiscales by encouraging synergistic interaction among research groups with different areas of interest in nanoscale modeling and simulation. The goal was to support three to five groups, each focusing on a set of coupled phenomena over a few length scales and a set of methodologies. The intent of the overall initiative has been to support an assemblage of groups that cover a broad range of phenomena and processes in key areas. It has been expected that a synergistic relationship among the funded groups will develop over time.

The activities in U.S. and other countries were fragmented, nanotechnology had various definitions, and a unifying vision was needed. The White House National Science and Technology Council (NSTC) established the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in October 1998, in order to develop a vision, a strategy and a plan of action for advancing nanotechnology. The first activity was a workshop with a broad spectrum of about 150 leading experts in the field equally distributed among academe, private sector and government experts. The results were summarized in "Nanotechnology Research Directions: Vision for Nanotechnology in the Next Decade" [2].

On behalf of IWGN, I have proposed the National Nanotechnology Initiative (NNI) at the meeting on March 10, 1999 of the White House, Office of Science and Technology Policy, Committee of Technology. The proposed plan would ensure that the fundamental sciences and key technological opportunities of nanotechnology would reach their potential sooner, a flexible and balanced infrastructure and educated workforce would be available for nanotechnology development, and key technological grand challenges would be addressed (see “NNI: The Initiative and the Implementation Plan”, NSTC, 2000 [3]). After the NNI planning process was completed, NSTC has established the Subcommittee on Nanoscale Science, Engineering and Technology (NSET) in August 2000. NSET succeeds the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) as the primary interagency coordination mechanism. Its goal is to work toward NNI implementation, facilitate interagency collaboration for nanoscale R&D, continue to improve the vision for nanotechnology, and provide a framework for establishing U.S. R&D priorities and budget. The NSET will coordinate planning, budgeting, implementing, and reviewing the NNI to ensure a broad and balanced initiative. The Subcommittee is composed of representatives from agencies and White House officials with interest in the NNI.

The FY 2002 Budget request by President Bush is approximately $604 million (see Table 1), a 43% increase. The number of departments and independent agencies in NSET has increased from 6 in

2000 to 15 in June 2001. International developments partially stimulated by NNI have created an even broader impact than envisioned initially.

The nanoscale science, engineering and technology investment of all U.S. Federal agencies of $116 million in fiscal year (FY) 1997 has increased to about $190 million in 1998, $255 million in 1999, and $270 million in 2000 (NSTC, 2000). The report “Nanotechnology Research Directions” called for a national initiative in FY 2001 that would significantly increase the Federal government annual investment to about a half billion dollars. On November 18, 1999, the Presidential Council of Advisers in Science and Technology (PCAST) Nanotechnology Panel met to discuss the IWGN proposal and made a positive recommendation to the Administration. Then President Clinton announced NNI in January 2000 and submitted the NNI plan to Congress in February 2000 [4]. The White House, Office of Management and Budget (OMB) approved the NNI budget at the beginning of November 2000. A White House letter signed jointly by the OSTP and the OMB, which was sent to all agencies in late summer 2000, placed nanotechnology at the top of the list of emerging fields of research and development in the U.S. where agencies should collaborate. In October 2000, the U.S. Congress enacted the Federal nanotechnology investment portfolio of $422 for FY 2001. The FY 2002 Budget under President Bush is approximately $604 million (see Table 1).

The NSET members are from DOD, DOE, DOJ, DOS, DOTreas, DOT, EPA, NASA, NIH, NIST, NRC, NSF, USDA, and White House offices (National Economic Council, NSTC, OMB, and OSTP). The key challenges and opportunities of the NNI from the societal point of view have been addressed in a series of publication: “Societal Implications of Nanoscience and Nanotechnology” [1], "Nanoscience and Nanotechnology: Shaping Biomedical Research" [5], and “Nanotechnology - Shaping the World Atom by Atom” [6].

Table 1.
Summary of Federal nanotechnology investment in FY 2002 Budget Request (in million of dollars)

Department/Agency	**FY 2000** NNI Budget	**FY 2001** Enacted	**FY 2002** Request / Enacted
Department of Defense	70	110	133 / 180.0
Department of Energy	58	93	97 / 91.1
Department of Justice	-	-	1.4 / 1.4
Department of Transportation (FAA)	-	-	- / 2
Environmental Protection Agency	-	-	5 / 5
National Aeronautics and Space Admin	5	20	46 / 46
National Institutes of Health	32	39	45 / 40.8
National Institute of Standards and Techn.	8	10	17.5 / 37.6
National Science Foundation	97	150	174 / 199.0
US Department of Agriculture	-	-	- / 1.5
Total*	**270**	**422**	**518.9 / 604.4** (+ 43%)

(*) Figures are not available for five organizations that participate in the federal nanotechnology investment starting with January 2001: Department of Commerce (DOC), Department of State (DOS), Department of Treasury (DOTreas), NOAA, and Nuclear Regulatory Commission (NRC).

The key transforming strategy of NNI are:

- *Focus on fundamental research:* This strategy aims to encourage revolutionary discoveries and open a broader net of results as compared to development projects for the same resources.

- *Policy of inclusion and partnerships:* This applies to various disciplines, areas of relevance, research providers and users, technology and societal aspects, and international integration.

- *Recognize the importance of visionary, macroscale management measures:* It includes defining the vision of nanotechnology, establishing the R&D priorities and interagency implementation plan, integrating short-term technological developments into the broader loop of long-term R&D opportunities and societal implications, using peer review for NNI, developing a suitable legal framework, and integrating some international efforts.

- *Prepare the nanotechnology workforce*: A main challenge is to educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The concepts at the nanoscale (atomic, molecular and supramolecular levels) should penetrate the education system in the next decade in a similar manner to how the microscopic approach made inroads in the last forty-fifty years. It is estimated that about 2 million nanotechnology workers will be needed worldwide in 10-15 years [6].

- *Address broad humanity goals:* Nanoscale science and engineering will lead to a better understanding of nature, and improved wealth, health, sustainability, and peace.

3 2002 NNI PLAN OF ACTION

The NNI research and development priorities have been developed in consultation with experts from academe, private sector and government laboratories, as well as through the coordination of the funding agencies. This investment of $568 million is still a small fraction (0.6%) of the federal R&D budget. The main activities are:

- *Long-term fundamental nanoscience and engineering research* - NSF will make the largest investment in fundamental research of $199 million in FY 2001, or about 5% of its research budget. NSF programs embrace topics from chemistry, materials, molecular biology and engineering to revolutionary computing, mathematics, geosciences and social sciences. About 1,000 projects with over 5,000 faculty and students, and about 15 centers, will be supported in FY 2001. DOE, DOD, NIH and NASA also sponsor fundamental aspects of nanotechnology.
- *Grand Challenges* – areas where potential breakthroughs could provide major, broad-based economic benefits, as well as dramatically improve the quality of life. The FY 2002 has identified 11 areas of Grand Challenges (see NNI Implementation Plan, 2000). Nine areas for "grand challenges" are targeted by all participating funding agencies in the first year of NNI:

  - Nanostructured materials 'by design'

  - Nanoelectronics, optoelectronics, and magnetics

  - Advanced healthcare, therapeutics, and diagnostics

  - Nanoscale processes for environmental improvement

  - Efficient energy conversion and storage

  - Microcraft space exploration, and industrialization

  - Nanoscale instrumentation and metrology

  - Manufacturing processes at the nanoscale

  - Chemical/bio/radiological/explosive detection and protection

- Applications to economical and safe transportation

- Applications to national security.

- *Centers and Networks of Excellence* - will encourage research networking and shared academic users' facilities. These nanotechnology research centers will play an important role in development and utilization of specific tools, and in promoting partnerships in the coming years.
- *Research Infrastructure* **-** includes funding for metrology (measurement science), instrumentation, modeling and simulation, and user facilities. The goal is to develop a flexible and enabling infrastructure both in support of fundamental research and of U.S. industry's ability to commercialize the new discoveries and innovations rapidly.
- *Ethical, Legal, and Societal Implications, and Workforce Education and Training* - efforts will promote a new generation of skilled workers with the multidisciplinary perspectives necessary for rapid progress in nanotechnology. Nanotechnology's effect on society -- legal, ethical, social, economic, and workforce preparation -- will be studied to help identify potential concerns and ways to address them.

The NNI implementation plan in FY 2001 (October 2000 - September 2001) includes the proposed funding themes and modes of support by the U.S. funding agencies, as well as coordinated activities in order to increase synergism, avoid unnecessary overlapping, and create a balance and flexible infrastructure. Program solicitations for FY 2002 proposals have been issued by NSF, DOD, DOE, NASA, EPA and other agencies as part of the NNI implementation plan (full information is available on http://nano.gov). The NSF Nanoscale Science and Engineering program announcement (NSF 01-157) includes the research and education theme on "*Societal and Education Implications of Scientific and Technological Advances on the Nanoscale":* Exploitation of scientific and engineering advances at the nanoscale will impact society in expected and sometimes unexpected ways. Nanoscience is likely to enhance understanding of the universe, from living systems to astronomy. The development and use of nanoscale technologies is likely to change the design, production and use of many goods and services, ranging from vaccines to computers to automobile tires. In order to understand the scope and influence of these changes, and anticipate and respond effectively to them, research on the ethical, legal, social, economic and workforce implications of nanotechnology is necessary. Studies might include, for example: economic assessments and business models for nanoscale development and use; knowledge barriers preventing the adoption of nanotechnology by commercial firms; educational needs; life cycle assessment of manufacturing processes; the ethical and legal ramifications of nanotechnology in health, medicine, law, and the environment; an understanding of its diffusion patterns; how the public understands nanoscience and technology; and the implications of nanotechnology for everyday life. Each of the first five themes will emphasize the integration of research and education, including course development, student fellowships, and other aspects according to the nature of the project. This theme aims at a long-term vision for educational implications of nanoscience and nanotechnology. " Three workshops targeted on Societal and Educational Implications and one grantees workshop have reviewed these activities in 2000 and 2001: (a) "Societal Implications of Nanoscience and Nanotechnology", Workshop held at NSF in September 2000; published report by NSF and Kluwer Academic Publishers; (b) "Partnership in nanotechnology", NSF Grantees Conference, January 2001; and (c) "Converging Technologies (nano-bio-info-cogno) for Improving Human Performance", December 2001, at NSF. Nanoscale science and engineering educational activities sponsored at least partially by NSF in FY 2001 (FY 2001 funding at approximately $8 million) supported student fellowships and traineeships, curriculum development on nanoscience and engineering, new teaching tools, and studies on the socio-ethical-economic impact of nanotechnology.

4 FUTURE CHALLENGES

It is estimated that in 2001 we are at the beginning of the development curve where the rate of discovery is increasing and we need about five years to reach the rising sector of the classical "S" curve. In addition to technical Grand Challenges, other challenges for the advancement of nanotechnology must be considered:

- *Interdisciplinarity and unity in research and education*: Nanoscale science and engineering research is intrinsically interdisciplinary but it is performed in an academic environment that principally rewards individual performance. Creative approaches are envisioned in order to change the focus from single discipline to a system approach. The unity of principles in nanoscience, no matter the discipline and area of relevance, is another important challenge. At a larger scale, we look for increased synergism between nano-, bio-, info- technologies and social sciences with a focus on the human dimension.

- *Timely education and training:* The educational foundation in science and engineering will move from the microscopic to the molecular level. Changes in teaching from kindergarten to graduate students, as well as continuing education activities for retraining, are envisioned. An important corollary activity is the retraining of teachers themselves. Interdisciplinary fellowships in graduate schools are necessary. It is estimated that nanotechnology will enter our lives in a significant manner in 10-15 years. The availability of sufficient scientists and industrial experts is in question if we continue on the path adopted in the last years. One may consider changes in the way we structure the information on nanotechnology in order to improve learning and disseminate the results.[7] A five-year goal is to ensure that 50 % of research institutions' faculty and students have access to the full range of nanoscale research facilities, and access to nanoscience and engineering education for students is enabled in at least 25% of research universities.

- *Nanoscale manufacturing*: No research at the nanoscale can be performed without synthesis and processing of nanostructures and fabrication of nanosystems, and no nanotechnology would exist without developing economical approaches to large scale production of the same. Three new Grand Challenge areas that have been identified for FY 2002-2003 are: manufacturing at the nanoscale; nanoscale instrumentation and metrology; and chemical/bio/radiological/explosive detection and protection that has a key component on fabrication of sensors. Rudimentary nanostructures such as thin layers and nanoparticle dispersions have already made inroads in manufacturing. Important challenges are developing systematic methods for economical fabrication of three-dimensional nanostructures, establishing nanoscale manufacturing capabilities and the markets for nanotechnology producers and users. Another important challenge is establishing standardized, reproducible, microfabrication approaches to nanocharacterization, nanomanipulation and nanodevices.

- *Societal implications and continuing funding*: Societal implications include the envisioned benefits from nanotechnology as well as the second-order consequences, such as potential risks, disruptive technologies, and ethical aspects. Further long-term developments of the field depend on the way one addresses the 'societal challenges' of nanotechnology. The NSTC interagency subcommittee is actively seeking input from research groups, social and economical experts, professional societies and industry on this issue.

- *International challenges:* Virtually all industrialized countries have in development or have established a plan for nanotechnology at the national level in recent years (see for illustration [8], [9], [10]). There are good opportunities for win-win agreements in the precompetitive research areas. A synopsis of the worldwide developments shows different R&D areas of strength in each geographical zone [11]. The levels of nanotechnology government investments in Europe, Japan, U.S. and other countries have increased by about three times since 1997. Estimated government sponsored R&D in $ millions/year are shown in Table 2. The worldwide nanotechnology research and development (R&D) investment reported by government organizations has increased by a factor of 3.5 between 1997 and 2001, and the highest rate of 90% is in 2001.

	1997	*1998*	*1999*	*2000*	*2001*	*2002*
W. Europe	126	151	179	200	est. 225	
Japan	120	135	157	245	410 +140*	
USA	116	190	255	270	422	604
Others (~)	70	83	96	110	est. 380	
Total	*432*	*559*	*687*	*825*	*1,577*	

Table 2. *Estimated government sponsored R&D in $ millions/year (Note: "W. Europe" includes countries in EU and Switzerland; "Others" include Australia, Canada, China, FSU, Korea, Singapore, Taiwan and other countries with nanotechnology R&D. These estimations use the nanotechnology definition as in NNI (see [2]), and include the publicly reported government spending. (*) Japan has supplemented its initial $410 million nanotechnology investment in 2001 with about $140 million for materials including nanostructured metals and polymers.*

5 CLOSING REMARKS

I would like to close this brief overview of NNI with several comments regarding international collaborations in the future. Nanoscale science and engineering R&D is mostly in a precompetitive phase. International collaboration in fundamental research, long-term technical challenges, metrology, education and studies on societal implications will play an important role in the affirmation and growth of the field. The vision setting and collaborative model of NNI has received international acceptance, and most industrialized countries are establishing or are planning to establish their own programs. Opportunities for collaboration toward an international nanotechnology effort, particularly in the precompetitive areas, will amplify once those national programs are in place. An increased number of companies act globally with significant flow of ideas, capital, and people. This trend will accelerate and will be the environment in which nanotechnology will develop.

Priority goals may be envisioned for international collaboration in nanoscale research and education: better comprehension of nature, increasing productivity, sustainable development, and development of humanity and civilization. Examples include understanding single molecules and operation of single cells, improving health and human performance, simulation and measuring methods, assembly and fabrication tools for the building blocks of matter, highly efficient solar energy conversion and water desalinization for sustainable development. Societal and educational implications is an area with good potential for international collaboration, including the exploration of the revolutionary promises of the new technology on society, coordination of ethical and legal measures, and education of the workforce.

Acknowledgements

Opinions expressed here are those of the author and do not necessarily reflect the position of NSTC/NSET or NSF.

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TOWARDS A EUROPEAN ROAD MAP FOR NANOTECHNOLOGY

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1. INTRODUCTION

The border of nanotechnology, and hence its precise definition, are becoming more and more difficult to identify. As shown in Fig.1 nanotechnology is a cross disciplinar field merging physics, biology, chemistry, engineering, and probably , in the near future, medicine as well. In this respect it is almost impossible to define a single road map for nanotechnology. Instead individual road maps have to be drawn for each specific field of interest. Something similar has happened in the XX century with the engineering, which has been specialized to so many fields (mechanical , nuclear, electronic, informatic, chemical, materials, etc.) that it is now a day impossible to give a unique definition of the engineering itself.

Following figure 1, let us see how we can envisage the progress of nanotechnology in different areas: the cultural core of nanotechnology stands in the merge of new concepts and new architectures (often inspired by biological and natural systems), with new materials (in most cases properly functionalized or engineered at nanoscale), and new nanoscale fabrication, manipulation and measuring processes and instruments. Such a complex approach, represented by the central circle in Fig.1, enables the development of totally different disciplines, only partially represented by the boxes in Fig.1. Besides basic research on fundamental quantum phenomena (topmost box), several other applied and fundamental areas are boosted by nanotechnology. The research on new materials, for instance, spans from new coatings and inks to reinforced materials through the inclusion of nanoparticles. These can find application in many fields, such as aerospace and automotive (bottom box) which make use of ultralight ultra strong materials, high efficiency solar cells, new sensors etc.. The field of energy and environment is another relevant “arena” for nanotechnologies. Improved catalysis for cars and chemical industries, as well as the development of environmentally friendly materials or new techniques for the protection of cultural heritages employ more and more nanotechnologies for the functionalization of membranes and surfaces, for the inclusion of nanoparticles in different materials (e.g. Silica particles in car-tires to reduce friction and thus consumption) and to monitor with unsurpassed resolution ultra low percentages of pollutants in the atmosphere.

Health is another fundamental area where nanotechnologies might revolutionize methods and tools. The increasing attention to molecular motors and intelligent pills, makes the drug delivery in situ a quite promising technique for non aggressive therapies. Advanced diagnostic, exploiting electronics and imaging techniques normally adopted in advanced research labs for material and chemical characterization (e.g. three dimensional reconstruction of radiographies), as well as artificial bones and tissues with biocompatible mechanical and electrical characteristics are now becoming feasible.

It is interesting to note that nanoelectronics (including information technology) , though being the discipline which boosted the development of nanotechnologies at their beginning, is now just one of the possible application field of nanoscience. In what follows we will try to analyze the possible development of a road map for nanoelectronics [1] and information technology, with special attention to the new cross disciplinar concepts raising form the application of biology and chemistry to electronic and computing devices. It is clear that a similar attempt has to be done as soon as possible for all the other fields discussed above, in the attempt of providing a more comprehensive description of the future of nanotechnology, and hence of its impact on our society.

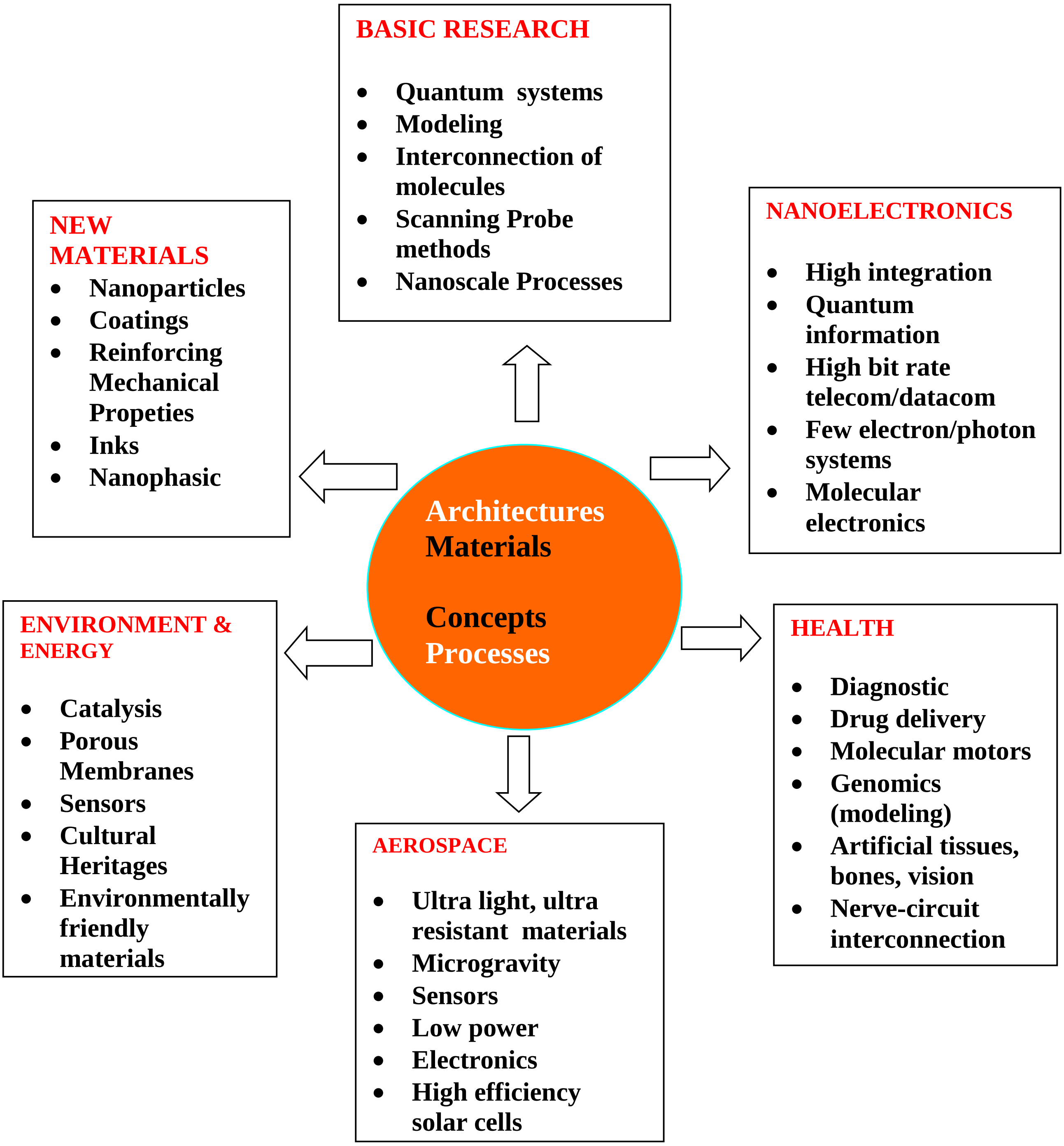

Fig.1 Trends of Nanotechnology

2. NEW CONCEPTS FOR NANOELECTRONICS AND COMPUTING

Electronics has pushed up the progress of nanotechnology, at least in its early stage, due to the increasing demand of miniaturization of the electronic industries. This is well represented by the Moore's law (blue line in Fig.2) which describes the decrease of the feature size (gate length) in integrated circuits over the years. In Fig.2 we also indicate, for comparison, some of the most relevant achievements which have led to the overall progress of nanoscience, namely the invention of Scanning Tunneling Microscopy, the polymerase chain reaction, the demonstration of DNA conductivity, the fabrication of the first organic field effect transistor etc.. Clearly the top down approach of the Moore's law is quickly approaching the quantum limit, i.e. a minimum feature size below 100 nm. Even though this will probably not affect the electronic market for several decades, it is on the other hand clear that the fabrication and manipulation of electronic devices in the range of tens of nm requires the application of different concepts and architectures. This is the so called bottom-up approach , which basically attempts to control the assembling of matter starting from atoms or molecules.

Despite it is immediately realized that this is quite reasonable from the point of view of the size of the final material, as we are dealing with sub 100 nm objects consisting of only several thousands of atoms (i.e. much closer to a molecule than to a crystal), it is however clear that this approach departs from the well know lithographic approaches developed by the physicists, and makes use of chemical and biological concepts typical of the self-organization and specialization of organic and living systems. This opens up the interesting field of the molecular electronics as a possible way to circumvent the bottleneck of the top-down approach when the quantum limit will be reached [2]. It is interesting to note that the race for integration has strongly influenced also the photonic market and the entire telecom/datacom area. In Fig. 3 we display the increasing demand in terabit/sec for voice (telephone) and data (internet) traffic. Also in this case the dramatic increase of the demand for photonic networks forces the research towards the development of single photon systems, photonic band gaps, ultrafast/ultra low dissipation devices, which need nanofabrication and possibly new concepts and design.

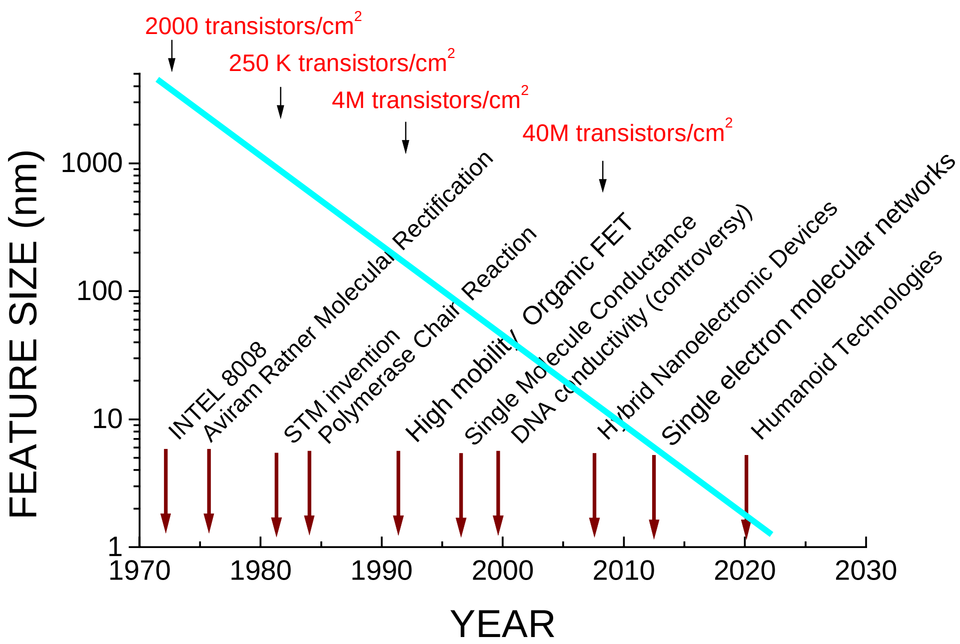

Fig. 2

Fig.2 Moore's Law for electronics (blue line) and some milestones of different fields such as biology, chemistry, and physics. Possible developments of hybrid nanoelectronic devices, single electron molecular networks and interconnection of these systems to human body (humanoid technologies) are expected in the next 20 years.

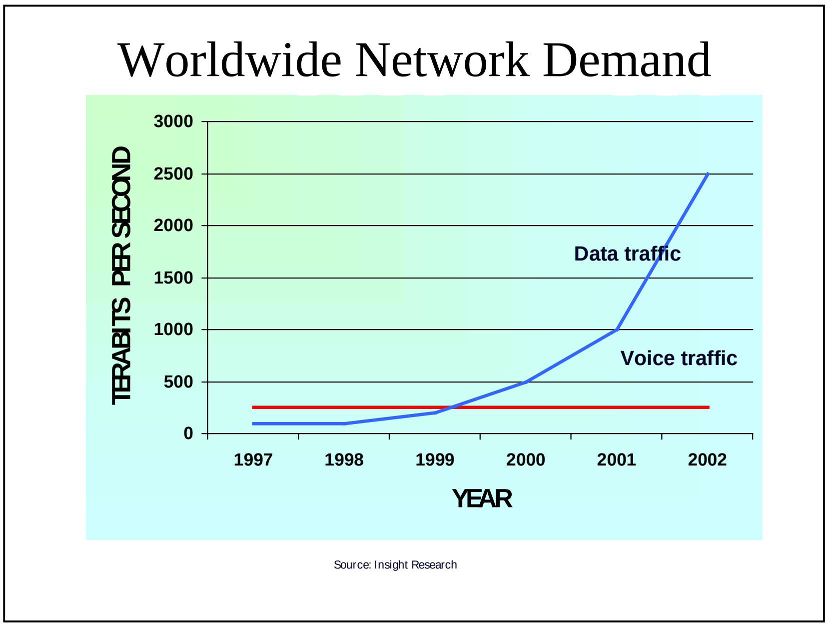

Fig.3 Worldwide demand of voice traffic and data traffic

For sake of simplicity we will focus our analysis on the issue of computation, as a representative field for nanoelectronics and computers. In Tab.1 we figure out a possible evolution of the bottom up approach for the development of new electronic devices. This has to be compared to the extrapolation of the Moore's law to the next decades which will result in conventional semiconductor circuits (field effect transistors, ambipolar transistors etc..) whose improved perfomances (integrability, power consumption, speed etc..) will be essentially due to the reduction of size. Tab 1 is organized as follows: the first column describes the main feature of the bottom-up approach, whereas the second column describes the building blocks to be used for the innovative devices . The third column describes the main processes involved in the fabrication, whereas the fourth column describes whether the "architecture" is conventional , e.g. resulting in a conventional device with improved characteristics with respect to the existing, or completely new, such as hybrid biomolecular devices, or living circuits (e.g. neuronal) . The fifth column describes the materials to which the approach is going to be applied, and the sixth column describes the operation principle, which can be very different depending on whether we are dealing with a semiconductor device, a molecular device or a biological device.

The present approaches (first and second lines) are clearly based on the exploitation of semiconductor quantum dots in electronic (few electron devices, electron memories) and photonic devices (semiconductor lasers integrable on GaAs) . This obviously results in conventional devices, fabricated by epitaxy, and based on strain driven self organization. The concepts exploited by these systems rely on quantum size effect and all the standard physical phenomena normally involved in optoelectronic devices. A second class of conventional devices is represented by the planar devices consisting of inorganic as well as organic semiconductors physisorbed on a device surface. Plastic chips, organic FET, organic light emitters and devices based on ultrathin semiconductor and oxide layers belong to this class. In this case the bottom up feature stands again in the self assembling capability, while the materials and the processes are rather conventional, as well as the architectures of the devices. The novelty might come from the use of some biomolecules with strong self-assembling capability.

A representative example of such strategy is shown in Fig.4, where we display a DNA-based circuit [3]. Fig.4a shows the deoxiguanosine molecules and their ribbon-like structures formed in the solid state. The molecules are chosen because of their self recognition and self assembling properties originating from the presence of H-acceptor groups on the left hand side and of H-donors groups on the right hand side of the molecule. The self organization into a ribbon-like structure occurs spontaneously in liquid solution, and can be reproduced in the solid state upon well controlled evaporation of the solvent. To this aim different clorophorm solutions were prepared and gently evaporated in a dry environment onto a nanometer sized gap opened between two gold nanoelectrodes (Fig.4b). The self-organization of the molecules in the gold nanogap was carefully checked by AFM measurements (Fig.4c). The molecules form a ordered lamellar structure, where the ribbons extend over a scale length of typically 100nm. Over such a length scale, the material has the properties of a nanocrystal, with unit cell formed by aligned deoxiguanosine molecules. For longer distances, the orientation is lost, and different clusters of randomly oriented ribbons form, just like in amorphous policrystalline materials. The ribbons in each BNC are closely packed and parallel, and they are aligned randomly with respect to the contact axis. The typical size of the ribbon is 2.5 nm in width and about 100 nm in length. The gap between the gold electrodes was purposely varied in the range $30<L<120$nm, in order to measure the current transport within a single BNC ($L<100$ nm), and of the amorphous ensemble of BNC ($L>100$ nm). Fig.5 shows the diode like characteristic of one of these devices having a contact gap of about 60 nm. The measurement is performed at room temperature and in the dark. The strong polarity of the device originates from the existence of a strong molecular dipole in the Guanosine ribbon. Interestingly, these devices are quite long living and they do not show any degradation for currents as large as a few microAmpere with 10 V bias.

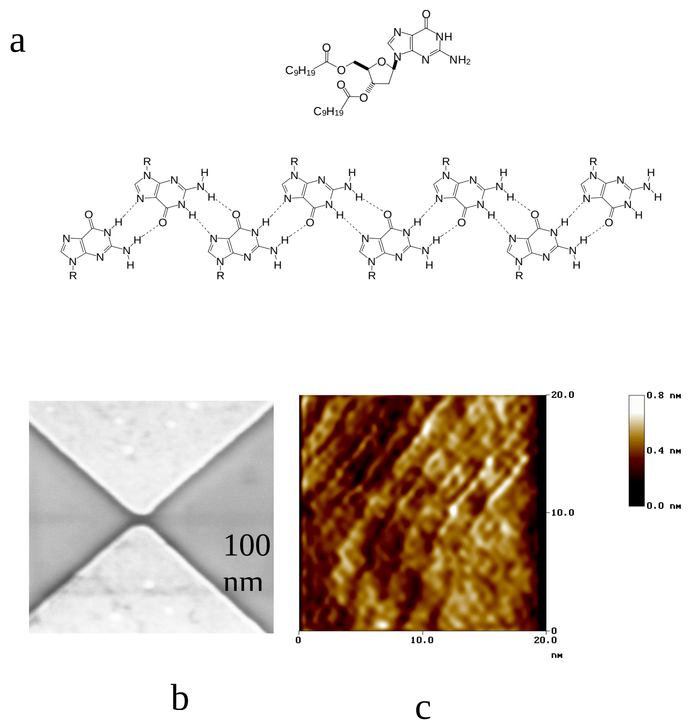

Fig.4 a) Top: Scheme of an individual guanosine molecule and of a ribbon of guanosine molecules

b) Au nanocontacts on SiO_2, fabricated by electron beam lithography

c) Self assembled guanosine ribbons deposited in the gap of the metallic contacts upon controlled evaporation of the solution.

Such basic studies clearly indicate that the fundamental goal of bioelectronics stands in the realization of nanoscale devices in which self assembled biomolecules physisorbed or chemisorbed on a solid state surface can be used to transfer and process an electronic signal. In order to design and realize such molecular devices, several steps are required: *i)* immobilization of the molecule onto an electronic substrate, *ii)* interconnection to contacts, *iii)* processing of the device, *iv)* recognition of molecular information, and *v)* processing of the information. The combination of molecular biology for the engineering of proteins (either their functional yield or self-assembling capabilities) and nanotechnology, thus becomes the tool to realize a new class of nanometer-size electronic elements.

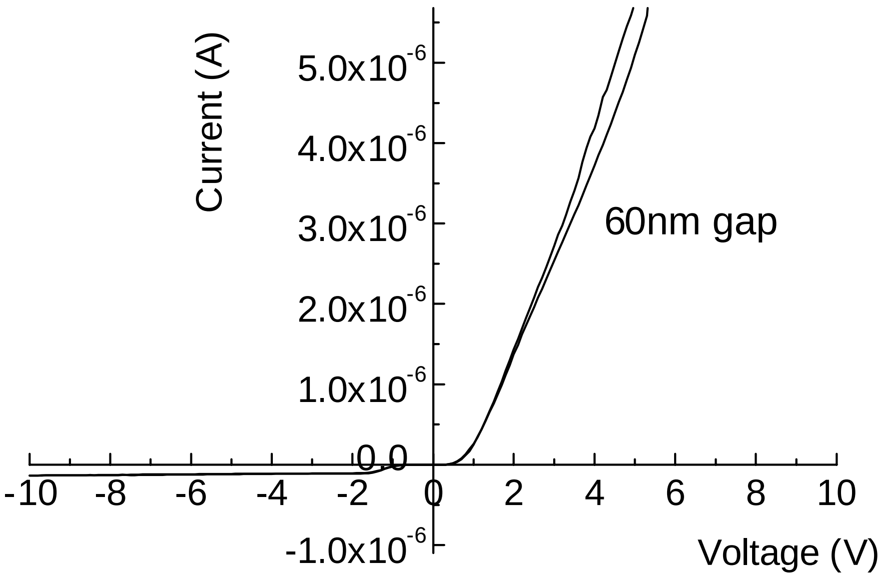

Fig.5 Current rectification in the Gaunosine device of Fig. 4 with a gap of 60 nm. The polarity is due to the existence of a macroscopic dipole along the molecular ribbon

A step forward towards the realization of biomolecular devices in tab. 1 is represented by the hybrid organic/inorganic systems were covalent bonding of an organic molecule is achieved onto an inorganic (metal, oxide, semiconductor) surface. In this case biomolecules or organic molecules are chemisorbed onto the inorganic surface through specific building blocks, such as thiols+, silanes or other small molecules providing the covalent bond for the organic species. Due to the inherently different architecture of such devices, the basic operation principle differs from that of conventional devices, and involves mechanisms such as reduction and oxidation, charge transfer, tunneling etc…A representative example of such methodology is shown in Fig.6, where we describe a biomolecular electron rectifier in the solid state obtained by interconnecting a protein monolayer immobilized on SiO_2 with two gold nano-electrodes. As the protein we used a copper metalloprotein named Azurin, having a surface disulfide bridge (Cys3-Cys26) that can be used to bind the protein to gold (or other electronically soft metals) with different orientations and different degree of ordering. The achievement of oriented immobilization is extremely important for electronic applications in which charge transport benefits of the long range order of the transporting material. This device exhibits a clear rectifying behavior with some discrete current steps in the positive wing of the I-V curve, which are ascribed to resonant tunneling through the redox active center [4]. This result represents a fundamental step for the realization of protein-based electronic devices, such as field effect transistors (FET) or single electron transistors (SET).

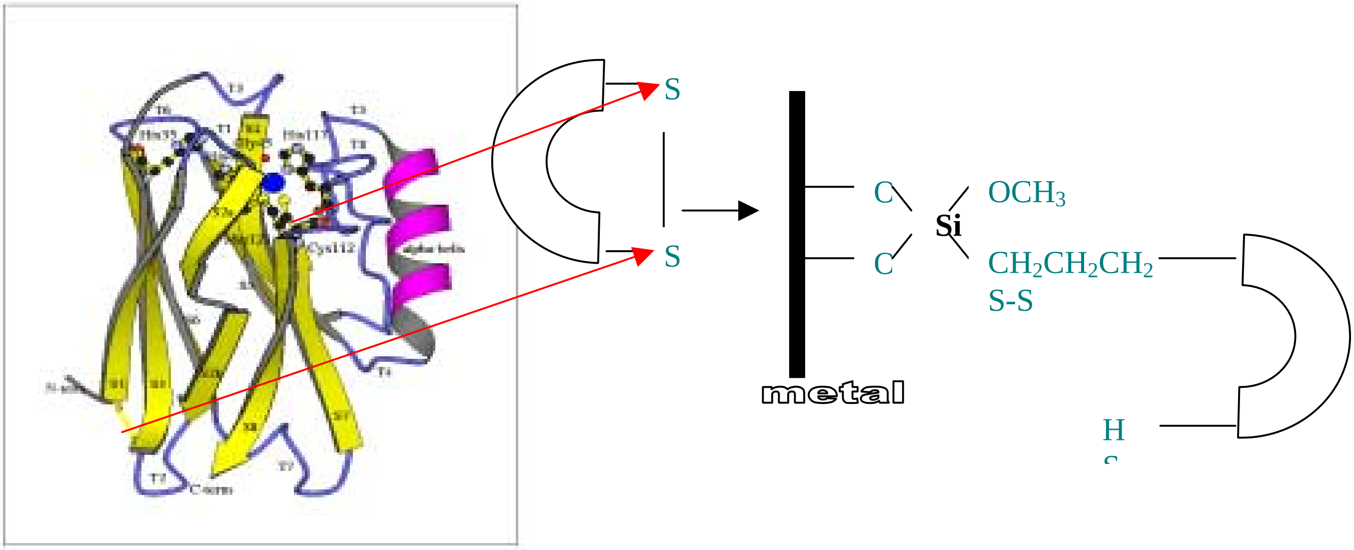

Fig.6 left: azurin protein. The blue dot is the copper atom acting as the redox center. Right: immobilization procedure between the metal surface and different sites of the biomolecule resulting in different orientation in the solid state protein film. The bonding through the unique S-S disulfide bridge (bottom arrow) results in oriented immobilization , whereas the bonding through one of the 12 cystein groups (top arrow) results in non oriented immobilization.

As opposed to the conventional electronic approaches, the hybrid approach uses building blocks such as small molecular groups for the surface immobilization, different processes, such as the surface functionalization, and, more important, operation principles far from the usual transport mechanisms. For instance, the charge transfer through the redox center of the protein has been demonstrated to be quite effective in determining transport through the device. It has to be noted, however, that even though the hybrid devices exploit unusual physical and chemical processes, they still operate in a way similar to the classic electronic devices, such as diode and transistors, i.e. they keep the standard architectures to accomplish rectification and switching.

A real advancement can be achieved by surpassing the conventional architectures and adopting the natural mechanisms for the formation of neuronal networks [5] or other biological networks based on ionic transfer (line 5 in Tab 1). Though far to be assessed, this approach is presently explored by several groups worldwide. The basic idea is to copy nature by using complex cells having self assembling capability and the possibility of adapting their response to an external stimulus. Obviously this requires physiological environment, possibly liquid and an electronic architecture which closer to the human brain than to any electronic computer. The basic concepts to be exploited are, for instance, the diffusion of ionic species in the solution, the delivery of ionic signals through membranes and the formation of networks favored, for instance, by the driven growth of assons of different neurons. Though at its early stage, this field is very interesting and there are already interesting studies in the literature showing simple neuronal networks where ionic signals can be addressed and detected [6,7].

Finally, in a somewhat visionary long-term picture we should mention the possibility of forcing the formation of semiconductors, metals and oxides by using biological peptide libraries in liquid solutions [8]. The pioneering studies in this field have demonstrated that Si, Au, ZnO and GaAs can be forced to form oriented microcrystals depending on the specific peptide library used to catalyse the crystal precipitation in solution. Such an innovative approach essentially uses the same mechanisms used by mother nature to differentiate the morphology of our bones in different part of the body and it could envisage a sort of biologically-driven production of engineered inorganic materials.

3. CONCLUSIONS

It is opinion of the writer that the evolution of nanotechnologies is so fast that drawing a road map now is a tremendously difficult task. In addition , due to its strong cross disciplinar character, nanotechnology requires a strong effort to break the existing cultural barriers among physics, biology, chemistry, and engineering, and to create a model of education for the young generations, which has to be more respectful of such cross-disciplinarity. The content of Tab 1, yet far from a real road map, may represent a starting point for the identification of the mainstream lines of nanoelectronics. Even though this will have to be updated and probably corrected in short time, it clearly indicates the need of a real synergy between disciplines traditionally considered to be quite independent of each other (e.g. physics and biology). This might be the key point for the development of nanotechnology, regardless of the specific field of application, as shown in Fig.1.

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TAB.1: BOTTOM UP APPROACHES

Bottom-up feature	Building Blocks	Processes	Architectures	Materials	Concepts
• Self organiz.	• Standard devices	• Epitaxy	**Conventional**	• Semiconduc • q.dots	• Quantum size effect • Transport • Rectification
• Self-organiz.	• Films • Planar devices	• Lithography • Evaporation • Spin cast	**Conventional**	• Metals-Oxides • Semicond. • Molecules	• Transport • Rectification • Physisorption
• Covalent bonding • Self Organiz.	• Thiols • Isocyanates • Silanes	• Litho • Soft Litho • Evaporation • Functionalizat	**Hybrid**	• Inorganics • Organics • Biologic	• Redox • Oxidation • Charge transf. • Tunneling • Chemisorption
• Adaptive • Self calibrating • Self recognition	• Functionalizatio n • Aminoacids • Fisiological environment	• Liquid solutions	**Natural**	• Neurons • Living cells	• Diffusion • Osmosys • Membranes • Ionic transport
• Living systems	• Peptide libraries	• Liquid environment	**Forced**	• Inorganics	• Biological software

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