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SETTING SCIENCE AGENDAS FOR EUROPE

SCIENTIFIC FORWARD LOOK

Nanoscience and the Long-Term Future of Information Technology (NSIT)

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1. Introduction

Nanoscience, that is the observation, understanding and manipulation of matter at the nanometre scale is expected to have a strong impact on tomorrow's products. Various areas should benefit from these developments, such as materials science, medicine and information technology. Indeed, information and communication technologies (ICT) have already derived much benefit from the downsizing of components since the 1960s. This trend is often represented by the well-known Moore's law which describes the exponential downscaling of transistors with a doubling of the number of transistors per unit area every 18 months. Semiconductor technology has recently entered the nanoscale world as the microelectronics industry is now producing transistors with critical dimensions below 100 nm.

It is expected, however, that the ever-increasing computing performance and storage capacities achievable with existing technologies will eventually reach a plateau in 10 to 15 years time with storage capacities of Tbytes and a peak performance of TeraFlops[(1)] for a standard chip. This prediction has fostered the exploration of technological alternatives to extend IT capabilities beyond the limitations of current CMOS (complementary metal oxide semiconductor) technology. Today, several emerging alternatives are being considered at research laboratory level, such as molecular electronics or spintronics.

The expected increase in the capability of logic systems, together with other similar trends such as the increase of storage capacity or the fast growth of communication bandwidth (according to Gilder's law the total bandwidth of communication systems triples every 12 months), will obviously lead to new products which could have a strong impact.

In 2005 the ESF organised the NSIT Forward Look to investigate the consequences of nanotechnology in the domain of information technology. The present semiconductor (or CMOS) technology had already entered the nanoscale world some years earlier. Since 2002, the microelectronics industry had been producing transistors with critical dimensions below 100 nm. Various points have been addressed:

- What are the challenges, what could be the goals of today's research?
- What are the expected developments in the next 10 years?
- What are the possible impacts on society?
- What can be said about organisation of research?

1. FLOPS being an acronym for Floating point Operations per Second

2. Challenges

2.1 Limit of downscaling for computing and mass storage

Nanoscience researches pursue various goals which could be summarised as follows:

The *'More of Moore'* approach

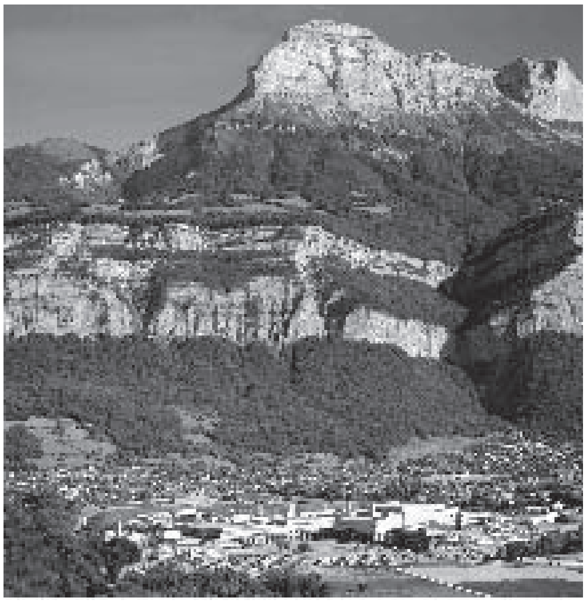
The reference to measure progress in the race for improving the performance of integrated circuits is the International Technology Roadmap for Semiconductors (ITRS) of the Semiconductor Industry Association (SIA). It defines milestones called 'technology nodes', defined as the minimum metal pitch used on any product. In 2005, transistors are being manufactured at the 90 nm technology node, with a transistor density of about 80 million/cm^2. The prediction for the next five years is reliable since it deals with already existing prototypes currently being industrialised. For the longer term, industry uses this roadmap as a reference to identify future issues, synchronise various developments and to make forecasts for future applications.

It is expected that the 40 year-old Moore's law will still hold good for at least 10 years, so the 45 nm technology node should come on line in 2010 and the 22 nm technology node in 2016 with transistor densities around 1.2 billion/cm^2. At this time, expected channel[(2)] lengths would be around 9 nm (i.e., ~ 22 atoms[(3)]).

These predictions are conservative in the short term, since they take into account industrial developments. On the other hand, for the longer term, that is, after 2010, they become less and less reliable because they depend on the ability to develop manufacturing techniques with the required accuracy (lithography, interface quality). In addition, scaling laws indicate that some concepts cannot be simply extrapolated and new physical effects that have been negligible up to now, have to be taken into account. The following new developments are required:

- **Materials:** Since the 1970s, it has been necessary to replace materials when components were shrunk, and new developments are likely to be required in this field for further shrinking of transistors. An example of this is the silicon oxide gate dielectric, which must now be replaced by a higher permitivity dielectric. Indeed, gate insulators must remain thick enough to be effective. This is also the case for metallic connections which must become increasingly smaller while still keeping a low resistivity.
- **New geometry:** Below the 45 nm node, the aspect ratio of the channel (thick and short) prevents the use of a single gate. Non-conventional geometries must therefore be sought, among which three-gate systems could be an option.

2. The active part in a transistor inside which the current is modulated.
3. Assuming lattice constant of roughly 4A



Crolles site, France. Close proximity between manufacturing and academia.

- **Power consumption.** Smaller components mean higher energy dissipation. This is because of the increasing leakage current (tunnelling current through thin gates), resistive losses in interconnects, the increasing number of logic operations per second, and unit area increase in the transistor density (nowadays transistors dissipate typically 1 fJ per logic operation[(4)]; that is, much more than the kTln2 lower limit for ideal reversible computing, which would correspond to energies in the range 10 millions smaller.
- **Architecture.** The general design of circuits should evolve to take into account increasing complexity, the need for fault tolerance, limitation of the space available for the number of connections and also the information propagation time.
- **Understanding new physical effects.** Around a few tens of nm, various quantum effects appear even at room temperature. The inhomogeneity of materials will also render poor reproducibility to the components (offset charge, no stable doping).

It is expected that it will be difficult to go beyond the 22 nm node using a 'conservative' point of view. Even before any of these fundamental limits becomes a serious problem the semiconductor industry is mostly worried by the rising manufacturing costs for each successive technology generation, particularly regarding lithography equipment. The end of Moore's law could also stem from economic reasons, small-scale transis-

4. 1 femtojoule = 10^{-15} J

tors being feasible but too expensive to replace more conservative ones. Nanotechnology could help planar CMOS technology to further shrink the dimensions of integrated circuits, for instance:

- By embedding nanotubes, nanowires or single molecules in CMOS-based integrated circuits. Most of these bottom-up nano-elements could advantageously replace lithographically designed ones which could become highly irreproducible when the standard technology is pushed too far.
- Instead of considering new effects appearing at smaller scale as parasitic ones, they could be used to develop new concepts. A first example is the recent development of flash memories using nanoparticles and single electron transistors.
- Also self assembly, or sophisticated chemistry could be used to achieve some steps at the small scale.

Considering time frames for the industrial developments, the impact of this could only become stronger in the longer term (beyond 10 years), namely for components beyond the next generations for which industry is being prepared now. Furthermore, the most successful concepts for extending Moore's law are likely to be those which could become compatible with the existing technology.

The *'More than Moore'* approach

In order to meet the needs of increasingly demanding IT markets and industries, it will be necessary to diversify the functionality of devices, rather than simply increase their performance. This implies moving beyond 'More *of* Moore' towards the 'More *than* Moore' scenario. More than Moore means integrating other technologies into CMOS – photonics, spintronics, radio frequency components and in the longer term, quantum devices, etc. – which allows the merging of new functions into one single component. The EU technology roadmap for nanoelectronics also envisages hybrid optical chips as a way of delivering More than Moore. Examples include fabricated 3D photonic crystals containing artificial points that emit light at optical communications wavelengths, all-optical switches, light trapping in dots (cavities) and wires (waveguides), compression of light into volumes of sub-wavelength dimensions and plasmonic control of light by nm-thick metal layers or particles. In the More than Moore scenario, the challenge is not to increase the number of transistors, but to expand the functionalities per component, in particular by converging various technologies. Well-known examples are laboratories and pills on chips. As described later in this report, this functional diversification will ultimately enable the realisation of 'ambient intelligence'.

Mass storage concepts

Many information systems require mass storage. Unlike computing devices which are designed using a single transistor-based technology, mass storage can be based on various paradigms. The most efficient ones (magnetic and optical recording) currently rely on the modification of a continuous. The storage density per unit area has been increasing steadily since the 1960s, thanks to improvement of both the recording media and the read/write head. The gain is about a factor of one million since 1960. In 2005, standard densities are of the order of 15 gigabit/cm^2, that is, a single bit lies in a square of about 80 × 80 nm^2 (i.e. typically 200 atoms × 200 atoms[(5)]). This scale length demonstrates that mass storage is already relevant to nanotechnology. One of the key targets for the future is a further increase in density.

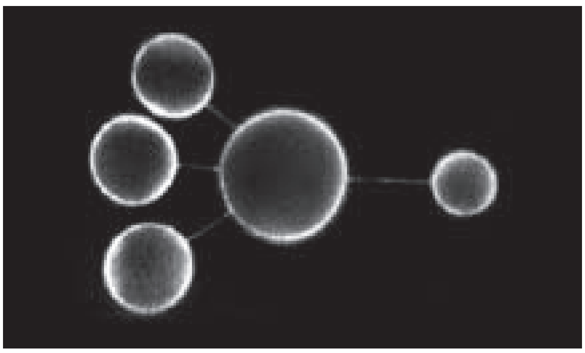
- For **magnetic recording**, this means that the magnetised volume representing a single bit must decrease. The challenge is to find a trade off between the ability of an information bit to keep its magnetisation for a long time, and the requirement to be able to modify it easily. New concepts are under development, such as thermally assisted writing, new geometries for the magnetic field, or medium improvement (magnetic nanoparticles, patterning). It is expected that these plans would allow densities to reach 150 gigabit/cm^2 by 2012 (i.e. one bit in a square of 26 × 26 nm^2 in a single layer storage system).
- **New concepts** could replace magnetic recording especially if they allow the storage of one bit within a few atoms, while allowing a reasonable access time. An example is the millipede development in the IBM laboratory in Zurich. This system uses a technology close to tunnel microscopy to thermally modify the surface of a polymer. Prototypes already allow a storage density of about 200 gigabit/cm^2. This technique could become a competitor to magnetic recording.
- **Optical recording.** There is high potential for optical storage using phase change media, with multistate storage per memory cell and with improved access times if future phase-change memories will work with sub-ns pulses.
- Ultimately **3D storage** could replace 2D storage to reach high storage capacity. Magnetic tapes can be considered as 3D media (once wound) and have already multiterabyte capability at the expense of a slow access time. New ideas could arise in future based, for instance, on optical media or self assembly. Note that a 1 micron^3 volume bit would correspond to 1 000 gigabit/cm^3.

5. Assuming lattice constant of roughly 4A

2.2 New paradigms for computing

During the twentieth century, computing systems were successively based on electromechanics, vacuum tubes, transistors and integrated circuits. This allowed a roughly twelve orders of magnitude gain in computing efficiency. Since CMOS technology is likely to reach a plateau in 10 to 15 years' time, a key question is whether a new paradigm could allow this trend to continue. A huge variety of approaches have the potential to transcend the current semiconductor-based model, through:

- Architectures, which should be scalable, fault tolerant, self-testing, self-repairing, reconfigurable, and low power. The biomimetic approach is one of these research areas. Several ideas exist to mimic nature, including neuronal networks, systems capable of self assembly (using vesicles for instance), direct use of actual neural networks (see below) and even the use of genetically modified cells to create computing capability.
- New fabrication methods, including: bottom up, top down self-assembled and templated.
- Novel structures in one, two and three dimensions, including nanotubes. Use of new materials such as narrow gap semiconductors, high-κ dielectrics, polymers, DNA and RNA.
- Quantum computing. This requires specially designed quantum algorithms. Only a few of these algorithms are currently available but interestingly one of them (the Shor's algorithm for number factorisation) is much more efficient than its classical counterpart.
- Information carriers based on charge, spins, photons and phonons.
- Nanowires, quantum dots, single molecules and spintronic devices.
- New functions beyond logic and memory, such as sensors and actuators.
- Novel energy transfer mechanisms and nanoscale thermal management.



Example of research on biomimetic systems: network of liposomes (diameter in the range of 4-10 microns) connected by nanotubes.

A few promising examples are:

- Semiconductor nanowire-based electronics using wires with diameters as small as 5 nm, which can be structured to form multiple tunnel barriers and junctions.
- Magnetic logic and magnetic random access memory (MRAM) based on magnetic tunnel junctions (MTJs), using both charge and spin. Advantages of this technology include non-volatility, low power consumption, radiation hardness, fast read and write, long-term stability, possible compatibility with CMOS (though this is still an issue) and the possibility of one single technology platform for memory and logic.
- Photons, which provide another non-charge state variable for nanotechnology and storage.
- Quantum information processing using atom traps, ion traps, nuclear spins, electron spins, Josephson junction flux or charge, electrons or excitons in semiconducting quantum dots, carbon nanotube peapods, single molecules and impuities.
- Bottom-up building blocks for molecular electronics, such as synthetic molecules, biomolecules and nanoparticles.
- Carbon nanotubes (CNTs) are typically1-20 nm in diameter, atomically perfect, chemically inert, 100 times stronger than steel, can be ideal (ballistic) conductors of electrons, or insulators, ideal heat conductors. CNTs have an extremely high melting temperature, do not appear to pre-melt near defects and can self-heal certain defects. They can be electrically gated and can be functionalised either by adsorption or encapsulation of other molecules.

These approaches potentially exhibit the following advantages:

- **High density of integration,** beyond the capability of lithography using existing small-scale objects, such as specially designed molecules, nanotubes or nanowires, perhaps using chemistry to assemble the components. Another way to reach high density is to design systems with a very simple architecture requiring fewer interconnects. This is the case, for instance, for quantum cellular automata or arrays of single non-linear components such as resonant tunnelling diodes.
- **High frequency operation.** Systems such as single flux quantum components (RSFQ) allow very high frequency operation (tens of GHz) while requiring much less power than in other components (1 attojoule per operation, i.e. 1 000 times less than a transistor).
- **New uses.** For several years, a number of teams have been pursuing the goal of building quantum computers. Here the goal is not the downsizing of components, but rather designing systems which are much larger than natural quantum systems, such as

atoms, while retaining quantum coherence. These machines are close to reversibility but to operate in a coherent quantum state, they must be decoupled from the outside world.

Experiments already exist showing the feasibility of most of these concepts, and their expected advantages with respect to existing technology. However, currently they are not in competition with CMOS technology for two reasons:
- the former ones do not take into account all the design constraints of commercial data processing;
- compared with the CMOS-technology reference point, none of these technologies present clear-cut advantages. Each potential candidate has advantages and drawbacks and therefore for the future, they are likely to fulfil niche roles inside a single heterogenous device.

These research initiatives are essential to provide new knowledge that eventually can lead to new technologies that enhance CMOS capabilities or develop new concepts. In addition, new breakthroughs are needed in the longer term to cope with the ever-increasing demand in performance as well as to render technology that enables new applications which could not be envisaged with CMOS.

2.3 Power supplies and nanotechnology

As discussed below, the trend to go for nomadic or embedded systems is increasing in IT. These systems must be powered by batteries or by scavenging energy from the environment. Progress in this domain has been far slower than those discussed above. Power densities remain in the range of 10 mW/cm^2 for batteries and photovoltaic devices, and 200 mW/cm^2 for fuel cells. This has to be compared with the 2 W/cm^2 which are required in a low power chip, in 2005. Despite progress in power management and lower operating voltages, this figure is expected to increase by 50% in the next 10 years because of the larger number of transistors, higher operating speed, leakage current (through gate insulators) and interconnects. Nanotechnology could play a key role in increasing the performance of power supply mainly because most energy transfer mechanisms occur at the nanoscale. For instance, this could apply to photovoltaic, thermoelectric, mechanical or chemical systems.

2.4 Grand challenges for software[(6)]

Although this domain is not the central focus of the Forward Look it is widely recognised that software is as important as hardware for future developments. In addition it will become increasingly difficult to separate hardware and software. Specific new challenges include:

• Dealing with complexity at the level of a chip: Densities larger than one billion transistors/cm^2 on a single chip will raise new issues associated with connectivity, signal propagation between various parts of a single chip and more generally overall organisation of the chip since these transistors must work together as efficiently as possible. This could require new architectures, reconfigurable parts, and new type of software designed to optimise the use of such systems.

- Dealing with complexity. As will be discussed later, it is likely that software-intensive systems will be embedded in a rising number of everyday objects with the ability to communicate through a global network. The ability to deal with large-scale distributed sets of heterogeneous objects possibly able to reconfigure themselves is a new challenge for computer science.
- This requires development of languages simultaneously allowing a high level of abstraction and high reliability, tools for system analysis and verification, and methods to ensure safety and privacy.
- New capacities for storage, leading to petabytes of on-line heterogeneous data will mean that the human capacity for attention will become the bottleneck. This will require the development of intelligent agents able to find and possibly synthesise large amounts of data (text, graphics, video, sound) in response to a given question.
- Teraflop computing power on a single chip[(7)] will induce new uses, such as the ability to deal with natural language, virtual images and emotional communication. This raises new issues at the interface between computer science and cognition sciences, including the modelling of our environment and the language of facial expression, to construct realistic artificial worlds or humans, or provide a deep understanding of context.
- New paradigms for computing also prompt new types of questions, such as algorithms compatible with quantum systems and understanding the relationship between brain and mind.

6. See Appendix for the Robin Milner and Martin Wirsing contribution.
7. In 2005 the largest supercomputers in the world are in the range 50-100 Teraflops.

3. New trends for information technologies

3.1 Towards complexity

Information and communication technology inside devices is becoming increasingly complex while device interfaces with humans are becoming increasingly simple. In next-generation devices, information and communication functionalities will be hidden, embedded in many objects surrounding us in our everyday life. ICT will become more and more pervasive and at the same time more and more invisible, leading to a world of ambient intelligence. Some key concepts in this vision are:

- **Pervasive ICT** with computers everywhere, including our homes, cars, public transport, working place, city streets, etc.
- **Embedded ICT,** where technology will extend its traditional grounds (computers, mobile phones and other 'obvious' electronic devices) to become part of all objects of our daily living: domestic appliances, lamps, blinds, clothes, etc.
- **Context awareness.** In the framework of IT, a device or system is context-aware if it is able to use the information characterising its environment (location, neighbouring persons or objects, including the user, resources etc.) in order to assist the user.
- **Networked objects.** Objects will be interconnected through an increasingly all-pervading network.
- **Intelligent agents.** The so-called 'intelligent agents' use technologies to provide active assistance for computer-based tasks.
- **Self-configuration.** ICT systems will be sensitive, adaptive and responsive in order to adapt their configuration in response to changing environmental conditions and user requirements.
- **Natural interaction.** The interface between user and device will operate through multimodal mechanisms, such as pen, touch, voice and gesture.

Such concepts are related to new scientific and technical issues such as the one described in the Section 2.4 above. In addition, if this technology develops this would raise new questions about the interaction between people and this new living environment, as will be discussed below.

3.2 Links with biology

The brain is a natural powerful information-processing system with low power dissipation. Some of its features are unique compared with artificial 3D systems; for example high connectivity (each neuron is connected to typically 10 000 other ones so that there is about one billion synapses per cubic millimetre), self-assembly, configuration evolving in time. It remains a fascinating object and is sometimes presented as a proof that there exists at least one paradigm going further than CMOS technology, even if cannot yet be man-made. However, progress in biology and instrumentation (imagery, microelectrode technology) together with closer analogies between brain and more artificial complex systems induces a convergence between classical information science and what could be called the natural information science (that is, processing data with living systems, sometimes called the 'wetware'). This convergence is motivated by a number of issues:

- **Understanding the brain,** in order to design new drugs in a more systematic way, there is a need to perform computer simulations of the brain and design new hardware architectures.
- The **interface between the central nerve system and IT** devices, with important applications in the treatment of disabled patients. Existing devices include cochlear implants to restore audition or deep brain implants to attenuate effects of Parkinson's disease. More ambitious longer-term projects exist, such as neuroprostheses for paralysed patients or systems to restore vision for blind people.
- **New exciting challenges include the creation of 'intelligent' machines mimicking the brain** and able to adapt to unforeseen situations and to foster the development of new tools for neuroscience. A deeper insight into the mechanisms and architectures of the brain will probably allow computer scientists to progress towards increasingly complex systems.

This convergence, although promising, raises ethical issues, as discussed below.

4. Information technology and society

The progress described in preceding sections, often enabled by nanotechnology, will lead to processors with significant computing power able to manipulate video and natural language, mass storage allowing access to huge amounts of information including multimedia content, high bandwidth communication linking any system to a quasi-infinite reservoir of information. At the same time, even if productivity increases, and transistors are cheaper, the amount of investment to build factories to produce circuits increases (from €3 billion now to €10 billion in the future). This unique situation raises new issues.

4.1 Market evolution

During the early stages of its development, ICT was driven by a few large-scale applications in computing, the defence and space industries, and communication networks usually stimulated by nation states or large organisations. This scheme became drastically modified when new products for the general public appeared in the 1980s, such as personal computers and video games, and more recently smart mobile phones, personal digital assistants (PDAs) and personal global positioning systems (GPSs). Drastic changes are foreseen in the next 10 years, by which time each individual in developed countries could own (unconsciously) in excess of 100 processors embedded in various objects. With such an 'intelligent environment', personal computers as individual objects could even disappear. This trend to offer an increasing number of IT-based products is reinforced by the fact that new uses and new markets are required to ensure that the increasing investment needed to sustain Moore's law are profitable. The market driving the IT industry has the following characteristics:

• This is a technology-driven market
The market has been traditionally driven by the demands of customers. However, advanced technologies have resulted in new products or services that were beyond any need that was initially envisaged by the public: The market is therefore technology-driven rather than consumer driven. The best known example of this situation is the mobile phone market. Only a few people could foresee that the mobile phone would become the must-have fashion icon of school children and adults alike.

• The increasing importance of the human factor
Although technology is the main driver, the link between technology and market is not straightforward. Indeed the design of ICT products is increasingly driven by customer convenience and the development of new uses, which often are hardly foreseeable. This will raise new challenges. In particular, designers should take into account that:

- New products and ways of using them are created simultaneously. A deeper comprehension of user acceptance of technology is necessary to improve design. In particular the complexity of new products, their potentially sophisticated behaviour and also their ubiquity raise the issue of interfaces or even acceptance. This requires multidisciplinary teams including not only engineers, physicists, chemists, biologists and computer scientists, but also psychologists and sociologists.
- Moreover, in an ICT-intensive environment the questions may not be related to the interaction between the user and a particular device but to the user and more generally the society with this environment[8].
- Cultural and social aspects may have a strong influence on acceptance of this technology. A variety of feelings about ICT already exist among the public; this technology being associated with slavery by some or with empowerment by others. There is also a high variability of acceptability between countries and communities.

Opening markets to objects
Technology will allow the production of low-cost, small-size intelligent systems, which could render objects more user-friendly. This trend is already very strong in the automobile industry, but ultimately, in the world of pervasive computing, ICT systems could be embedded in most manufactured products. One could even say that, in future, objects could be considered as virtual customers. However, the needs of the market depend strongly on use and acceptance, so that the eventual nature of embeddedness is hardly predictable.

4.2 Security and reliability

Since the foreseeable future involves increasing amounts of digitised data, interconnected with many sensors and control systems to a global network, two issues become paramount:

• Safety
It is necessary to find ways to overcome the fragility and uncontrollability associated with extreme complexity and high connectivity.

- Failures are already well known in large-scale power distribution or telecommunication systems. The same questions arise when considering large (possibly world-wide) networks of interconnected systems,

8. See Appendix for Leena Norros's contribution.

with a growing capability to reconfigure themselves and the possible emergence of collective instability. It is not yet known if the stability of ambient intelligence systems (pervasive computing and ubiquitous wireless network) is just a matter of reliability of the embedded software, or whether there could be unforeseen, inherent instabilities at the image of what is happening in large-scale physical systems[9].
- New types of delinquency or unwanted behaviour may appear as an extension of already existing spammers, hackers and pirates.

• Security of data

This is a serious issue for non-technical users of ICT technologies, exacerbated by the increasing size of storage so that the value of data per unit volume becomes higher and higher. Some issues which are not addressed at present could be taken more seriously. For instance, huge memory storage could lead to the concept of 'numerical patrimonium' (which can be destroyed or stolen) or even numerical assassination encompassing, for instance, all personal data (video, pictures, memories etc.). The ability of a data store to protect data for life, guarantee privacy and be long lived could become an important issue. It is also essential to find effective solutions to authenticate sources and recipients of data, and to ensure the privacy of confidential information.

On the other hand, acceptability of systems able to record more and more data (no matter how insignificant) for years could become an issue. Paradoxically this could lead to new concepts such as memory being able to 'forget' after a period of time.

4.3 Impact on society: ethical issues

The appearance of mobile phones, the Internet and large-scale information systems has had an impact on society in the field of employment, social relationships, the concept of privacy and laws. An even stronger impact is expected with intelligent environments and ubiquitous computing[10]. This induces two types of feelings: on the one hand there is a fascination for all the new possibilities offered by technology; on the other hand there is a growing anxiousness about the impact of these new products on individuals and society. The question arises about the lack of global control of this evolution. Several topics are relevant, as follows.

• Privacy

ICT can potentially provide outstanding services. Often this must be at the expense of sharing personal data (localisation, record of various actions) with a global interconnected system. Even if these data are benign their accumulation in a global worldwide information system raises questions and this requires international regulation.

• Impact of new use

For instance virtual reality, the interface between humans and various intelligent agents may cause a change in social life as television did in the past. This raises some concerns about the contrast between the 'faster, cheaper, more efficient' aspect of ICT and the quality of life[11]. Another example is the appearance of new legal issues related to ICT.

• Social role of intelligent systems

Automated systems could achieve some tasks that up to now have been undertaken by human beings. Some of them imply the involvement of drastic decision making; for instance, virtual lawyers, physicians, or even soldiers.

• Ethical issues

Concerns regarding the involvement of human beings and biological samples do arise in nanotechnologies (biochips, implants, brain interface), but are not unique to IT.

• Impact on economics

Virtual agents, large bandwidth communication, virtual environment, intelligent environment will have an impact on localisation of richness production, employment, possibly dependency relations.

Obviously development of ICT relies on societal aspects at least as much as technical ones. This encompasses basic marketing issues (how to design a new product to maximise its attractiveness) to much more general question such as how a democracy organises itself to decides how technical progress should be implemented.

9. See Appendix for the contributions of Branislav Rovan and Françoise Roure for concerns in this area.
10. See Appendix for the contributions of Sonia Miller and Françoise Roure.
11. See Appendix for Branislav Rovan's contribution.

5. Science policy strategy

Nanosciences will be a crucial enabler in meeting future demands in performance (computing power, data transfer or high capacity storage), environmental requirements, and the development of new market paradigms such as the concept of 'objects as virtual customers'. The target horizon for collaborations between research centres and companies should be 10 years, since the 5-year term is already determined in corporate research labs. Competitive development of ICT requires that research and industry are organised to ensure a smooth transfer from research to industry. The required organisation is not straightforward. Indeed, various viewpoints must be considered.

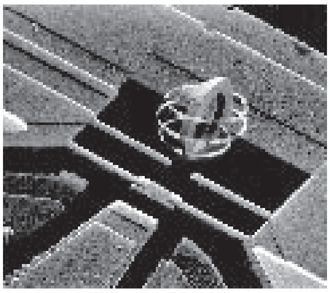
5.1 Impact of nanotechnology: a variety of situations

As discussed in Section 2, nanoscience research encompasses a number of different transfer schemes. The challenging goals for the next 10 to 15 years are superior performance (operations/second, storage volume and access time), reduced power consumption, enhanced functionality and new uses. In addition, there is an increasing need to handle complexity and to design fault-tolerant architectures. The impact of nanotechnology can be seen as fourfold:

• **Improvement of the existing technology**
- For the short to medium term (up to 2015), new processes, and new materials will be required to shrink down the transistor size. As discussed above, the most promising route is the integration of different technologies to produce hybrid systems for new applications with novel functions and most likely multifunctionality.
- In the longer term (beyond 2015) when the transistor scale length will be around 10 nm, there is a real need for new feasible concepts to cope with the expected evolution from the classical transistor scheme.

• **Niche applications**

For some specific domains which are not currently dominated by silicon technology there are plenty of opportunities for innovation:
- *Data storage.* Existing storage densities relate to cells that are already in the nanoscale domain. Although magnetic systems were traditionally taking the lead, there are nowadays at least three different commercial systems that are broadly used depending on the application. Therefore, diversity of devices as opposed to a single device for everything appears as one of the trends in the storage domain.
- *Energy sources*, able to meet future technological and environmental demands, are badly needed.



Qbit circuit prototype.

• **The search for new paradigms**

The main goal of the fundamental research is to build the knowledge required to continue beyond CMOS industrial developments. Some of the new concepts already investigated exhibit a strong potential and they could lead to new applications and possibly to a new large-scale industry in the long term (beyond 2020).

• **Implementing the converge of technologies**

Scientists, particularly in the domain of nanoscience, will be compelled to exchange knowledge and expertise across disciplinary borders. Most exciting breakthroughs can be expected from the convergence of nanoscience with information technologies, biotechnology and medical-cognitive sciences. A recent success of converging technologies for the benefit of human quality of life is the convergence of IT with neuroscience to produce an external device that can be integrated into the brain of a disabled patient to help him/her interact with their environment. Other possibilities are implants, complex prosthetic devices, etc.

5.2 Links with industry

It is widely acknowledged that industry needs input from research as the basic way to technology development and breakthroughs. It is also true that academia can greatly benefit from the knowledge of technologies developed for industry. Indeed, often, nanosystems need a microsupport which is achieved using standard industrial techniques. Often the research requires moderate size clean rooms (in the range 100-500 m^2) or flexible technological support associated with short term, exotic experiments, involving a single device which evolves as a function of results. As this research matures, improvements of CMOS technology will require larger-scale facilities, since it must be compatible with existing industrial processes (for instance wafer diameter). Nevertheless, some nanoscience applications are independent of existing large-scale industry. For instance this is the case in new mass storage concepts, or it could occur if research on RSFQ (see

Section 2) allowed the development of a faster router with industrial processes.

A key issue is the rapid and effective transfer of knowledge to industry. The required organisation and time constant vary between 'improvement of CMOS', 'niche application', 'new paradigm' and 'implementing the convergence' schemes discussed above. Two mechanisms for this are:

- The promotion of start-ups, in connection with research centres and scientific-technological parks. The main obstacle for scientists interested in entrepreneurship is usually their lack of managerial skills. Therefore, they should be assisted by either specific entrepreneurial training and management assessment provided by experienced entrepreneurs or, alternatively, by helping them to contact suitable managers. In this sense, managers should also be educated in the understanding of the characteristics of technology-based companies; for example, by including a technological orientation in specialised MBAs. This scheme is well suited for products that correspond to the 'niche applications' discussed above or for products which are related to the mainstream CMOS technology but which can be externalised by big companies.
- The transfer to an existing industry. This can be facilitated by university-industry partnerships, which deal with intellectual property issues in advance of discoveries and creating joint positions.

5.3 Dealing with interdisciplinarity

Successful development of the above research vectors involves cooperation between biologists, chemists, engineers and solid state physicists. To create programmable, reconfigurable, fault-tolerant and manufacturable systems, there also needs to be a dialogue between device-oriented scientists and system architects. For applications, the idea for their use is as important as the technical aspects. Public acceptance is an issue that requires close collaboration between hard science and social sciences.

5.4 Observations about organisation of research

Nanosciences exhibits unique features such as:

- the very wide area covered by this research as well as for the applications;
- the multidisciplinary character of this domain, including hard sciences as well as social sciences;
- the importance of fostering both curiosity-driven and targeted-driven research, but also strong and complex links between fundamental and targeted research;
- the requirement of various sizes of equipment from small-size flexible facilities to large clean rooms.

A consequence is that **there is no unique organisational scheme for basic research**. Acknowledgement of the importance of freedom and creativity for fundamental research is essential, since usefulness often appears after, not before the research is carried out. If everything is targeted, creativity can be stifled and there is a risk of missing important results, thereby weakening the European scientific base. Nevertheless, interaction with industry is important to fundamental research as it is a source of new ideas and problems, often leading to technology transfer to other domains, as shown by recent developments in biochips. However, industry is conservative and independent teams are required to propose entirely new ideas rather than simply miniaturising existing ones.

The European research landscape is rather diverse, including:

- **Transnational projects.** These typically involve tens of partners, spontaneously organised around shared goals. Since these are not constrained by national boundaries, they often embody excellent individual teams, create enhanced environments for transnational training and leverage added value from existing national resources. Often they involve a mix of academic and industrial teams across several disciplines.
- **'Local ecosystems' including laboratories** both those close to applications and others that are curiosity-driven. They should bring together talented scientists in all disciplines relevant to nanoscience and provide all necessary equipment and infrastructure requirements. They should provide high quality specialised postgraduate training in nanoscience and nanotechnology and act as a focus for creativity and innovation, through the interaction of disciplines and perspectives. They should also provide an interface for the interaction of academic research and interested industries.
  Indeed there exists a hierarchy of such pockets/poles from medium-sized regional areas to the three large ones (LETI, IMEC, Dresden). All of them play a role. However, one challenge for Europe is to focus its strength on maintaining world-class facilities with ever-increasing size as required to stay close to industry while investment costs are growing rapidly.
- **Network:** These are loosely connected communities structured around Grand Challenges, such as quantum computing or computational materials science. One must stress the importance of networking to generate awareness of skills and breakthroughs,

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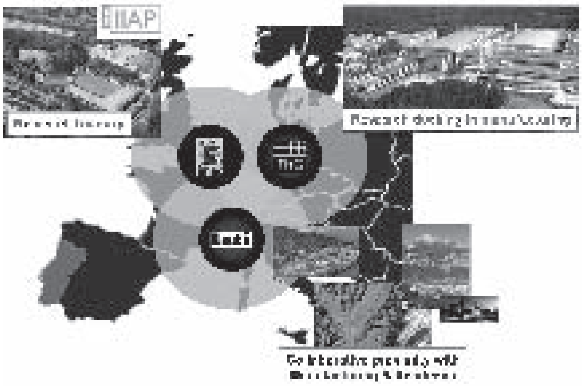

Three major centres for nanoelectronics in Europe.

accelerate dissemination and promote mobility and training. Note that the existence of various teams everywhere in Europe is useful to facilitate creativity and links with education but also to ensure a closer link between science and the general public.

Whereas transnational projects and networks are usually bottom-up, science-driven activities, which respond rapidly to new developments and have a dynamic membership, local ecosystems are usually managed environments with more static communities of scientists.

5.5 Transnational coordination

It is generally acknowledged that Europe has established a strong lead in nanoscience, particularly with regard to fundamental research. There are dedicated nanoresearch national programmes in virtually all European countries. Some of them have been running for several years and represent an important financial and strategic effort. At the EU level, nanotechnology has been an explicit priority since the Sixth Framework Programme(12).

However, the financial input of EU Framework Programmes, even after the proposed budget increase of the Seventh Framework Programme, is minor in comparison with national budgets. As a consequence, the European Research Area exhibits a lack of central coordination, in contrast with its main competitors, the USA(13) and Japan. Public and private investment in nanoscience and its application to information technologies is increasing all over the world – including Europe – and this rise in funding can only be most welcome. However, given the characteristics inherent in nanoscience as well as the particular conditions of research funding in Europe (as described above) a strategically coordinated investment of these funds is of paramount importance in order to help Europe to maintain its leading role. One should note the recent initiative to develop the ERA-NET 'NanoSci-ERA' which is a consortium of 12 national agencies.

5.6 The human factor: education and training; the nanoscience career

Our current research labour force still owes much to initiatives developed in the past. In the present situation, and in order to ensure the medium- to long-term future of nanoscience in Europe, important measures should be taken at all levels of education:

- At the tertiary level. Because of the strong interdisciplinarity of nanoscience, it is necessary to develop special training programmes that will produce the highly educated professionals demanded by nanoscience and nanotechnologies. Some European countries have started to develop such programmes and this should be further encouraged and extended all over Europe.
- At the secondary level. The disciplines involved in nanotechnology are usually perceived by students as hard and little-rewarding. This perception should be changed by initiatives showing young people the attractiveness and rewards of a career in nanoscience, such as those schemes developed in the USA. In addition, teachers should also be appropriately trained to convey the value of science to their students.

The concept of a 'career in nanoscience' does not currently exist in a meaningful sense. For example, established disciplines such as engineering, chemistry and physics have their own professional bodies and recognised degrees. These do not exist for nanoscience. Nowadays, a great number of students and young researchers are discouraged from following a career in nanoscience, particularly in Europe, because of the uncertainties and the lack of economic and professional rewards. It is therefore essential to create a clear and sound career path with a short- as well as a long-term perspective, especially after the PhD and postdoctoral stages. There are already good initiatives in this sense, such as the Marie Curie actions of the EU Framework Programme, the 'money follows researcher' agreement among European research councils and the ESF's European Young Investigator Awards, but these should be further developed and extended.

12. See also the Appendix for the contribution of Patrick Van Hove.
13. See appendix for more details in the contribution of Roland Hérino.

6. Summary – recommendations

6.1 The impact of nanosciences

Technical challenges, for the next 10 to 15 years are: superior performance (operations per second, storage volume and access time), lower power consumption, and diversification of functionality. In addition there is an increasing need to handle complexity and design defect tolerant architectures. For the next 10 years, new processes and new materials will be required to reduce the transistor size. In addition, it will be necessary to integrate different technologies (logic elements, photonic devices, sensors, radio-frequency modules, etc.) to produce hybrid systems for new applications. Beyond 10 years, when the transistor scale length will be around 10 nm, additional concepts will also be needed beyond the current transistor scheme. Some of them could be innovative spin offs from research on new paradigms not constrained by silicon, such as data storage (particularly 3D), energy sources, displays and high-frequency routers. Many of these new concepts appear very promising today. They could lead to new applications and possibly a new large-scale industry. To accelerate progress, there is also an urgent need to improve predictive simulations of nanostructured materials, which interface to higher level design tools for the holistic design of systems with billions of transistors.

6.2 Science, society and the market

Scientists, particularly in the domain of nanoscience, will be compelled to exchange knowledge and expertise across disciplinary borders. Most exciting breakthroughs can be expected from the convergence of nanoscience with information technologies, biotechnology and medical-cognitive sciences. A striking point is that often these new developments could have a strong impact on everyday life or even raise new ethical issues. Attention should be paid to the following factors.

• The human factor
The applications of nanoscience to information and communication technologies will have important implications both for the institutional bodies and policy makers and for the general public. Research in the field of ICT should be accompanied by programmes in social sciences to investigate the human factor and more generally the consequences of the implementation of new products. Apart from the considerations about the market, social acceptance and economic development, it is important to formulate long-term aims for these programmes in terms of societal goals: health, safety, culture, e-democracy, helping disabled people etc.

• Communication
It is extremely important to provide policy makers and the public with information about the potential benefits that nanotechnologies will bring to society, including security, health, leisure etc. but it is also important to inform them of the possible drawbacks or misuses. Dissemination activities should be strongly promoted: publications, open-house initiatives, public dissemination events etc.

• Building trust
Implementation of revolutionary technologies can be built only by providing information, debate and transparency. Debate occurs if the usefulness of new products is not obvious. This is not a trivial issue: the market is a regulation mechanism for products sold to the general public, but not for ICT products sold to institutions or retailers, which could endanger privacy of citizens or customers. In addition it is necessary to convey to the public that the necessary measures are being taken to ensure the safety of citizens. Particularly, regulations should anticipate emerging issues related to privacy and control of information, the potential impact on economic growth etc. The weight public research community, its proximity to the general public are likely important factors.

• Anticipation
One can not deny that, for better or worse, we are living in a global world based on ICT; and the key factor to shape its future will be anticipation. Experts in law and ethics, and policy makers should come together to discuss the necessary regulations that will lead to an improved quality of life for all.

6.3 Organisation of research

Nanoscience, and particularly those areas having a potential impact on information and communication technologies, are characterised by three factors whose concurrence has set it apart from other revolutionary fields of science and technology:
- Industrial impact. Nano-applications will be integral to a wide range of industries, but they will not generate a single nanotech industry itself – unlike the case of the semiconductor electronics industry.
- Strong interdisciplinary requirements. The development of nanoscience and nanotechnology requires personnel highly qualified in more than one scientific-technological discipline.
- Capital intensive. The required equipment, infrastructures and human resources are increasingly demanding in terms of funding.

The relationship between science and technology is rather complex and is analogous to a bacteria ecosystem, exhibiting phenomena such a symbiosis, horizontal transfer of genetic material.

For profitable ‘cross-fertilisation’ the following conditions are required:

- **The coexistence** of various schemes with the following complementary goals:
  – academic teams with strong networking activities to cope with long-term challenges;
  – local clusters (pockets or poles of excellence or innovation). These structures which can handle long-term technological research, the largest ones being more dedicated to research industry transfer. In most of the cases the results from fundamental research require additional development to be implemented in a fabrication process.

– **Contact and exchange between academia and industry to detect new opportunities.** These opportunities can be of various types: improvement of the existing technology (downsizing devices), niche applications (such as storage), new paradigms (such as quantum computing), implementing the convergence of technologies. The nature and organisation of exchange vary for these schemes. This exchange should be promoted by means of science fairs and other joint events as well as the creation of poles/pockets of innovation. However, industry should never determine the direction of basic research. Therefore, fundamental science funding should remain essentially public.

- To take into account and where possible to reduce culture and time constant mismatch between scientists and engineers.

- The **building of a critical mass** at a European transnational level, particularly in relation to networked human resources, research infrastructures and centres/areas of excellence. This should be accomplished, not only through EU Framework Programmes, but also through the coordination of national programmes. Given the relatively small fraction of European-level funding compared with national programmes, it may be more fruitful to concentrate EU-level investment on promoting multidisciplinary teams of nanotechnology researchers and system architects, leaving major infrastructure funding to joint efforts of national funding agencies.

- An **efficient multidisciplinary coordination**, since breakthroughs are likely to come from joint efforts of multidisciplinary teams of researchers from the fields of biology, chemistry, microsystems and information technology. Emerging examples of collaborative transnational efforts are the recently launched ERA-NETs in nanoscience and the ESF EUROCORES programme in Fundamentals of Nanoelectronics. This kind of initiative should be further developed and encouraged in the future.

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Appendix 1

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Appendix 2 – Contributions

Nanosciences and Information Technologies: US policy

Professor Roland Hérino

Research and development in the USA is mostly performed by three different agencies, the Federal Government, the universities and industry. The private effort, focused on applied research and development, is the most important. Basic research is conducted mostly by universities and federal institutions. The global budget of R&D in the universities is in the range of US$30 to 35 billion per year; 60% of this amount comes from the Federal Government and another 20% from state or local public funding. Research priorities are determined mainly by the policy and the programmes of the Federal Government, the major contributor to their financial support.

The US Government's policies are defined with the help of the Office of Science and Technology Policy (OSTP) from the Executive Office of the White House. The OSTP serves as a source of scientific and technological analysis and judgement for the President with respect to major policies, plans and programmes of the government. It is headed by John Marburger, who also chairs the President's Council of Advisors on Science and Technology (PCAST); this body consists of 23 members appointed by the President and drawn from industry, education and research institutions, and other nongovernmental organisations. The National Science and Technology Council (NSTC) is the council that prepares research and development strategies coordinated through federal agencies. Information technology and nanotechnology are two of the six interagency R&D priorities approved by the President. They are coordinated by Interagency Working Groups (IWG) in which the staff members of the agencies meet to discuss their plans and programmes. In 2001, the National Nanotechnology Initiative was set up and the IWG on Nanotechnology was disbanded.

The National Nanotechnology Initiative (NNI) is a federal programme established to coordinate the multi-agency efforts in nanoscale science, engineering and technology. The NNI is managed by the Nanoscale Science Engineering and Technology (NSET) subcommittee of the NSTC, which coordinates planning, budgeting, programme implementation and review.

Federal funding for nanotechnology has increased more that twofold since the setup of the NNI in 2001 and will reach an estimated $1.081 million for 2005, 65% of which will support academic research. The major part of this sum is allocated to six main agencies; about 75% goes to the National Science Foundation (NSF), the Department of Defense (DoD) and Department of Energy (DoE). The largest investments are made by NSF (more than 30% of the budget), reflecting that agency's broad mission in supporting fundamental research. The second, with about the quarter of the budget, is DoD, with its emphasis on development of materials, devices and systems that address the agency mission. DOE, with nearly 20% of the budget, is in the process of completing five Nanoscale Science Research Centers that will provide equipment and infrastructure to the scientific community. The big increase in the budget of Health and Human Services ($145 million compared with $80 million in 2004) now consists of about 14% of the total federal funding results of the National Institutes of Health's (NIH) new programmes which emphasise nanotechnology-based biomedical research. The two other big contributions come from the Department of Commerce, through the laboratory activities of the National Institute of Standards and Technology, and from NASA which funds four of its own research centres.

The NNI funding strategy is based on five modes of investments. The first one supports a balanced investment in fundamental research across the entire breadth of science and engineering; specific areas of focus include:

- novel phenomena, material structures, processes and properties;
- nano-biosystems;
- nanoscale devices and system architecture; and
- theory, modelling, and simulation.

The second investment mode focuses on nine specific R&D areas, known as the Grand challenges, that are more directly related to applications of nanotechnology and that have been identified as having significant economic, governmental, and societal impact. These nine areas are:

- nanostructured materials by design;
- manufacturing at the nanoscale;
- chemical-biological-radiological-explosive detection and protection;
- nanoscale instrumentation and metrology;
- nano-electronics, nanophotonics, and nanomagnetics;
- healthcare, therapeutics and diagnostics;
- efficient energy conversion and storage;
- microcrafts and robotics; and
- nanoscale processes for environmental improvement.

The third mode of investment supports centres of excellence that pursue multidisciplinary projects together with researchers from different sectors, including academia, industry and governmental institutions.

The fourth investment mode funds the development of infrastructure, instrumentation, computational capabilities and other research tools dedicated to nanoscale R&D. This type of funding has been used to develop the National Nanotechnology Infrastructure Network (NNIN), which consists of 13 centres with user facilities that are available to all researchers on a proposal-reviewed basis.

The fifth and final investment mode recognises and funds research that addresses the ethical, social, legal, economic and workforce implications of nanosciences and nanotechnology.

One of the important missions of the NNI is to facilitate the transfer of the nanotechnology discoveries from the laboratory to commercial use and public benefit. One approach is to foster the interaction between the R&D actors and those who manufacture and sell. This is done by establishing NNI-industry liaison groups to promote exchange of information on NNI research programmes and industry needs that relate to nanotechnology, by funding multidisciplinary research teams that include industry and university researchers. This is achieved through programmes such as GOALI (Grant Opportunities for Academic Liaison with Industry), by encouraging exchange of researchers between universities and industry, and by supporting meetings to facilitate interaction among researchers from academia, government and industry.

The worldwide workforce necessary to support the field of nanotechnology is estimated to be two million by 2015, and there is an increasing need for nanotechnology related education at all levels and for all ages. The NNI uses various approaches to develop educational resources. The geographically distributed centres of the NNIN provide graduate students and young researchers with access to state-of-the-art facilities: training programmes are implemented, such as the Research Experience for Undergraduates programme which allows engineering and science students to spend 10 weeks during the summer in one of the NNIN centres. Only a few universities offer degrees in nanotechnology, some for educating nanotechnicians, others provide a master's degree, whereas only three universities have a doctoral programme related to nanotechnology. On the other hand, a vast number of research universities offer introductory courses in the field, giving students who are pursuing fundamental studies in their discipline the opportunity to learn about nanotechnology and the chance to develop an interest in nanoscience doctoral studies.

Contribution to the ESF Forward Look on Nanosciences and the Future of Information Technology

Professor Manolis Katevenis,
Dr. Kostas Marias, Dr. Alexandros Lappas

Policy issues related to nanotechnology

Nanotechnology is a multidisciplinary research field targeted at the development of novel materials and tools for enhancing the performance of sensors, actuators, computers etc. While the first commercial platforms for nanomanipulation, nanometry and nano-assembly are being launched, several scientific questions concerning the robustness, usability and rapid dissemination of nanotechnology advances remain unanswered.

Nanotechnology promises new disruptive functionalities in the domain of data handling, storage and communication. While Europe has set to itself the goal of becoming a world leader in Information Technology (IT) within the next decade, it is still weak in architectures and systems software whereas the USA (and the Far East) appear to be uncontested leaders and are aggressively moving ahead into successive new architectures.

IT is based on technology layers (levels of abstraction) where the next layer up is based on the previous layers down, and where the *raison d'être* of the layers below is to support and make possible the layers on top; for example:

- nanoelectronics and IC fabrication
- electronic design automation tools
- digital systems architecture
- systems software (compilers, operating systems, tun-time systems, middleware;
- applications software
- services.

While Europe is quite strong in the field, and has dedicated R&D funding, in several of these layers, it is weak in architectures and systems software. Unless Europe becomes strong in all of these layers, it cannot claim the world leader position that it deserves, and the external dependencies that will ensue will constantly endanger any progress on all of the layers including nanotechnology. We believe that such advanced applications require new, advanced hardware platforms and therefore Europe should actively support hardware architecture and computer systems while it considers the future of nanotechnology.

Scientific objectives and considerations

From the scientific research standpoint, FORTH (Foundation for Research and Technology – Hellas, Greece) has actively been involved in discussions and proposals for defining the new challenges concerning the development of software components for accurate manipulation of nanoscale objects. Theoretical investigations on the other hand have two basic targets, namely the justification of the experimental findings and assisting experimental efforts to choose the optimum set of materials that will be suitable for the production of electronic nanostructures with predetermined properties. The aim is to uncover a way to exploit functionality through theoretical understanding and implement the benefits of new and technologically oriented nanomaterials in potential applications.

Furthermore, modelling and image analysis for various nanostructures, both in atomic force microscopy (AFM) and scanning tunnelling microscopy (SFM), image data since these two modalities have complementary advantages. This research direction is particularly attractive for FORTH since it possesses valuable and complementary experience in computer vision, image processing, multichannel data fusion, human–computer interfaces and VLSI design.

From the materials point of view, major breakthroughs could be achieved via a balanced combination of cost efficient 'bottom up', easily installed, customised chemical methods and 'top-down' technological exploitation, thus realising templates of nanostructured compounds that can set the stage to exploit modern technologies, such as field emission, high density magnetic or optical data recording, energy storage/production, interconnects, biological sensing/labelling, etc.

Integrating in the former (that is, bottom up), new processing methods, such as wet-filling of simple polymeric membranes for manufacturing nanowires grown out of 'core/shell', onion-like materials calls for multidisciplinary approaches to achieve the objectives. The prerequisite is to offer easily modified model systems, with strong interactions between their magnetic, electronic and crystal degrees of freedom which, however, can be tuned by controlling aspects such as length, diameter and channel separation of the templating membranes. This offers a great advantage over nanostructures engineered by combining a range of technological methods, which although they produce comparable qualities (that is, narrow size distribution, lack of defects, enhanced structural coherence), they do require, however, highly-demanding epitaxial growth of the constituent materials.

Bottom-up approaches, carefully combined with microelectronic methods for construction of patterns and interconnects offers an alternative approach for producing nanomaterials with a high degree of order. For example, it is very difficult to find a suitable combination of grain types and natural substrates that can lead to self-organised grain-arrays exhibiting high (magnetic) blocking temperatures. On the other hand, patterned-substrates alone, used for technically imposing self-organisation do not yet meet technological needs regarding density and quality of patterns. Instead, combining the latter with bottom-up methods allows suitable control of the properties of nanometre-size structures leading to new science as well as new products and devices, avoiding possible limitations imposed on the abilities of instrumentation (for example, for miniaturisation) by current advancement of technologies.

In this respect a particular area of interest is the development of novel computational-imaging techniques for tracking nanoscale structures over time as well as combining information from different channels into the same display/interface in order to maximise manipulation efficiency and accuracy. Complementarities can be drawn through 'pump-probe' methodologies that uniquely build on physical processes via time-resolved studies. In addition, the response of dynamical phenomena at the nanoscale to external stimuli warrants a 'reach field' of novel interactions. Identification of collective dynamics of molecule-based entities, including microscopic relaxation mechanisms such as electron-phonon, spin-reorientation, or spin-oscillation can provide a better understanding of technologies in the field of magneto-electronics (for example, computer storage, magnetic random access memory etc.) and suggest or unravel means to control size-dependent effects that may arise from nanostructuring and integrating such materials into multifunctional (opto-magneto-electronic) devices.

FORTH has secured international collaboration for promoting these research objectives, also aiming at extending them towards the robotic manipulation of nanosurfaces and in the long term, to the design of nanoscale electronic circuits that could potentially be constructed by manipulating carbon nanotubes. The prospect of nanomanipulating biological entities is also of great importance for future collaborations amongst the FORTH's institutions in Crete.

It is also important to mention that the difficulties in integrating sparse resources and expertise from heterogeneous disciplines are a significant limitation for the advancement of nanotechnology both within the Greek and the European research community. Apart from promoting international collaboration and conducting basic research as stated above, a basic ambition of FORTH is to inspire local institutes in Crete that hold complementary resources and technology

(AFM scanner, UV microbeam laser) to collaborate in order to promote integrated research focused on nanotechnology.

Law in a New Frontier

Mrs. Sonia E. Miller

> 'History is, in large measure, the study of change…
> But the changes now upon us are qualitatively different from those that have gone before…we are beginning to understand what truly revolutionary change means…Quite a new frontier. And, as in any frontier, it takes time and experience before
> the relevant mores, rules, and laws can be fully defined and
> the appropriate social and economic structures put into place…
> In the interim, we frontier people must function with one foot – or, should we say, one part of our minds and spirits –
> in the old world, and one in the new.'
>
> Roberta R. Katz, *Justice Matters* (1997)

With the arrival of the Internet, the physical plane through which we identified and defined our relationships and reference points disintegrated. The non-physical terrain of cyberspace dissolved geographic boundaries and demarcations. Borders became invisible and new business, economic, political, educational, social, cultural, ethical and communication forms evolved. International space and time collapsed at a moment's click. The World Wide Web was foreign territory just a few years ago. Yet legislation was drafted and case law decisions made as if the world's geography had gone unchanged. Efforts at fitting square pegs into round holes continue today as the US and international legal systems still base their jurisdiction over legal issues by circumscribed lines within a spatial environment – local courts, state courts, federal courts and regulatory agencies.

Enter nanotechnology – the building block of the small. This is a tool which represents the enabling ability to transcend the unthinkable – such as to automatically dispense specific biochemicals and pharmaceuticals to particular body tissues as needed via smart nanoscale drug-delivery devices, detect and image worn or damaged body parts through smart embedded sensors, advance computational powers beyond Moore's law, enhance material properties, advance molecular-cluster manufacturing, develop carbon nanotube products and ceramic nanoparticles for use across industries.

While nanoscale materials are already embedded in many products such as cosmetics, sunscreens that incorporate titanium dioxide nanoparticles to prevent sunburn, clothing that is made from hydrophobic nanofibres to help resist stains, and power machinery, our current manufacturing processes, educational systems, business models, economic structures, healthcare, environment, defence, space, energy and societal infrastructures will be transformed without recognition as further advances in nanotechnology research and development, and commercialisation of the applications of this scientific discovery are integrated. These global benefits also carry unintended societal consequences and legal ramifications.

While the need to address the legal and regulatory implications of nanotechnology is often mentioned in reports, workshops and conferences, the broad complexity of the issues within the multiple clusters of legal practice areas remains overlooked or ignored. Historically, the law has lagged behind scientific and technological advances by at least a decade. The law cannot continue to live in the past, nor should society and the scientific and engineering communities accept that as its standard mode of existence. With science and technology's relentless advances and society's centrifugal forces, the civil justice system of the twenty-first century must come out of obsolescence to lead and help shape the new values, standards and rules of play wrought by this new frontier.

What active blueprint for change will enable today's US and international legal systems to forge collaborative relationships with diverse partners to diffuse the societal and economic implications of nanotechnology?

1. **Establish a consistent and accepted definition of terms and communication protocols within scientific disciplines globally and within international legal systems**
   What is nanotechnology, its worldwide market, applications, industry and competitive value?
   What is the legal definition of 'human', 'person'? When does life form? What constitutes human life?
2. **An understanding that the law must be viewed from a broad perspective through the convergence and possible integration of multiple legal practice areas**
   As nanotechnology and nanoscience converge with other sciences and technologies, and advanced computing and human–machine integration speeds forward, the resulting issues and impacts will cut across several legal practice areas as follows:
   - Criminal law through DNA forensics, its determination of 'free will', and human-trial experimentation.
   - Family law as a result of genetic intervention capabilities, creation of artificial life forms, and stem cell research.
   - Health law and the US Department of Labor's Employee Retirement Income Security Act (ERISA) resulting from nanoconvergence with medicine and biotechnology.
   - Environmental law because of the unknown risks of radically new technologies, such as the effects of inhaled nanoparticles and the fact that they change shape as they move from liquid solutions to the air, the release of buckyballs into the air and water and its effect on pollution and the food chain, and the likelihood of animals and people being exposed to hazardous materials and toxicity.
   - Energy as new possibilities and forms are developed and the effects of their use undetermined.
   - Transportation as new developments are incorporated into the automotive and aerospace industries.
   - Elder law resulting from an ageing demographic arising from improved medical processes.
   - Torts because of the potential for personal injury arising from product misuse or mishap whether intentional or negligent, and trespass of nanoparticles.
   - Intellectual property; for example patenting of all life forms, both engineered and enhanced, intellectual property rights of multiple parties, the question of who owns innovation by machines and human-machine hybrids (artificial intelligence and genetic algorithms), the need for due diligence prior to commencement of research to determine possible infringement, revisitation of the Bayh-Doyle Act[1] and the commercialisation of converging products from laboratory to market by multiple licensees, protection of trade secrets, copyrights and trademarks, maskworks, and international recognition of rights and assets.
   - Corporate law and contracts, formation of new entities, agency and partnership relationships, mergers and acquisitions, licensing of multiple parties who hold multiple patents, technology transfer confidentiality and non-disclosure agreements, patent cluster portfolios and other new forms of agreements.
   - Constitutional law, the courts, the judiciary, protection of individual rights and equal protection as privacy rights, security and surveillance become more invisible through advances in computing, biometrics, e-commerce, and federal legislation.
   - Employment and labour law and the potential for discrimination resulting from issues of equity, distribution, and access.
   - Tax of and incentives for new product entries.
   - Real property law.
   - International trade laws, trade regulation, cus-

1. This US Act sets out the dispositions of inventions made with federal assistance.

toms and cross-border jurisdiction as the issues impact interstate commerce and anti-trust concerns as more competing parties collaborate.
- Civil procedure, litigation and medical malpractice.

3. **Provide for open discussion with stakeholders regarding the pros and cons of regulating the industry versus self-regulation**

4. **Invest in training and development in the federal agencies, regulatory bodies and judicial systems**
As monies are allocated for research and development in new sciences and technologies to improve humanity and the quality of life, so too must monies be allocated to the agencies and systems which must understand, oversee and be ready to respond to the new frontiers. Otherwise lack of expertise will create bottlenecks to commercialisation of emerging technologies extending the timeline to market for a product. The US Patent and Trademark Office (USPTO) lacks a specialised nanotechnology examining group, technology centre or art unit. Examiners are not trained to understand the multidisciplinary legal issues which may result from nanotechnology. Applications could thereby be delayed slowing the commercialisation process. The Food and Drug Administration (FDA) needs additional training in understanding the differences between a medical device, a drug, a biological or chemical entity and when a product may look like food but act like medicine. The delays encountered in the patent process at the USPTO trickle down to the review process at the FDA. The Environmental Protection Agency (EPA) must have the capacity to work in concert with the USPTO and the FDA, as well as the Consumer Products Safety Commission and the Federal Trade Commission, as the implications of new discoveries arising from nanotechnology intersect across several regulatory and oversight bodies. This begs the question: should a central oversight agency or commission be developed? Are the currently enacted regulatory and policy models sufficient to resolve the issues of unknown and unforeseen risks?

5. **Consider the adoption of specialised courts for converging science and technology cases, and court laboratories for training and development – the courtrooms of the future**
Judges, legislators and policy makers need to understand the lexicon and the short- and long-term cross- and multijurisdictional impact and effects of the complex issues expected to be raised by new applications. Maryland, with the enactment of Rule 16-205 on 1 January 2003, became the first state in the USA to adopt a specialised court for business and technology cases. Under Rule 16-205, each circuit court is charged with establishing a special track for business and technology cases, creating a procedure for assigning cases to that track, assigning specific judges to the programme who are specially trained in business and technology, and with developing alternative dispute-resolution proceedings conducted by individuals specially trained in the issues. Our judicial system continues to function based on the needs of the Industrial Age. As Maryland has recognised, we must take measures to bring the courts into the present, at least forward to the Information Age, and then to the new frontier – the nanotechnology revolution.

6. **Educate the scientist, engineer and technologist in the science of business, ethics and jurisprudence**
As there is a call to educate the legal infrastructure, so too must the scientific, engineering and technological communities understand the issues from the laboratory to the marketplace, the ethical implications of research claims of novel innovations, the dissemination of research results, and the interplay of law with business and new inventions.

7. **Call for an international convention through the United Nations**
The effects of nanoscience and nanotechnology transcend global boundaries. Dialogue should begin to address international implications, commerce, foreign policy and the possible need for treaties.

8. **Begin to educate the consumer in the facts versus the fiction of nanotechnology**
Monies continue to be poured into studies to determine consumer attitudes, and into research schools to convene open discussions with peers about the issues. It is time to convert the passive approach of studies and research into active consumer protection education and review of the current laws. Television, the press, books and movies are feeding the consumer while advocacy groups are providing unsubstantiated studies of the adverse effects of nanotechnology. Fears must be properly assuaged, now. This is critical

for nanoscience and nanotechnology to realise its true potential.

9. **Create legal shops for the small business entrepreneur**
   Legal costs run high for a start up entrepreneur thereby ousting him or her from the competitive nano-marketplace. Offering unbundled legal services can reduce the cost of lawyer's fees while teaching an entrepreneur how to individually manage certain legal processes. The lawyer and patent agent thereby become legal information engineers in a consultancy capacity.

We live in a transitional era. While this is not a comprehensive list of legal concerns and recommendations, it is a small representation of the vision we must employ concerning the implications of this new frontier. Advocating that the laws, policies, regulations and legal systems currently in place need to be completely overhauled or eradicated to meet the challenges of nanotechnology would be absurd. It does mean, however, that we must be vigilant to the societal impact and implications that accompany exponentially rapid change. Current laws, regulations and policies must be analysed to determine those that continue to apply and those which must be modified to meet today's challenges. Our judicial infrastructure must be evaluated. Our agencies and commissions must work in concert. Today, we have the opportunity to lay a new foundation, to design anticipatory legal and policy measures, propose new legislation, and develop novel and unique regulatory infrastructures to address the potential risks of tomorrow.

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Challenges for Nano-based IT Systems

Professor Robin Milner and
Professor Martin Wirsing

The emergence of nanotechnologies in IT will be fuelling a 'silent revolution' in computing. Nano-based devices will possess orders of magnitude, more computing power and memory than the machines of today. They will shrink in size to the microscale, possibly nanoscale, as biochips and quantum computing devices will be integrated with more conventional chip technologies.

This silent revolution will accelerate the advent of pervasive computing which is already proceeding even without nanodevices. A growing population of invisible computers will be with us and around us, embedded in our clothes and even our bodies, in the fabric of our homes, shops, offices, vehicles and public areas. Pervasive IT systems will help us command, control, communicate, do business, travel and entertain ourselves, and these invisible computers will be far more numerous than their desktop cousins. Further examples are emerging in the area of ambient intelligence, global ubiquitous computing, and service-oriented computing.

This development will be greatly accelerated by the emergence of nanodevices, since they will add further orders of magnitude to the available computing power and memory, and consequently to the complexity of pervasive systems. Nano-based IT systems will consist of visible and invisible devices with embedded nanocomputing technology which will be capable of computation, communication and information processing, will be able to interact with their surroundings and possibly be self-aware with adaptive and anticipatory behaviour and capabilities of self-diagnosis and self-repair.

These new nano-based IT systems present unique challenges to their developers. As the complexity of systems grows by orders of magnitude, and an increasing proportion of their devices becomes invisible, so will properties such as trust, privacy, security and reliability become ever more important. New programming and modelling abstractions that emerge with bio-, nano- and quantum computing need not only new sound construction principles, semantic foundations and powerful analysis techniques but also have to be made interoperable with actual object-oriented and real-time methods. Engineering techniques are needed which support the whole system life cycle including requirements, design, implementation, maintenance, reconfiguration and adaptation.

It is already recognised that the revolution of pervasive computing and in particular of nano-based pervasive computing requires a combined effort to derive new foundational theories, and new engineering techniques that are firmly based upon them. Research is required for:

- developing adequate programming and modelling abstractions for nano-based pervasive IT systems together with calculi, theories and automated tools allowing descriptive and predictive analysis of systems at many levels of abstraction;
- developing innovative engineering support for such systems, to ensure the required levels of quality. This includes guaranteeing properties such as security, privacy, safety, trust, reputation, fault tolerance, behavioural and real-time properties.

The importance, urgency and difficulty of achieving these goals are all sharply increased by extra orders of magnitude in system complexity that will inevitably follow the advent of nanosystems.

Improving Design by Understanding Usage – outline of an ecological design concept for smart environments

Dr. Leena Norros

Introduction

Information and communication technology (ICT) will have profound impacts on all spheres of life; for example, in everyday life, systems of production, and institutions and culture. New challenges for human–technology interaction (HTI) are expected particularly in the cross-sections between these traditional domains (Tuomi 2001). Traffic and communication systems, agriculture, or wellbeing industries are examples of new expanding HTI-utilisation areas.

Technology is conceived as the major driving force for economic growth and wellbeing in society. Consequently, much effort has been devoted to encouraging technical innovations. Several information technology roadmaps identify technologies that may affect HTI and user interfaces (Norros et al. 2003; Plomp et al. 2002; Ventä 2005). The future ICT is foreseen to enable a combination of a high level of user mobility and embedded technology, and multimodal user interface technologies will become available.

Critical analyses indicate, however, that neglecting the user in the design may create a bottleneck in the development of the knowledge society. The technology-led view is becoming balanced by views that stress the equal role of social innovations in the development of the knowledge society (Naumanen 2004; Norros et al. 2005). It is necessary that the rational relationship to nature that becomes manifest in scientific knowledge would be completed by a rational practical relationship to nature. Such an attitude protects us from technological hubris in our attempts to control the laws of nature by offering an opportunity to reflect on the long-term effects of technology on the quality of human life and the living environment (Von Wright 1998). In this paper I shall discuss research and design approaches that could promote such a deeply rational and human-centred development of technology. I propose that at least three issues are important in concretising this trajectory: The first deals with understanding the generic characteristics of ICT as an artefact compared with any earlier technologies. The second issue deals with the need to comprehend smart technologies as a new living environment. Finally, I argue that there is a need to bridge the deep-rooted conceptual and practical di-vision between design and usage, and, eventually, to make use of their complementary roles in the artefact genesis.

ICT is a universal technology with instrumental, cognitive and communicative functions

Compared with any earlier methods of information dissemination and communication, ICT is a far more general and even universal technology that has practically no alternative. As such, ICT not only changes concrete activities but revolutionises the societal activity structure as a whole and the complete relations of activity and consciousness (Rückriem 2003). Hence, when we study the use of ICT it is necessary to consider it both as a tool for making and as a medium for making sense of things. Hence a comprehensive analysis of ICT considers the tools and media in their instrumental, cognitive and communicative functions.

We made use of the above distinction between the roles of ICT when considering the future HTI research issues in VTT roadmap work (Norros et al. 2003). In this connection we found, however, that because these functions of technology are typically tackled within different research traditions, new theoretical challenges emerge when aiming at their holistic understanding. The relationships between theories of human action and activity, on the one hand, and media theories on the other, need to be revisited and their mutual connections analysed. It has been proposed that systems theory would offer some help in bridging the gaps between theories and in improving understanding of the generic cultural impetus of ICT.

An ecological methodology to guide research and design of smart objects and environments

Human–technology interaction (HTI) research has traditionally focused on the analysis of single tools. This claim applies to both major traditions of HTI, namely ergonomics and human-factors research that mainly focuses on complex industrial work, and the human–computer interaction research that originated in office work but currently flourishes in the usability analysis of consumer appliances. At the same time as ICT technology has brought the target domains and research issues of these two research traditions closer to each other, we can also identify a further trend. By enabling mobility, embedded solutions and new user interfaces, ICT is transforming work and everyday living environments in a comprehensive sense. It becomes evident that human action does not deal with interaction with separate objects (human–computer interaction) but rather with the environment as a whole. Consequently, new more systemic approaches are needed to analyse, design and evaluate activity in smart environments. On the initiative of VTT, The Finnish National Funding Agency for Technology Innovations (TEKES) launched a research project aimed at new research and design concepts for smart environments from an ecological point of view (ÄES 2005).

Within the ÄES project we are currently defining the principles of an ecological approach to smart environment design. We see at least four principles that we are planning to elaborate conceptually and demonstrate empirically in the project. These tentative principles are:

1. **Human–environment interaction is one functional system**
   In the design of smart environments the human–environment interaction (transaction) should, from a methodological point of view, be conceived as one functional system (Ingold 2000; Järvilehto 2000). Such a functional system explains behaviour as being structured according to its results and with regard to the constraints and possibilities of maintaining action. It does not perceive behaviour in simple linear causal relations terms. Cognition is conceived as embedded and distributed within the elements of the system and intelligence is characteristic of the whole (Hollan et al. 2000). Ecological design of smart environments focuses on developing appropriate functional systems.

2. **In the design of smart environments we focus on the dynamics of human environment system**
   As the notion of ecology assumes it is necessary to analyse the interactions and developmental dynamic phenomena that take place within the human environment system. We see it important to develop means to understand the result-oriented organisation of human behaviour in smart environments, to elaborate the organisation by understanding the diverse spatial and temporal connections between different functional systems and activities in which people may be involved simultaneously.

   We also consider that an historical dimension is necessary to understand the structuring of activities. Challenging thoughts of the role of technology in moulding human perception and consciousness were brought up by Marshal McLuhan (McLuhan 1964). By the expression ‘the media is the message’ he claimed that media provide the background that shapes human perception and consciousness. We see possibilities to make use of McLuhan’s conceptualisations of the generic dynamics of the influence of technologies (McLuhan and McLuhan 1988). It may be particularly relevant to consider his ideas of the nature of the electric medium. According to McLuhan it is the role of the artist to reveal the impact of the media on our perception, thinking and action. Without artists, he claims, human actors merely adapt to their technology. I consider that human–technology interaction research should be able to learn from the arts and strive for the articulation and understanding of the immediate background effect of technologies.

3. Usage and design – two functions in artefact genesis

There are three issues that every approach within HTI research has to tackle. The first is the conception of design, the second the conception of the user activity (which was discussed above), and the third is the conception of interaction between design and usage (Carrol 1997). In developing the ecological design it is necessary that we analyse our relationship in all these issues.

Design is today usually considered as an iterative process. This definition of the process of design is of course an important starting point. We claim, however, that the current design concepts could benefit from extending their definition of what is the object of design. We see that today the product is usually conceived as the object of design. Consequently, the design process itself will be tackled as a very tightly constrained linear (even though iterative) process of actions that enable the production of the result. It will also be evaluated against well-defined success criteria, and the quality of the design process is defined through a good controllability of the process. If the object of the design is understood as the creation of new possibilities for human activity the process becomes much more uncertain but also creative. This is what so-called 'concept design' is all about. There are examples that show that leading manufacturers in particular domains have adopted concept design as a tool to project their future business activities and to envisage new ways and values of usage (Keinonen and Jääskö 2003).

Interaction between design and usage has, of course, long been identified as an important issue in good design. This principle is already implicit in the concept of iterative design. We argue however, that these two activities have often been treated as interacting with each other in a more or less external manner, without themselves becoming obliged to transform in this interaction. Design is treated from a process point of view, usage sporadically via user tests. In the ecological design concept that is more and more interested in creating new possibilities and ways for living, it also necessary to pay more attention to understanding the activity through which the these possibilities may be created.

The approach that has been termed the 'instrumental genesis' approach (Beguin and Rabardel 2000) advocates the idea of parallel development of activity (instrumentation) and the tool (instrumentalisation). This process takes place in a collaborative process in which both designers and users are active actors and undergo a learning process. In our own studies we have been able to describe and verify the learning processes of users with reference to their subjective disposition to the developing instruments and their conception their own role as users (Norros 1996).

4. Design of smart environments requires integrated evaluation of the appropriateness of the design outcome

Evaluation of usability of artefacts is an existing practice in human–technology interaction research. It should be no surprise that in an ecological design approach new evaluation concepts must be developed. More problematic is to understand how the present evaluation processes, practices, indicators and criteria should be developed so that they can grasp essential features of the benefits of smart environments. In the following, some tentative ideas are raised.

In our own ongoing work we have used the concept of system usability as a tool for incorporating the developing evaluation concept (Savioja and Norros 2004; 2005). The notion system indicates first, the need to understand the smart artefact or environment in a holistic manner. The artefact will, according to our ideas of the technological nature of ICT, serve the above-mentioned three basic functions at the same time. These were the instrumental, the cognitive and the communicative function. Accordingly, it is necessary to reflect the artefact from all these points of view. We see further that in order to succeed in such an integrated evaluation the artefact must be studied in usage. Consequently, performance-based evaluations are necessary. In performance-based evaluations we have proposed a concept to distinguish between outcome evaluation and evaluation of practices. The former is seen to express what has been called the 'external' good of practice, whereas the latter focuses on what is considered as the 'internal' good of practice (MacIntyre 1984).

The most important integrative indicator in the evaluation is connected to the experiences of the users and, also of the designers, of the potentiality of the concept or the designed product becoming a part of a significant practice. This indicator is emotionally laden, which is the strength of the indicator. It may be argued that the users will experience a positive emotion when they, as experts of their work and everyday life, identify a genuine new possibility for action. The evaluator should, however, remember that when seeking proof of such experiences it is necessary to consider the effect of the artefact in both a theoretically rational and a practically rational sense, as Von Wright would demand of humanistic development of technology.

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New Ethics for Nanosciences and the Future of Information Technology? Let the limits move.

Dr. Françoise Roure

When addressing the convergence between nanoscience and information technology, as individuals taking one modest part in a cultural mosaic, we must admit that we are confronted with the prospect of an increasing complexity which, subsequently gives access to an unlimited universe of uncertainty. The potentially unlimited combinations of nanotechnologies and IT on the one hand and, taken together, the combinations with biotechnologies and neurotechnologies (I would not address the cognitive sciences in this presentation) on the other hand, increases the perception of uncertainty.

And we, as individuals, feel uncomfortable. Unless a clear-cut ethical code enlightens choice, it is unclear whether the decision, for instance, to make an experiment directly involving, or potentially modifying the information system and the ‘ conscience’ embedded in the human body, will involve an emotional state of guilt or not.

As a matter of fact, convergence between nanotechnologies and IT brings together all good, productive and useful applications of nanosciences – for example medical repairing applications – and non-desirable or even not acceptable intentions and implementations. It raises the question of risk governance and its dilemma for policy makers, torn between too much protection, or losing public trust.

It is here that the question of **limits** comes in.

The cultural, professional reaction to this negative feeling is to adopt a routine attitude, a protective and also a professional one, which consists in mapping and assessing risks related to breakthroughs, by following a rigid, once and for all established technical guide, which prevents us addressing the normative ambiguity related to the way in which we interpret the assessment results.

Which ‘routine’ are we talking about here?

The one which is referred to as a reassuring, well known working instruction: ‘find **the right balance between risks and benefits**’, let institutions give it the green light, once and for all, and go ahead. What it means is that, depending on the degree of openness related to the scientific and industrial knowledge, the norm, here, the ‘limit’ between ‘do’ and ‘don’t’, is settled once and for all.

The legal norm itself is linked to society by the ethics this society implicitly adopts and implements. In a democracy there is a consensus to which thinks that intelligent solutions to problems are preferable to what are usually described as ‘emotional solutions’.

One major difficulty comes with the new ways and means of interaction between technological artifacts and human nature, or future IT-created and nano-convergence, whose impacts are a matter for public deliberation. If we assume that we have not yet fully defined the nature of the human species (here I refer to the NEST programme of the European Commission’s DG Research whose title is What Does it Mean to be Human), how could we assess risks without knowing the whole scenario. Because of this consideration, I should be tempted to follow Professor Jan Staman of the Rathenaus Institute, when he explained in a forum dedicated to Science in Society in March 2005 in Brussels, that technology assessment and foresight go hand in hand.

Examples of potential – if not likely – norms which seem under scrutiny as far as nanotechnology and its meta-convergence are concerned are the following

- **The precautionary principle** opens the door to a moratorium as being the new frontier, and refers to the call made in 2002 by the ETC group as regards nanotechnology. The hidden philosophy is ‘if you don’t know it, just let it drop until you know more’. The implementation of this principle implies that ‘regulators’ opt for a ‘no adverse effect level’ (NOAL), guarantee reversibility of any action and avoidance of irreversible damage. It shifts the burden of the proof to the supply side stakeholders.
- **The ‘duty of care’ guideline** was raised in the context of the EU REACH Directive negotiation on chemicals production and trade. It could lead to a combination of a legal, hortatory framework and a code of conduct to be implemented on a voluntary basis by suppliers. This is a more pragmatic approach than the one of a strictly applied principle of precaution.
- **International legal obligations.** For instance, the implementation of the Cartagena Convention on Biodiversity or of the Kyoto Convention relating to Climate Change and Sustainable Development, creates new international legal constraints for those countries who, on a voluntary basis, agreed to cooperate. In another specific field, nuclear safety, the international convention opened the door to mutual peer assessments, with a commonly agreed methodology.
- **Prohibition** on NBC(2) weapons of mass destruction is a last, but not least, example of the characterisation of a norm, or limit.

2. NBC: Nuclear, Bacteriological, Chemical weapons.

As those limits are so painfully slow to be imagined, defined, negotiated and adopted, implementation of the limit between 'do' and 'don't' will eventually be achieved in an environment which can be stable or, on the contrary, may follow a path of quick change. But by then, it will be too late to change the limits: whatever the level of knowledge about voluntary or involuntary impacts on health and environment, and whatever the imagination of human beings for benign experiment –, not to mention for terrorist use – the limits are fixed.

Unfortunately, the strict application of the balance between risks and benefits, as a routine commonly accepted by risk assessment and management communities, may be challenged on three main points when we come to try and apply it to nanotechnologies and information technologies.

First, **it involves a static approach, not a systemic one**. It focuses on linear causalities linking one event to its impacts (for example, the release of engineered nanoparticles and toxicity/ecotoxicity studies); adjustment over time as well as the complexity related to combinations do not fit the risk-benefit approach. Risk here is considered as the known uncertainty only. How can we fund research on a 'what we don't know we don't know' basis, without mixing foresight and a systemic risk-assessment methodology?

Second, **it carries implicit values which we may want to, or refuse to share**. In a competition-led approach, the hidden philosophy for action is 'if you don't know it, just try it'. The stakeholders are under a pressure to fulfil the expected rate of return on investment, for instance, no less than x%, within no more than (y) months or years. Unexpected impacts are considered as externalities to be supported by the whole community. In a more balanced approach combining market efficiency with social welfare, the norm could be different.

Other values we may not want to share are, for instance, human performance whatever the ethical consequences might be. Converging Technologies for Improving Human Performance is the title of an annual NBIC conference which takes place in the USA. The question here is: when convergence between nanotechnologies, information technologies, cognitive sciences and brain biology gives access to enhanced capacities, how do individuals and groups consider the freedom/ability to opt in favour of enhancement when confronted by competition, or opt out if they wish to – to refer to the analysis developed by Professor Sheila Jasanoff of Harvard University, author of Designs on Nature[3]

The model suggested by William Sims Baindbridge at the NBIC 2004 conference was one of an artificial intelligence personal adviser, in which an AI system provides personal advice to the individual by simulating a human friend/adviser. This interaction requires a significant degree of 'personal capture' involving the user. In this example of convergence, the cognitive sciences provide a design for judgement and decision making; IT supplies the AI information system; the artifact is based on emotional (physiological) responses, and nanotechnology allows nano-enabled extreme portability. Appropriation of such models is rooted deeply in a societal bet: 'if we build it so they will come…'

Confronted with such models suggested to scientists by the orientation of R&D funding, one cannot avoid the neuro-ethics questions raised by Sonia Miller: 'Could the possibility of altering an individual's thoughts and actions be used to forcibly control him in the future?' 'Who decides and on what basis?' 'What are the safeguards for protecting and disclosing the information?'[4].

I would like to add more fundamental questions around ownership, control and the social ends to which the converging technologies are being directed by those who determine and provide funds for scientific works; who benefits from it or is potentially harmed by it; who denies or edits out unpredictable social consequences in the long run; who takes responsibility?

Professor Alfred Nordmann, rapporteur of the High Level Expert Group on Foresighting the New Technology Wave established by the European Commission's DG Research wrote: 'The potential and limits of engineering for the mind and engineering of the mind need to be determined. Also, the effects on cognitive processes by technical environments should be investigated: if the video-game culture has altered how students learn, pervasive artificial environments of the future will have an even more profound effect'.

Professor Jean-Pierre Dupuy elaborated on the paradox that the triumph of scientific humanism brings with it the obsolescence of man, in mechanising the mind, in treating it as an artifact, the mind presumes to exercise power over this artifact to a degree that no psychology claiming to be scientific has ever dreamed of attaining. The mind can now hope not only to manipulate this mechanised version of itself at will, but even to reproduce and manufacture it in accordance with its own wishes and intentions. Accordingly, the technologies of the mind, present and future, open up a vast continent upon which man now has to impose norms if he wishes to give them meaning and purpose. The human subject will therefore need to have recourse to a supplementary endowment of will and conscience in order to determine, not what he can do, but what he ought to do or,

3. Jasanoff Sheila, Designs on Nature, Princeton: Princeton University Press, and Science in Society Forum, Brussels, 10 March, 2005.

4. Miller Sonia. 'The convergence of ITC. Legal issues emerge as cognitive science and IT become one'. In conference on NBIC Convergence 2004, February 25-27, 2004, New York.

rather, what he ought not to do. These new technologies will require a whole ethics to be elaborated….[5]

Third criticism, **it prevents the immediate recycling of the increase in knowledge about effects and impacts.** Significant factors that could influence the limits fixed by a given legal framework, such as the classification of scientific information related to strategic and safety issues, or the impact of patents governance, are not to be questioned in the classic risks-benefits assessment methodology.

International cooperation and information sharing used to be a powerful tool for the public evaluation of an existing legal framework, and can help strongly in adapting the norms at international, national and local levels. 'Adapting', here, means **to let the limits move, towards harder or softer ones** for individuals and entities, **when and where appropriate.**

In summary, the risk assessment approach based on the balance between risks and benefits is far too limited to answer adequately the societal questions raised by converging transformational technologies, in particular between IT and nanotechnologies. This means that restricting risk assessment to this methodology opens the door to disillusionment unfortunately, to a loosen appointment with the great potentialities of nano and information technologies. Are we rich enough to throw the baby with the bath's water? No, indeed not. The ethical deadlock has to be broken in a context already characterised by the emergence of a public opinion trend (if not already a 'wave'), against all technologies perceived as privacy/liberty-depriving ones.[6]

We, with Professor Jean-Pierre Dupuy and Dr Alexei Grinbaum, would suggest substituting this traditional approach of a balance between risks and benefits, which is not as neutral as one would like to believe, with one more appropriate to nanotechnologies.

This new approach is one of an ongoing normative risk assessment methodology, because this is the only one which allows us to let the limits move, depending on what we actually know of the state of the art, its speed and foreseen paths. This concept, supporting a renewal approach, was presented at the Alexandria conference in June 2004, whose aim was to address the interest of nations for the elaboration of a responsible international dialogue for nanosciences and nanotechnologies. In particular, consideration of the limits of a linear and causal approach when assessing nanorisks was endorsed by the participants of this conference involving 26 country-representatives as being absolutely relevant to nanoscience-pervasive applications.

The ongoing, dynamic and systemic methodology for risk assessment should rely on a new tool to be conceived and implemented quickly from local to global levels, with the help of new grids. For the European Union, an important step would be the creation of a societal observatory of converging technologies whose ways and means have been described as follows:

The primary mission of this observatory is to study social drivers, economic and social opportunities and effects, ethics and human rights dimensions. It would rely on a standing committee for real-time monitoring and assessment of international converging technologies research. This observatory also serves as a clearing house and platform for public debate. Working groups will deal in multidisciplinarity collaborations with issues of patenting, the definition of commons and the allocation of property rights. The core members in the societal observatory represent policy and ethical perspectives while developing substantial technical and scientific expertise in converging technologies. They serve as intermediaries that bring societal concerns to the research community, and relate research visions to various public constituencies[7].

I had the opportunity to present this proposal to the European Commission High Level Expert Group on Foresighting the New Technology Wave. The proposal received full support from this group, and also from participants to the EC's Converging Technologies for a Diverse Europe conference (14-15 September 2004, Brussels), which is heartening. Indeed, although the European Commission is never committed to implementing recommendations from an expert group, it should consider the obvious welcome and election of this societal observatory recommendation from other people.

My interpretation of this strong support is that this kind of tool creates a place where visions could be articulated for promises and expectations of the converging information and nanotechnologies at an early stage, and make them the focal point of upstream public engagement[8]. For instance in France, the OPECST the French equivalent of the European Parliament's scientific evaluation body (STOA), is the only institutional body that provides scientific insights into international dialogue. Is it a stable situation or ought we better consider independent, alternative evaluation centres, coming from NGOs and supported by public fundings and linked to appropriate networks?

If ethics are to serve not stultify society, no ethical

5. Dupuy Jean-Pierre, 'The philosophical foundations of nanoethics. Arguments for a method'. Paper presented at the NanoEthics conference, University of South California, Columbia, SC, 2-5 March, 2005.
6. La micropuce implantable à l'être humain, Signature JAMEH (jamais avec la manipulation électronique de l'être humain, in http://www.forum-social-tarnais.org/Telechargement/Micropuce.pdf
7. Nordmann Alfred, Rapporteur, 'Converging technologies – Shaping the future of European societies'. Report 2004, HLEG Expert group Foresighting the New Technology Wave. European Commission DG Research.
8. Wildson James, Willis Rebecca, See-through Science Why Public Engagement Needs to Move Upstream, London: Demos, 2004.

decision should be irrevocable, even under uncertainty[9]. Building a shared vision on the foundations of a shared knowledge and a shared renewable risk assessment methodology will contribute to allowing the normative limits to move. An additional rationale in favour of this observatory is the potential bridge it creates with similar institutional dynamics on other continents and, furthermore, an additional incentive for mutual understanding and cooperation between peers.

In order to give a boost to such a process, several conditions should be fulfilled:

- awareness of the great potentials of nanociences combined with IT and other fields;
- awareness of uses, misuses and abuses and their potential impact on human beings and the environment, in particular when related to nano-bio new 'threats' against populations;
- willingness to enter a trusted international cooperation and information sharing of scientific studies about ongoing state-of-the-art reviews and studies related to effects/impacts for a better understanding and management of risks, including cognitive sciences and ethics;
- orientation of public research programmes and funds according to the priority given to observation, massive simulations by international grids, normative risk assessment and long-term perspective; an ongoing normative methodology for nanorisk assessment would be rooted in ELSA (ethical, legal and societal aspects) evaluation criteria[10];
- adoption of an appropriate framework to undertake, without delay, first steps in the definition of what should be the typology of criteria supporting the evaluation methodology (from local laboratories of fundamental research to global institutions). This framework should be inclusive (all countries welcomed) and focused both on upstream engagement and accountability to the public.

Taking as an example the GMO crisis, one can no longer consider trivial the statement that ignorance and fear feed the root of a simple rejection by civil society. In fact, the more that information was given, the higher the concerns relating to GMOs grew, because nobody was in a position to address correctly the long-term effects of involuntary dissemination. The GMO case constitutes a lesson for the future.

One can say that without a clever upstream input from civil society, the well-balanced and informed dialogues which are required to provide good incentives, funding and orientations to policy makers will simply not occur. Such a situation, if it were to happen in the nano case, would have the power to prevent the whole of society from reaping the benefits of the nano harvest in the short run, and eventually lead to a huge wasted public and private investment, ending in a no win game for everyone.

Our collective responsibility is to not allow it to happen. But we need to act quickly and explicitly opt in favour of responsible behaviour.

The European Commission has taken the lead in providing a 'common house' for the international responsible dialogue in the field of nanosciences and nanotechnologies. But since the approval in September 2004, by the Council, of the EC's Communication dedicated to a European strategy in the field of nanoscience and nanotechnology, stressing the need to strengthen international dialogue, we must admit that we face delays. The December meeting in Brussels organised by DG Research received the green light from the EU members' representatives to go ahead, provided that an inclusive approach is secured. Among the possibilities of organising this dialogue, the Commission proposed to consider the creation of a Carnegie group, following an informal proposal from Canada. The Carnegie group refers to G8 research ministers' regular meetings.

In fact, if this option were to be adopted, it would take place under the British G8 presidency which begins in July 2005. Then, everything would have to be done. I suggested at the meeting in Alexandria that we should consider the kick-off of a group whose roadmap would be to work on simple common criteria upon which an ongoing normative nano risk-assessment methodology could be built, beginning with nanosciences and nanotechnologies, but not limited to them, provided that convergence and its output are the actual societal and ethical challenge. This suggestion has been welcomed by the chairman of the National Nanotechnology Initiative (NNI) Mihail Roco, but delays in finding the appropriate formal framework to implement it prevented it happening at the international level.

Other initiatives already exist; relying on stakeholder (academia, industry, insurance representatives) initiatives, on a regional or global basis (for instance ICON, GNN). The European Commission DG Health and Consumer Protection has begun a process of intra-European networking for toxicology and ecotoxicology risk assessment. All of those dynamics are useful and contribute to a better understanding of what is going on in and outside the laboratory, but none of them is in a position to fully involve governments in a process of identifying their responsibilities and subsequently evaluate the appropriate limits and/or incentives to be chosen and implemented.

9. Humphrey J. H. 'A biologist's view of biological warfare', Discussion paper, in Biology and Ethics, F.J. Ebling (ed), London/New York: Academic Press, 1969, p. 138.
10. Cited by Pr. Jan Staman, Forum on Science in Society, March 2005, Brussels.

In the outcome of the open consultation on the European Strategy for Nanotechnology, published in December 2004, the chapter on Risk and Regulation received the following responses: Health and safety issues, toxicology, risk management/assessment, and establishing regulation were highlighted as crucial issues for which more R&D is needed. A wide span of views were given, including one respondent who asked for a complete moratorium on lab-research until compulsory safety protocols are introduced as well as a strict 'no patents' policy on new molecules. Among those who were positively minded towards nanotechnology, the patenting issue was addressed by asking for 'one EU patent'[(11)].

December 2004, within the Sixth Framework Programme/Thematic Area 3 related to nanotechnology and nanosciences, also saw the inclusion of knowledge-based multifunctional materials, new production processes and devices, and a work programme that identifies certain topics related to our concerns. For example, long-term interdisciplinary research into understanding phenomena, mastering processes and developing research tools for converging technologies, and also the interaction of engineered nanoparticles with the environment and the living world. An **ethical review of proposals** will be provided as a guideline to be followed by the relevant panel.

In particular, for research involving human beings, the ethical review panel will assess the information given to participants, the measures taken to protect participants' personal privacy and data, including genetic ones, recruitment criteria and the level of care offered to participants[(12)].

As a matter of fact, I am now convinced that we will have to wait for the Seventh Framework programme to see, eventually, a call for proposals related to the societal observatory described above. It will not be too late, but it will be too late to give good and early European insights into the international dialogue for a responsible development of nanotechnologies and nanosciences. In the meantime, European members will have to rely on their individual national capacities to elaborate, separately, their own methodology, if need be.

Perhaps the Forum of National Ethics Councils, established to implement Action 32 of the Science and Society EU action plan[(13)], whose expected outcomes are to help pan-European dialogues on ethical, legal and social implications of science and technology in general, could help to speed up the recognition that ethical and social dilemmas are increasingly relevant for nanotechnology, neurosciences, pervasive computing and artificial intelligence, and should be considered as relevant areas distinct from the now classical bioethics.

In November 2004, the Department of Cybernetics of the University of Reading (Berkshire, UK), became part of the European Network of Excellence of the €5.5 million European project Future of Identity in the Information Society (FIDIS). Headed by Professor Kevin Warwick, who experimented with an RFID implant under the project known as Cyborg 2.0, this department describes itself as having considerable experience in the evolution of Cyborg entities (linking humans and technologies together) as well as tagging and tracking issues, especially through implant technology and in ambient intelligence environments.

It stresses as a matter of specific interest the contrast found between the evolution of identity perception in collective Cyborg scenarios and the typical concept of self. Among the outcomes of this FIDIS European research programme, legal, socio-economic, usability and application requirements were foreseen. On the 21 January 2005, the case study outcome[(14)] was issued as a set of interesting scenarios, but no developments and foresight of nano and IT convergence were introduced, even if the ethical questions raised by RFID applications in general were analysed.

This observation, for me, indicates clearly that the legal, societal and ethical questions raised by nanosciences when combined with IT, neurosciences and neurotechnologies, while being addressed by European research, are not, in the current situation, given sufficient priority.

We need, through the European Commission, to build a robust implementation of ethical principles. Its willingness to lead the dialogue at international and governmental levels, aimed at establishing a framework of shared principles for safe, sustainable, responsible and socially acceptable development and use of nanotechnology, has a price: in time investment in the appropriate toolboxes, scientific, technical and relational ones, such as a societal observatory, aimed at enlightening and securing public and private approval, which are the most important in the long run.

Sometimes, the best opportunities for a win-win responsible policy is to let the limits move.

11. Outcome of the open consultation on the European strategy for nanotechnology. December 2004, p. 106, in http://www.nanoforum.org
12. Integrating and Strengthening the European Research Agenda, Thematic Area 3. Work programme, Edition December 2004, p. 42.
13. Science and Society Action Portfolio. Today's science for tomorrow's society. European Commission Projects, in http://europa.eu.int/comm/research/society2005.html
14. FIDIS Future of Identity in the Information Society. Set of useful cases and scenarios. Main editor Thierry Nabeth (collective) 21 January 2005, 83pp. in http://www.fidis.net

ESF Forward Look on Nanosciences and the Future of Information Technology

Professor Branislav Rovan

Some (sometimes provocative) observations

1. What is important in ICT

The area of Information and Communication Technology (ICT) plays two major roles. The first one, the one that is generally best perceived, is the role of a 'service provide'. ICT is expected to enable new things (services, products etc.) to make the existing things more efficient, faster, more reliable etc. The solutions which ICT are expected to provide in this role often do require basic research, but the results are expected to come fast and to 'prove themselves' useful. The second role is to deliver a better understanding of our world (especially from the point of view of information and information processing) and a better understanding of ICT. Here the results are in general not expected to be delivered quickly. Unfortunately, they are often not expected to be useful at all (especially by those doing the 'real' informatics).

Good policy for basic research in ICT has to strike a good balance between the support for or emphasis on the two roles.

One of the hallmarks of the area of ICT is that the technology (hardware) attracts most of the attention and money and the 'soft' areas are lagging behind. As a result we usually have technology that, in the best case, we are not really able to use to its full potential and, in the usual case, we use in ways that create trouble and make us vulnerable to unforeseen hazards.

The scenario and programme of this meeting is also following this footpath. It creates the impression that the most important challenge is to store more data and have smaller and faster machines. True, I can see applications where this might be useful. However, it is clear that we are not able to master even the existing hardware and technology. The problems in the software design area are recognised by the meeting organisers and will certainly be addressed by the excellent invited speakers.

I find 'coping with complexity' to be the challenge that has been with us for some time and that is taking on new shapes and dimensions. I would like to stress especially the complexity of the 'information space'. For the time being we are busy making it bigger. It is high time to learn how to make use of it, how to keep our information environment 'clean' of 'pollution' etc.

One could mention other areas, but the list presented by one person would be incomplete anyhow.

The ICT area is enjoying the benefit and the curse of its usability in many areas. Frequently, those using computers believe they are experts in informatics. The development of the hard core of ideas and methods of informatics is being neglected. In fact parts of it are 'snatched away' by eager application fields. As a result we may soon find ourselves deficient of new ideas in informatics and the application fields will be looking down a dry well.

ICT needs to concentrate on its roots, on its core, and the funding agencies should realise the need. Are we sure, for example, that the old Shannon's concept of information is useful for today's information systems and the ways we are using and handling information today? I am convinced the very basic concepts of informatics need to be re-thought and new foundations built. All this needs to be funded.

The EU Framework Programmes are expected to make Europe more competitive. Between the lines this seems to mean more competitive in existing industries (aerospace, automotive, chemical etc.). We are talking about information and knowledge society (in being or in transition to becoming, depending on the degree of optimism). I am not sure what it really means. In any case it should bring new types of 'industry'. Providing information/knowledge on demand may be profitable. Could Europe position itself as an information/knowledge provider?

Humankind appears to be fascinated by making everything faster (and smaller). I am not sure I understand what it is good for. The one who is faster (in delivering the new product/service to the market, in performing the task etc.) is the winner, the fittest, the one who survives the competition. ICT is expected to 'help survival' and contribute substantially to speeding up the race.

Could ICT contribute to a graceful slowdown of our lives before the inevitable crash?

2. Organising research

Stressing the excellence too much may, with a little exaggeration, lead to a situation where we could have in Europe one institution doing research in an area A, one institution in an area B, etc. Apart from the fact that the areas will necessarily have to be narrow, the number of people understanding the results sufficiently to make use of them will be small.

Bad research should not be supported. But a good balance between supporting excellent research and supporting good research will contribute to a broader base of people capable of understanding and using research results and, via job migration, to increasing competence in industry. This is likely to improve the uptake of new ideas and innovation in industry. The evaluation procedures, in a praise-worthy effort to be 'objective', tend to rely on 'measurable' criteria. The system favours publishing five papers gradually improving on some intermediate results to one better (and longer) thought-out paper presenting only the final result.

The need 'to claim one's results' in this ICT-supported fast research world also contributes to this trend. As a result we are flooded with a large number of papers and distinguishing the most important ones is becoming a problem; therefore it desirable to come up with some new ideas and procedures for evaluation.

Administrative rules in Europe in general seem to be designed 'to prevent fraud'. I am not sure this approach is necessary. It might be less costly to learn to live with a little bit of fraud (and punish it when discovered). Knowing the rules, managing projects, and writing frequent reports consumes a lot of time and energy. (I wonder whether there is some estimate on the amount of money this costs.) The system should allow a newcomer to take part in the European Research Area with no need for a consulting company.

3. Some policy suggestions

Strive for a broader base of competence in Europe. Universities are the natural focus for this effort. The funding instruments should encourage participation of students in research and university-industry cooperation. (Defining what 'competence' means may lead to curricula redesign and changes in the structure and functioning of research teams.) Consider a 'staircase' model of financing. In a given area define one to three excellent labs/groups and give them long-term generous EU financing; five to ten really good labs/groups, still well financed, and sprinkle some 'keep alive' finances to groups/individuals vitally contributing to spreading the competence to students and industry. Cooperation and mobility among the parties would be expected. The size of the cluster and its structure will depend on the perceived need and capacity in the particular area. Once the cluster is defined, the level of administration and reporting could be brought down to a minimum.

Consider (small) individual two to three-year basic research grants as a support measure for being active in the ERA in a particular area. The grants should have simple administration and, in general, need not be renewable.

Consider supporting regional research institutes that could serve as focal points for university-industry cooperation in acceding countries, using the expertise/experience of (nearby) EU countries.

Consider piloting a 'trust based' financing and reporting model in some areas of the EC Seventh Framework Programme. Consider adopting Europe as the centre of competence and source of information and knowledge as a potential strategy for future prosperity in the EU.

Advanced Research in Information Processing Components Initiatives at European Level

Dr. Patrick Van Hove

Excellence in components is at the root of advances in all areas of Information and Communication Technology (ICT). Europe has a strong industrial base in micro/nanoelectronics, and the ENIAC European Technology Platform on nanoelectronics[15] has identified in its 2020 Vision document, a key role for long-term research in universities and research centres to offer a range of novel approaches for the realisation of future devices.

During the EU's Fifth Framework Programme, FP5 (1998-2002), the **Nanotechnology Information Devices** (NID) initiative of IST FET promoted alternative approaches for the realisation of information processing components. The initiative is now mostly complete. A total of about 50 projects with an EC financing of €70 million was supported, many of the projects showing a high degree of novelty. The projects covered areas of devices, architectures and fabrication methods, and gathered a strongly multidisciplinary community.

In FP6 (2002-06), the IST priority supports advanced research in components through a number of focused initiatives. As part of the strategic objective on 'pushing the limits of CMOS', the SiNANO network of excellence launched early 2004 integrates teams active in ultimate CMOS research. Other initiatives covering **emerging nanoelectronics, quantum information processing** and **advanced computing architectures** are also being implemented with integrated projects and networks of excellence. The first projects for these actions are expected to start in September 2005.

In preparation for FP7 (2007-13), the IST Future and Emerging Technologies unit organised a number of events to help shape an eventual programme in advanced ICT research. At a consultation meeting on 16 December 2004[16], driving factors for advanced research on components were highlighted, and lessons taken from the recent developments in the ITRS roadmap chapter on Emerging Research Devices. Participants of the ENIAC technology platform were present at the discussion.

A substantial motivation for research on components is to continue progress according to Moore's law, integrating logic and memory devices that are **increasingly small, fast, cheap and consume less power**. This is the **'More of Moore'** agenda.

A second motivation for components research is to pursue the creation of interfaces between the 'brains' of the chips of the future, made of logic and memory, and the outside world so that chips acquire a higher added value by interacting with their environment. This line of research is referred to as the **'More than Moore'** agenda.

The ITRS roadmap provides guidelines on how conventional and unconventional CMOS logic devices could reach the 22 nm node in the year 2016. Further progress will require breakthrough technologies, with a first set of candidates based on new binary logic devices using charge transport such as nanotube- or nanowire-transistors and ballistic devices. More exotic candidates include technologies that are not based on charge transfer, such as quantum computing, spintronics or molecular electronics.

For memories, several competitive technologies are already well developed, such as ferro-electric (FRAM), magneto-resistive (MRAM) or phase-change memories (PCRAM). Beyond these, novel concepts need to be researched to reach ultimate limits of storage.

At an earlier workshop on 21-22 April 2004 in Brussels[17], the following Grand challenges and visionary ideas for future components were identified:

- **Adding functionality to silicon-based devices and systems,** through the use of nanometre-size material structures for the realisation of new types of functions in sensing, actuating, interfaces, opto-electronics, links with living systems, etc.
- **Combining and interfacing different materials, functions, devices and information carriers**, researching functions that would not represent information by electron charges, but may rely on photons, spins, ions, phonons, or quantum objects.
- **Fabrication of complex nanoscale systems in a cost-effective way**. A challenge is to combine elements of self-organisation with those of top-down manufacturing.
- **Miniaturisation down to the 1 nm limit**, looking at radical ways to represent and process information, for example in molecular electronics.
- **Master the complexity of gigascale systems**, with new methods allowing fault tolerance, and simplifying the design tasks.

These lines of research are already supported in part by the FP6-targeted initiatives composed of inte-

15. European Nanoelectronics Initiative Advisory Council http://www.cordis.lu/ist/eniac/
16. Emerging Nanoelectronics: Preparing for upstream Non-CMOS R&D in FP7 Brussels, 16 December 2004, ftp://ftp.cordis.lu/pub/ist/docs/fet/enano-2.pdf
17. New Directions for ICTs in FP7: Grand challenges for basic research, 21-22 April 2004, Brussels, http://www.cordis.lu/ist/fet/7fp.htm

grated projects including Emerging Nanoelectronics, Advanced Computing Architectures, including operating systems and compilers; Quantum Computing and Communications. These could be further pursued, and complemented by initiatives such as:

- Proof of concept of radically new devices
- Nano-Electro-Mechanical Systems (NEMS)
- Electronic devices exploiting materials found in biological systems
- Fault-tolerant circuit and system architectures
- Atomic-scale technology

In such initiatives, the development of proven concepts up to a level where the promises for industrial R&D can be fully assessed could be undertaken in large collaborative projects assembling partners from university, research institutes and industry. More upstream projects could be smaller and have a heavier academic participation.

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