Collaborative Basic Research in ICTs in FP7

Findings from a FET workshop held in Brussels on 21 and 22 April 2004

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Foreword

Over the last ten years, the Internet, the web, broadband wired & wireless communications and other early ICT technology innovations have gradually embraced the whole of business and society and are increasingly permeating every aspect of our life. Driven by miniaturisation and the accelerating convergence between computing, communications, media and knowledge technologies, a new generation of ICTs is emerging that will likely foster profound changes for at least one-two more decades.

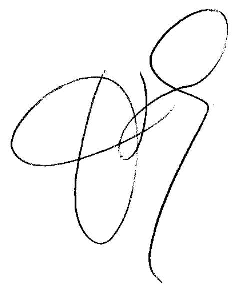
Indeed, there are plenty of blossoming technological breakthroughs simmering beneath the surface as in labs all around the world researchers pursue the technology race for ever smaller-size, cheaper and higher gigahertz computing power and terabit memory capacity, and for fem-to-second optical pulses and gigabits per second communication bandwidths. The new challenges include: further exploring the new miniaturisation and computing frontiers; harnessing the increasing complexity of networked computing and communication systems, comprising myriads of interconnected heterogeneous components with terabytes of flowing data, spanning from the nano-scale to the planetary-scale; and, designing and building ever more intelligent systems and personalised products and services.

At the same time, the boundaries of ICT research are now further expanding. Prospects for further growth are also increasingly relying upon synergies and cross-fertilisation of ICTs with many other S&T disciplines. Examples include the key role of ICTs in science-based predictions and more generally in computational sciences and the combination of ICTs with new materials and with biology and the life sciences. This accelerated integration of many S&T disciplines, where ICT will be playing a primary role, drives the emergence of a whole range of new technologies and disciplines, from meta-materials & nanotechnologies, to bio-informatics, bio-computing, bio-sensors, and wet interfaces, etc. It is bound to be at the origin of the next revolution(s) in medicine, in energy and in many other application fields.

Research in ICT however is not an end in itself. It must also address social needs such as the need for more security, the need for improved healthcare and how to deal with a longer active working life and a graceful ageing of people in Europe. And as more aspects of business and personal life come to depend on computers & networks, a strong collaboration between research in ICT and – for instance – the social and economic sciences will be required to address the new complex organisational, societal and ethical challenges we will be facing.

For reflecting on the above and on the other grand challenges that lie ahead of us in the coming 10 to 20 years, the Future & Emerging Technologies (FET) Unit of European Commission has called more than 100 leading S&T stakeholders in Europe to a major scientific gathering. The event took place in Brussels on 21-22 April 2004 and its main findings are described in this report.

I would like to warmly thank all the participants of the event for the time and attention they have devoted and wish the interested reader a most stimulating reading.



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Executive Summary

For preparing for the 7th Framework Programme (FP7), the Future & Emerging Technologies (FET) Unit of the Directorate General Information Society has organised on 21-22 April 2004 a 2-day workshop with the participation of leading scientists, industrialists and science policy makers. The event aimed at discussing the new grand S&T challenges that lie ahead of us, where collaborative basic research in ICTs would need to focalise in the coming years.

The event permitted to identify key and visionary basic research directions in the following three major ICT research areas: *Components, Complex Systems and Intelligence & Cognition.* In addition, a set of *strategies for ICT-based collaborative basic research* were also discussed. The main conclusions in each of these topics are as follows ([1]).

Strategies for ICT-based collaborative basic research in FP7

The importance of collaborative basic research in ICT is now widely recognised and has an essential role to play in FP7. Some of the new challenges to address include: Defining and promoting future research directions for collaborative basic research in ICTs at EU scale, fostering of trans-national research excellence, effective industry-academia collaboration, and integration of the new members states into the research fabric. In addition multi-disciplinarity will have an even more important role to play in the future.

Ingredients for a successful strategy in ICT-based collaborative basic research

- Promote basic technology research both in ***core ICTs*** and in their combination with ***many other S&T disciplines***
- Foster ***trans-national and multidisciplinary research excellence***
- Promote strong and effective ***industry-academia research collaborations***
- Measures for full ***integration of the new Member States*** into the EU research fabric

Today, as the boundaries of ICT research are rapidly expanding, ICTs are increasingly cross-fertilising with many other S&T fields. In this respect, three mechanisms for selecting ***future basic research directions in ICTs*** were recommended: First, through identification of grand challenges, i.e., visionary themes demanding breakthroughs in basic research and engineering in many key technologies focusing 10+ years in the future. Second, through identification of key technological issues having major importance to economic growth. And third, *derived from major social and societal drivers.*

Irrespective of the mechanism used for selecting it, a basic research direction would have to address the following four major aspects: *what* is the issue and *how* can we best address it, *for whom* is it addressed, and *by whom*. In addition, it is necessary to foresee a "planning phase" during which relevant stakeholders are brought together to build a consensus on the primary motivation and basis for a new research programme. In this planning phase, multi-disciplinary representation is a key issue. Multi-disciplinarity does not imply though that in a research programme there must be equal participation across all relevant disciplines concerned.

Research excellence beyond national boundaries is often a prerequisite to ensure excellence. New programmes must be designed to attract the best researchers in each of the disciplines concerned and provide methods to train new generations of researchers but also researchers in industry. Education and training have to become an integral part of future EU programmes.

Excellent research will often be characterised by co-sponsoring from national funding agencies. Such co-sponsorship is highly desirable and mechanisms for achieving it need to be put in place. Co-sponsored programmes need to remain open to participation from all member states and not limited only to the states whose agencies are co-financing them.

([1]) Further information on the FET-FP7 event can be found at: http://www.cordis.lu/ist/fet/7fp.htm

Aiming for excellence in new research programmes calls for a definition of excellence. While a number of methods now exist on how to measure excellence, individual projects need also to define metrics through which their excellence can be measured. Metrics of progress need also to be defined at the level of a new research programme.

Strong ***industrial involvement*** in new research programmes is to be sought. This involvement may take many different forms, from project observers to "matching of research funds". Explorative research should primarily be carried out in an open environment. At the same time, industrial involvement can leverage the research directions and the later take-up of results. The rules for industrial participation and the associated rules for IPR ownership must though be clear from the start and at the level of a new programme.

The ten ***new member countries*** have a long tradition of excellent research. There is however a strong need there to consider initiatives for added infrastructure support and methods to get researchers more tightly integrated into the EU research community, in particular by better exploiting the existing networks of excellence and co-ordination actions.

Research in Components

In the coming decade, **ambient intelligence applications** focusing on health, comfort and leisure, communication, mobility, safety and security will guide application-driven research in components. Opportunity-driven innovations will increasingly be based on novel nanodevice building blocks and related nanofabrication techniques, on new component design and architectures, and likely on bio-inspired approaches and concepts. Such developments will complement the mainstream RTD efforts that are spelled out in the ITRS roadmap.

With nano-scale devices reaching ~10 nanometres (nm) in 2015-2020, new opportunities will emerge to combine ultimate "top-down" semiconductor platforms with "bottom-up" developments in materials, physics, chemistry and biology. The following major challenges and multidisciplinary research themes need to be addressed for transforming today's visions into tomorrow's innovations.

Research Challenges in ICT Components

- Add ***functionality and performance to devices and systems*** on existing silicon platforms
- Enable the combination and ***interfacing among a growing diversity of materials, functions, devices and information carriers***
- Develop ***new cost-effective fabrication methods for complex systems with deep nanoscale devices***
- Push the limits of ***miniaturization to the nanometre scale***
- Master the ***giga-complexity of systems and architectures*** integrating billions of nano-devices

Advances in (*nano-scale*) ***materials science*** will provide the basis for ***adding significant extra functionality and performance to devices and systems on mainstream silicon platforms***. These in turn will require the design and development of new system architectures. Issues of particular attention here are heat generation and dissipation, and architectures. Inorganic nanowires and nanotubes will likely have a prominent position in these developments.

The second grand challenge is to enable the ***combination and interfacing of a growing diversity of materials, functions, devices and information carriers***. These "information carriers" could be electrons, photons, spins, ions, etc.

New materials, devices and circuits will require ***cost-effective fabrication techniques for complex systems integrating deep nanometre scale devices***. Nano-scale components must be grown and patterned at scales around and below 10 nm, going far beyond the current limitations of lithography. Self-assembly of nano-objects mediated by (bio-)chemical interactions is one of the promising routes for manufacturing downscaled nano-components.

Pushing the limits of miniaturisation to the nanometre scale requires new methods and tools to accurately model, manipulate, fabricate and characterise nano-objects down to the atomic scale. It also requires new paradigms to exchange information with single atoms or molecules.

Denser integration and combination of top-down, bottom up and self-organised devices will vastly increase the complexity of ICT components and architectures. These call for ***methods and tools to master the giga-complexity of future ICT architectures***, integrating billions of devices with nano-scale dimensions and coping with variability, defects and energy-dissipation issues. Inspiration from bio-systems is likely to lead to innovative solutions.

A number of new physical phenomena or properties of matter at the meso-scale have recently been discovered or demonstrated. These should be further investigated and, as appropriate, developed into new functions or technological developments for the ICT. ***Research for the discovery and further investigation of such new phenomena*** also needs to be supported.

Today, the boundaries between ICT and other related fields, such as material sciences, physics, chemistry, biochemistry and life sciences, are increasingly fading. Future research in Components is thus expected to become more multidisciplinary and be based on strong and effective integration of excellent researchers from all these disciplines.

Research in Complex Systems

Large scale systems like communication networks, large databases and software systems, the Internet, large distributed control systems, businesses and the global economy, are examples of huge, interdependent open information-processing systems with behaviour that is increasingly difficult to predict and control. *Modelling, simulation, design and control* of such large scale systems in technology, business and the sciences are major research issues to address.

Research Challenges in Complex Systems

- ***Infer system models*** from incomplete & inconsistent information
- Address the design of ***Human Responsive ICT systems***
- Develop the underpinning foundations for ***software-intensive systems engineering***
- Investigate the ***Control and Integrated Design*** of Complex Systems
- Address ***Many level, Many Unit, Many Purpose Systems***

Present and prospective developments are the basis for understanding how to address the challenges of building systems that are robust, resilient, dependable and secure, exhibit multi-purpose functionality, and guarantee operation in mission critical tasks. Interdisciplinary research is now essential if we are to establish new paradigms within which to address the challenges ahead. The following five research directions were identified.

The first direction addresses the need to ***infer system models even when only inconsistent and incomplete information is available*** about their functioning and interactions. We need to develop techniques for inferring the dynamics of complex systems, the laws governing their interaction, and ways to describe their behaviour, in order to simulate many systems for which there is at present insufficient direct knowledge.

The second direction addresses the design of ***human responsive ICT systems***. Today, we can no longer treat ICT systems as separate from their users. We need also to consider that the ICT system and the context in which it is deployed together form a system. Research is required to establish new design principles that accommodate the changing needs and desires of human participants in complex systems, rather than treating them as outside the system, and rather than presuming to know what they need. A better understanding of human behaviour is also needed, especially regarding group man-machine interactions, from which generative theories should inform the organisation of architectures that support and sustain participation, including participative co-design of the systems themselves.

Three complementary research directions address the need to ensure that systems built have the properties we demand. All of them insist on the need to underpin the formal description of such systems.

The first of this set of research directions is to develop underpinning ***'foundations' for software-intensive systems***. The aim is to make a fundamental leap in the scientific basis of software engineering technologies to capture evolution and dynamics, selfish interests of individual entities, various levels of bounded rationality, learning aspects and self-emerging behaviour, in a strict, yet tractable way. Advances required include new algorithmic techniques for distributed systems and property-aware compilation and implementation techniques for non-functional properties such as security, safety, scalability, resource optimisation, quality of service, and efficiency, in order to be able to guarantee these non-functional properties.

The last two research directions are ***"Control and Integrated Design of Complex Systems" and "Many level, Many Unit, Many Purpose Systems"*** and are closely inter-related. For systems comprising many interacting elements we currently lack techniques for modelling that enable prediction of the types of structures, the dynamic behaviour, and the properties that are likely to emerge at higher, collective levels of activity. A key characteristic of many such systems is that they involve components with uncertain operation and interactions, which are at least partially unpredictable and often not yet formalised in algorithmic terms. A number of biological, social, management and economic systems exhibit these properties, yet they must continue to function adaptably, malleably and resiliently, in the face of such unpredictability. The ambition is on the one hand to establish engineering guidelines that draw inspiration from complex natural, social, technological and economic systems and on the other, to establish an underpinning framework of formal or mathematical techniques. Together, they should enable us to find cost-effective solutions to problems that cannot be solved with current techniques.

Research in Intelligence and Cognition

Achieving true machine intelligence remains an illusive challenge for the perception, cognition and AI research communities. We need new promising research directions for achieving leap progress in this area through the understanding of the processes underpinning intelligence and cognition in living organisms.

The new vision is ***Toward Natural Cognition***, where the goal is to build artificial cognitive systems inspired by biology, in particular neuroscience, under the following two assumptions: Cognition by systems interacting with the real world is depending on and is facilitated by their body. The structure of this body, the environment and the body-environment interaction are inseparable from one another.

A new vision for Research in Intelligence & Cognition:

Toward Natural Cognition

- ***Building artificial cognitive systems inspired by biology:*** research on self-organisation and development as a natural framework for cognition
- ***Explore embodiment and interaction with the environment*** for new cognitive paradigms
- ***Exploit embodiment*** for achieving self regulation, self-maintenance, emergence of cognitive processes and high-level cognition via bottom-up organisations

Traditional cognitive science, cognitive psychology and AI make no commitment to the form of a cognitive system's implementation. Today, especially in cognitive neuroscience and robotics, the infrastructure (i.e. embodiment) is considered much more crucial to the understanding of cognition. One obvious difference between IT systems and biological cognition is the extent to which biology is self-programming, has adaptive configuration of sensors and effectors, and has extendable processing able to make analogies and cope with novel percepts.

Toward Natural Cognition is aimed at taking a relatively radical step away from classical AI-based IT approaches to cognition toward research on self-organisation and development as a natural framework for cognition. In this context, cognition is seen as more than just an inferential process. It is a property that results from the interaction of an organism with its environment. Embodiment, as the central notion in this vision, is characterised by a number of attributes, such as: Embodiment is intrinsically developmental and is structured by interaction with the environment. It enables affective interaction, the acquisition of meaning from percepts created through sensory-action integration and the grounding of "concepts" in the agent's sensory-motor and social interaction (which provides the basis for natural language). It facilitates learning by formation of cross-modal associations through induction and generation of correlations. It includes continuous dynamics with discrete attractor states, provides the basis for grounding and maintains the distinction between the description of cognition by external observers, and its underlying mechanisms.

The underlying research challenges of this vision include:

- The exploration of non-classical computation and the development of robust scalable self-constructing/repairing architectures;
- The exploitation of phylogenetic (evolutionary) and ontogenetic (individual) development and the development of cognitive systems with self-regulation and self-maintenance ('homeostasis') properties;
- The investigation and subsequent exploitation of emergent properties of large-scale structures (hardware and simulation) for cognitive processes;
- The attainment of high-level cognition by bottom-up organisation.

Relevant research topics to investigate include: new forms of biology-inspired analogue processing and related tools for implementing such large-scale biology-inspired systems; body construction or development and underlying materials and morphological issues; exploring "how much embodiment is sufficient", and the relationship between top-down knowledge, innateness and learning.

Toward Natural Cognition and its underlying challenges would require not only inspiration from biology (in particular, neuroscience) but also exploring the relationship between cognition and architecture. Trans-disciplinarity is also a must, offering a synergistic interaction of IT with neuro- or, more generally, life sciences.

1. Introduction

In preparation of the 7th Framework Programme (FP7), the Future and Emerging Technologies – FET Unit of the EC's Directorate General Information Society has organised a major scientific gathering that took place on 21-22 April 2004 in Brussels. The event was targeted to a wide spectrum of leading scientists, industrialists and science policy makers and was attended by more than 120 participants (the list of attendees is provided in the Annex).

The main objectives of this event were the following:

- identify major new grand S&T challenges that lie ahead of us where collaborative basic research in ICTs and in their combination with other disciplines would need to focalise in the coming years.;
- draw major visionary basic research directions at the frontiers of S&T and relating interdisciplinary research areas for addressing the above new grand S&T challenges;
- discuss the likely impact of this research on the economy and society;
- discuss and formulate basic research strategies at European level and measures to effectively implement them;
- come up with a set of concrete recommendations to implement the findings.

The following major ICT research areas were addressed at the event:

1. *Research in ICT Components*
2. *Research in Complex Systems*
3. *Research in Intelligence & Cognition*

In addition, there were also discussed:

4. *Strategies for ICT-based collaborative basic research in FP7.*

The main findings and conclusions on each of the above 4 topics are described in the following sections. Further information on the event can be found at: http://www.cordis.lu/ist/fet/7fp.htm.

2. Strategies for ICT-based collaborative basic research in FP7

The high added value and importance of basic research in ICTs are now widely recognised as being crucial for the sustainable economic and social development, competitiveness and employment in the knowledge based society in Europe. There exists also a general agreement about the positive impact that high quality basic research will have on society as a whole. Defining and deploying a successful strategy in FP7 for supporting & promoting collaborative basic technology research of the highest quality at EU scale is therefore of critical importance. The following four inter-related subjects were extensively discussed:

- Methods to select future basic research directions and actors to involve;
- Fostering research excellence beyond national boundaries;
- Academia-industry collaboration;
- Integrating the new member states into the EU's basic research fabric.

2.1 Methods for selecting future basic research directions in ICTs

Within FP7, research will be performed on all types of research from industry driven research, over collaborative research to purely curiosity driven basic research. Here, only issues relating to ***collaborative basic research in ICTs*** are addressed.

Today, in many areas, ICTs are maturing. They are increasingly serving many other sectors and permeating many aspects of life. Successive advances in computing and communication technologies continuously fuel the pace of ICT development. Exploring the new miniaturisation frontiers, harnessing the increasing complexity of computing and communication systems and building more intelligent systems and more personalised products and services are just a few of the new challenges. At the same time, the boundaries of ICT research are further expanding and prospects for further advances are increasingly relying upon cross-fertilisation of ICTs with many other disciplines. This accelerated integration of many S&T fields, where ICTs will be playing a primary role, has to be reflected in the selection of new basic research directions. More broadly, ICTs in FP7 need to be seen within an enlarged perimeter and embrace research in core computing and communication technologies but also in their combination with other sciences, in particular material-, bio- and the life sciences.

In FP7, ICT Research needs to embrace research both in core computing and communication and in their combination with other S&T disciplines

Within the above framework, the following three major mechanisms for selecting research directions were identified:

1. Grand Challenges
2. Technological challenges
3. Social and societal drivers

Mechanisms for selecting new basic technology research directions:

– Grand Challenges lying at the edge of what might be possible

– Technological Challenges

– Social and societal Challenges

Grand Challenges: The IST Advisory Group (ISTAG) has initiated an effort to identify a number of grand challenges. These are defined as being visionary themes demanding breakthroughs in research and engineering in many key technologies focusing 10+ years in the future. Grand challenges should lead to concrete “pictures of the future” and lie at the edge of what “just might be possible”, so as to inspire researchers beyond the boundaries of ordinary thinking. These grand challenges exemplify application domains of particular promise for growth in Europe. They provide a methodology for definition of research directions. Based on a set of grand challenges it is possible to identify clusters of underlying technological issues that must be addressed. Consequently, the grand challenges provide a method to define technological roadmaps from where future basic research directions can be drawn.

Technological Challenges: Another approach to the definition of future research directions is through identification of key technological issues of major importance to economic growth. As an example, USA has identified “simulation” as a key technology for future growth. To enable major progress on simulation there is a need to address issues related to distributed computing, visualisation, modelling, software engineering, etc. Consequently, the identification of such a key technological issue can be an efficient mechanism for the definition of future research directions.

Social and Societal Challenges: Finally, major social and societal challenges can be considered as drivers for identifying major research issues to address them. As an example, the USA has recently identified “Homeland Security” as a major challenge. To address this issue, there is a need to make extensive recourse to ICTs. Advances in homeland security issues are related for example to major inroads in biometrics, access systems, data-mining, network security and dependability, etc. Social/societal challenges in Europe include: addressing *the needs of an ever longer active working life and a graceful aging of people* while maintaining them in good physical and mental *health*, providing enhanced security and addressing *the needs of an all-inclusive society*. All these challenge economic growth and health care and lead to the identification of a number of research directions to be addressed

Any of the above three mechanisms can be used for identifying research directions; the actual choice of one over the other was not addressed. Irrespective of the mechanism used, any research direction selected would have to clearly address the following four inter-relating major aspects: what is the issue to be addressed, how can it be best addressed, *for whom* is it addressed, and *by whom*.

Reasoning in terms of grand challenges becomes indispensable because these can *motivate researchers from many different disciplines* to engage in a research programme. At the same time, they are easy to understand and communicate by policy makers and industrial leaders to the large public.

Promote multi-disciplinary participation in every new Research Programme. This does not necessarily imply an equal participation across all disciplines concerned.

Once a grand challenge is identified, a process needs to be elaborated for receiving feedback and for engaging the actors to involve. As mentioned, research around grand challenges is a very strong attraction for several different disciplines and engaging excellent researchers working in different disciplines is now a **must**. They need to be involved early in the design phase of a new programme to stimulate their motivation & endorsement. Introducing a planning phase for consulting ***multi-disciplinary communities*** (2) and actively involving them in the definition of underlying research directions might be particularly beneficial. A similar mechanism has for example been used in foresight studies. Such planning phase would provide enough time for allowing researchers working in relevant disciplines to establish a common terminology and a solid basis for a programme. Multidisciplinary involvement should also be an integral part of evaluations at all stages of a programme, from definition to proposal selection and to final reviews. Multi-disciplinarity does not necessarily imply though that in a research programme there must be equal participation across all relevant disciplines concerned.

2.2 Fostering research excellence beyond national boundaries

The following issues were addressed:

- Research excellence in EU research programmes
- International co-operation
- Achieving a European Research Area (ERA) in ICT-based basic research;
- EU programmes and education & training
- Measuring “excellence”
- Dissemination and promotion of basic research results.

Collaborative research programmes should aim at attracting research excellence wherever this is located

Attracting **research excellence** should be the major objective for any collaborative basic research programme. Motivation is the key driver to attract, generate and promote research excellence. Europe has strong “research excellence” both within the region but also in the USA and in the other regions of the world, through its researchers who live and work there. Research excellence beyond national boundaries is often a prerequisite to ensure excellence. New research programmes must be designed to generate the best possible motivators for attracting the most excellent European researchers in each of the disciplines concerned. They must be designed to motivate European post-doctorate PhD researchers from the USA to join again Europe. They must be designed to motivate best people world wide to come and work in EU research programmes.

(2) The term community is here interpreted to include not only all the relevant research actors but also relevant industries and society at large.

Given the above, **international co-operation** should be seen as a tool and not as a mechanism for attracting excellence and making accessible essential knowledge not available in Europe. The objectives for international co-operation should then be twofold:

- Attracting internationally the "best brains";
- Breeding excellence.

International co-operation is a tool for attracting research excellence and for making accessible essential knowledge not available in Europe

In this respect, whenever research programmes call for international participation of researchers outside the EU, such participation should be facilitated. In particular, we need to have a standard template for IPR agreement governing participation of US researchers in EU programmes, as well as a standard Consortium Agreement for international participation.

European Research Area (ERA) in ICT-based basic research ERA: EU programmes involving excellent research could attract high interest from several national-funding agencies, which could co-sponsor them. Such co-sponsorship is highly desirable for fostering research themes and funding. Simple mechanisms need to be devised for making co-sponsorship feasible. Such co-sponsored programmes need to remain open to participation from researchers from all member states and not be limited only to researchers from co-sponsoring member state agencies.

National funding agencies could co-sponsor EU's excellent research programmes

In several member states there exist excellent examples of how strategic alliances of expertise have been set-up to pursue a common research objective (for examples, see next chapter). Through such alliances it is possible to promote excellence without the need to relocate research to a single venue. The setting up of such alliances is viewed as a very good mechanism for achieving critical mass. Players in these alliances can also make substantial contribution in the definition of new programmes. At the same time, it must be recognised that there might also be a need to set-up centres of excellence located at a single venue to enable the utilisation of community resources in terms of infrastructure, but also for technology benchmarking and testing facilities, etc.

EU programmes and their link to education and training: A major dimension of collaborative research in Europe and of ERA building activities is wide access to excellent human resources. To generate new excellence, there is a need to permeate research culture in all educational levels, including graduate levels. In terms of graduate training for example, there are already a number of good mechanisms for education across nations, such as the summer/winter schools that are part of several EU programmes. There is a need to go beyond the model where excellence is generating excellence in the same University and to implement mechanisms for a "staircase to excellence", so that other Universities in Europe can profit from excellence and start excelling themselves too.

– Permeate research culture in all educational levels

– Include new Education & Training models as an integral part of any new research programme

Given the need to ensure adequate human capital to pursue advanced research but also the need to train new generations of researchers and researchers in industry, various models of education and training should be designed to become an integral part of deliverables from EU sponsored projects. At the same time, it is recognised that change in educational curricula at EU level is a relative slow process. To adapt to changes in R&D it might be important to consider alternative models for degree programmes, as the certificate models at recognised US universities such as Stanford and MIT. Through use of such certificate programmes, it is possible to react quickly to changes in emphasis in a particular R&D domain.

Measuring excellence: In the set-up and implementation of new programmes and projects, the major aim is excellence. This obviously calls for a definition of excellence. There exist a number of defined methods and a long list of standard indicators to measure excellence (e.g. scientific publications, patents, awards, various R&D impact factors, etc.). One such method is the Intellectual Capital Reporting (ICR) methodology used in Austria ([3]). While no single measure of excellence can be defined, it is essential that different consortia consider in what they represent excellence. For example, all research projects should be able to define metrics through which their progress and achievement of excellence can be measured. Such self-evaluation is crucial for project benchmarking and later impact assessment. Metrics of progress should also be defined at the level of a new programme, from its beginning.

> **– Devise mechanisms for measuring excellence at project and programme level**
>
> **– Implement multi-faceted dissemination mechanisms**

Wide **dissemination and promotion of results** from research programmes needs to receive more attention in the future. Standard academic mechanisms for dissemination, such as archival publications and conferences, are obviously of importance, but they are not enough. Research projects must also consider more widespread dissemination of results to ensure take-up by industry and society at large. For this, multifaceted dissemination mechanisms need to be put in place. Examples include involving science journalists and other professionals responsible for general dissemination, appearances in the press and television media, writing books also targeting the public, but also focussed dissemination actions to industry (see next chapter), etc. It was also pointed out that wider promotion and dissemination could be achieved when research consortia are composed as "a pyramid of excellence", i.e., involving participation of not only excellent research teams but also of smaller but still good to excellent research teams. These last could broaden dissemination to a larger group of students and via them to industry across Europe.

2.3 Academia / Industry collaboration

Basic and long-term research should in principle be carried out in an open environment to ensure that it is accessible to the community at large. Industrial involvement in basic research programmes is to be sought though and encouraged for several reasons: industry can influence the definition of new research directions, get early access to new knowledge and research results and proceed to efficient knowledge transfer and rapid take-up of such results.

Industrial involvement is to be encouraged in all phases of a research programme, from its definition over implementation to take-up. There is no single model of industrial participation that applies to all research programmes and all projects. Many different forms have to be considered spanning the entire spectrum, from "project observers" to "matching of research funds":

> **Encourage strong industrial involvement in basic technology research programmes**

- In a definition phase, for example, industry could be involved both as an originator of research directions, in generating feedback on proposed programmes and in endorsing and promoting the research objectives.
- In the implementation of projects, when research results start becoming mature, other models are possible, e.g., through direct involvement (partners), as affiliates, through co-financing of research, etc., so as to ensure efficient transfer of knowledge and results to (multiple) potential industrial users.
- In the final phase of projects it might also be of interest to consider mechanisms such as "business plan competitions", which are widely used in local communities throughout Europe. These competitions provide an efficient instrument for evaluation of the business potential of results emerging from projects.

([3]) The IRC methodology has originated from the Austrian Research Centres, under the head of Prof. G. Koch in 1999. Electronic versions of template reports ("Wissensbilanz") are only available in German – see FET web page (http://www.cordis.lu/ist/fet/7fp-ws1.htm). At present, IRC is further developed by the top managers from large applied research organisations, the so called "EUROTECH group", see ftp://eurotech:icr@ftpstud.donau.uni.ac.at.

– Close industry-academia collaboration boosts knowledge & technology transfer, fosters innovation and serves as a platform for industry for training & access to new skills

– Several good industry-academia collaboration models are now emerging all over Europe

When companies are directly involved and invest in research projects, intellectual property rights (IPR) need to be clarified from the very beginning, since too much emphasis on IPRs is not necessarily beneficial to basic research. In particular, the rules for participation and the associated rules for IPR ownership must be clear. Such discussions should not necessarily be delegated to individual projects, as is the case in FP6 but need to be available at programme level.

In general, joint industry-academia undertakings constitute an excellent platform for strengthening relations and mutual understanding and for exchanging people and experiences. Closer co-operation not only boosts knowledge transfer and fosters innovation but can also have several other spin-off results as for example:

- For researchers, accessibility to better infrastructures necessary for advanced research and experimentation purposes but also increased opportunities for mobility.
- For industry, direct access to new skills and human capital.

Additional / complementary models of academia – industry collaboration are now emerging in several regions of Europe. Examples include:

- New real or virtual networked platforms, e.g., the Minatec campus in Grenoble – FR.
- New academic virtual centres of excellence, whose creation are a prime inducement for companies to join activities (e.g., the IMEC/NMRC/LETI/ CSEM virtual centre).
- Formation of national alliances of excellence / industry platforms facilitating the involvement of a broad industrial community (e.g., the ones piloted by the French ministry of research for the definition of new technology initiatives ([4])).
- Formation of regional networks of competence in ICTs, (e.g., REGINA ([5]), the regional industry club informatics Aachen, which consists of about 60 high-tech companies and 20 research institutes, its Dutch pendant REGITEL ([6]), etc.).

2.4 Integrating the new Member States into the EU's basic research fabric

The new member countries have a strong research tradition and a solid record of research excellence. For some of them, this has already led to significant involvement in earlier framework programmes. Excellence, quality and motivation should remain the primacy features for research and there seems to be no need for a positive discrimination of researchers from these countries in FP7. However, for improving their participation and integration in the EU's research fabric, the following two aspects need to be addressed:

- Improving the research infrastructure;
- Accelerating the *community building*.

Specific measures are needed for the new Member states for improving their research infrastructure and for accelerating the scientific "getting together" and the S&T community building

The research infrastructure is not well developed in many of these countries and this hinders effective research synergies and collaboration. In the future, infrastructure support could be obtained through EU's structural funds. Research projects could also permit the purchase of state-of-the-art ICT equipment in individual research labs.

([4]) See http://www.telecom.gouv.fr/rnrt/index_net.htm and http://www.telecom.gouv.fr/rntl/.
([5]) See http://www.regina.rwth-aachen.de/.
([6]) See http://www.regitel.nl/.

From the research programme point of view, the new member countries have the same opportunities as all the other member states to set up projects and centres of excellence that can attract the best researchers and train excellent researchers. Creating new research institutes, sorts of “condensation points” for researchers, and providing adequate research financing, are stimuli for keeping the best researchers in the country and attracting new researchers to join.

Several researchers in the new member countries are not tightly integrated yet into the research community that has emerged in Europe based on past and present EU programmes. There is a strong need to consider mechanisms for improving this integration. To some extent, such integration has started and could be further accelerated through existing research projects, and in particular through a number of FP6 networks of excellence and co-ordination actions. Through these programmes, community efforts such as summer/winter schools and other types of scientific events could be used for facilitating a higher degree of integration. More topical scientific events need though to be organised in the new member countries for accelerating the scientific “getting together” and the “community building”. Furthermore, in the consultations to define new research directions, representatives from the acceding countries need to be adequately involved, as such “planning phase” activities also provide a mechanism for broad community integration. When considering the set up of alliances of excellence, as mentioned in the previous chapter, it might also be valuable to have involvement of members from the new member countries.

At the same time it might be valuable for these countries to consider how they can organise information about existing research effort, so as to ensure that they are adequately promoted for integration into new research initiatives. Adequate links to relevant web pages of FET and Cordis could also help.

3. Research in ICT Components

For several decades now, Moore’s law drives steady improvements in the performance, cost, size, and power consumption of ICT devices. The practical implementation of Moore’s law through the “ITRS roadmap” puts forward a timetable for R&D supporting silicon technology, relying primarily on bulk materials and semi-classical physics. Huge industrial efforts and worldwide alliances are engaged to keep progressing in the downscaling race. For example, field effect transistors with dimensions below 5 nm have already been demonstrated. While they devices do not yet present the characteristics required for integration, intense efforts and huge investments are addressing the numerous technological roadblocks to further downsizing. In this context, it is most likely that for the next 10-20 years silicon CMOS will remain the basic enabling technology to implement ambient intelligence based on sensing, computing, communication & actuation devices.

In parallel to the CMOS developments, many new types of materials have been synthesized during the last decade, including nanoscale-engineered inorganic materials or functional organic materials such as polymers and biomaterials. These together with advances in bottom-up nanoscience are starting to enable and motivate the emergence of disruptive devices and components around and beyond conventional downscaled silicon. The main driving force for these innovations is not to push integration density or operating frequencies beyond those of CMOS electronics, but rather to exploit different existing technologies to add substantial functionality to integrated circuits (ICs) without necessarily pushing miniaturisation to extreme limits. The emerging consensus is that CMOS technologies will serve as a platform for integrating these additional functionalities such as RF, NEMS, chemical sensing, and many more functions, requiring substantial basic research support. This integration will lead to a fading of the boundaries between ICT and other disciplines such as life sciences, and will require crucial breakthroughs in the conception and manufacturing of hybrid systems. As a result, new horizons will open up for a sustainable development of ICT and knowledge-based industries, and their adaptation to emerging and future micro and nano-biotechnology markets.

At the workshop, a number of grand challenges were discussed. Some are similar to those of the ITRS roadmap, highlighting the need for close interaction between basic research, advanced research and technology development around (pre)-industrial platforms. Here, the emphasis is on more upstream and exploratory challenges requiring basic research during the 2nd half of this decade. These challenges are:

1. Add significant functionality & performance to existing devices and systems on silicon platforms.
2. Enable the combination and interfacing among a growing diversity of materials, functions, devices and information carriers in a multidisciplinary context of fading boundaries between ICT, material and life sciences.
3. Develop new cost-effective fabrication methods for complex systems with deep nanoscale devices.
4. Push the limits of miniaturization beyond the nanometre scale.
5. Master the giga-complexity of systems and architectures in a nanoscale world.

These grand challenges are described below. Europe is in an excellent position to compete successfully with the US, Japan and the Far-East in these advanced research fields, provided that the European efforts are coordinated in a flexible and open manner.

In addition to the above five technology-driven challenges, it was also stressed that ***Ambient Intelligence Applications (AmI)*** focussing on health, comfort & leisure, communication, mobility, safety and security will become the main drivers for usage-driven component research. Usage-driven requirements, combined with financial and market issues, will require manifold innovations in ICT. An important part of the application requirements will likely be met by scaling down to the ultimate top-down silicon platforms. Hybrid integration of emerging organic and bio-based components has a strong potential for sensing and actuation and may also contribute to functions such as memories, interconnections and others.

Grand Challenges

3.1 Add significant functionality and performance to existing devices and systems on existing silicon platforms

The first challenge is to develop and exploit innovative ***nano-scale materials*** into new ICT devices and systems and to integrate them in mainstream semiconductor platforms. Future shrinking of devices into "deep nanoscale" will indeed bring along and require novel unconventional device and circuit architectures. As an illustration, inorganic clusters, nanowires and nanotubes are emerging as promising targets for research into new phenomena and as novel building blocks for future devices. These building blocks, together with other by-products developed bottom-up, are expected to add innovative functions to CMOS and allow easier construction of 3D architectures. They should also contribute to better identify the road for interfacing with living matter, and thereby open up the link with life sciences, an area expected to become significant in the time frame of FP7. From a more fundamental perspective, new building blocks could also help prepare post-CMOS information processing systems, bringing about new paradigms for computation, new functionalities or cognitive-oriented concepts.

Inorganic clusters, nanowires and nanotubes are very promising building blocks for adding innovative functions to CMOS and for building 3D architectures

Particular functions could be added to the CMOS platform through the combination with 0D, 1D, 2D or even 3D structures. 0D structures, such as quantum dots, could add optical functions or single electron effects. 1D constituents such as nanotubes and nanowires, could provide active channels, optical sources, optical and electronic interconnects or platforms for further functionalisation. 2D structures

New 0-D, 1-D, 2-D and 3-D structures hold the promise of adding particular functions to CMOS platforms

potentially constructed using self-assembling monolayers (SAM) or engineered as e.g., 2D protein crystals could be functionalised in turn to act as selective surfaces. Semiconductor or metal nanoparticles could also be added in, for example, to sensitize the surface to light or to exploit surface plasmons for energy transfer. 3D structures could form the basis of cell cultures for interfacing with living tissue. Possibilities include protein crystals, amine intercalated tubes and possibly networks of other types of tubes. Growing cells on 3D platforms on silicon would provide a very interesting new research tool for neuro-informatics.

Among the building blocks under investigation for the development of non-CMOS devices, 1D systems have shown particular promises. Among these, carbon nanotubes have demonstrated nearly perfect ballistic conduction, whereas nanowires have shown particular potential for ultimate (single-photon based) nanophotonics. These 1D systems also show clear advantages for ultra-sensitive sensing devices, and open up new alternatives to combine electrical, optical and mechanical effects at the nanometre scale.

Carbon nanotubes are hollow cylinders with nanoscale diameters, while their length can be tuned from the nanometre to the micrometer range. Depending on their geometry (helical vector) nanotubes are either metallic or semiconducting. They are the subject of intense research in basic nanoscience and results such as real 1D-ballistic conduction have been demonstrated. Carbon nanotube-based ballistic transistors with highly competitive performances have been designed, although mainly implemented at the single(few)-device level. In addition the carbon-based chemical structure of nanotubes also facilitates their interfacing with organic and bio-materials (DNA, proteins, etc.), which are also based on carbon structures. Nanotubes can also be made from other inorganic materials; these offer an added degree of flexibility with regard to functionalisation. Their investigation is promising and underway. Europe has achieved leadership in this area.

1-D systems like nanotubes & nanowires open-up new alternatives for combining electrical, optical & mechanical effects at the nanoscale for sensing and computing

Similarly to nanotubes, inorganic nanowires based on Silicon or on III-V semiconductors can be chemically grown and open up new perspectives for both nanoelectronics and nanophotonics. In particular, III-V-semiconductor nanowires should enable the development of single-mode photonics sources, as well as unconventional hybrid devices, structures and 3D architectures. Oxide-based nanotubes, including functionalised layers between rolled-up structures, provide a new range of options to be explored.

1D systems such as nanotubes and nanowires are also promising supports for very-high performance sensing devices, especially for chemical and bio-molecular sensing. They could enable detectors with femtomolecular sensitivity to genotoxic agents, virus, cancerous cells, etc. The massive parallel integration of 1D nanoscale components could enable real-time studies of biological activities such as protein/enzyme-DNA interaction.

The miniaturisation of devices to the 1-10 nm scale also brings new prospects to exploit mechanical phenomena, given the strong coupling between mechanical and electrical phenomena and the very limited inertia of mechanical systems at that scale. Electromechanical control of such nano-components (NEMS) is likely to foster new application fields such as microwave signal processing, micro-nanofluidics and data storage based e.g. on probe detection for magnetic storage. NEMS could also present novel operational modes at the quantum limits (e.g. acting as electrochemical switching devices).

In view of their ballistic conduction properties and their very small size, 1D nanostructures could also play a role at the level of interconnections in large-scale integrated circuits (ICs). Indeed, although interconnects are usually considered as passive components that serve to convey information without processing, their role will be fundamental to distribute energy and currents inside the circuit, all the way to each active nano-component. New nanoscale interconnects could also provide solutions to the undesirable phenomenon of electromigration, linked with high current density requirements. A proper interfacing between passive and active nano-components might be a crucial issue to develop complex ICT components with nanoscale devices. A further challenge is to explore the limits of merging or integration of nanoelectronics and nanophotonics.

1-D nanostructures hold promise in:

– interconnections in large scale ICs

– new self-assembling techniques

– the interfacing with the living

1D nano-components could also offer real opportunities for new self-assembling techniques such as by chemical growth. These novel fabrication methods could guarantee a solution for cost-effective massive integration, even if their implementation will also require the use of conventional fabrication technologies and infrastructure. The integration of 1D structure components into ICT, a first step in the realisation of complex 3D structures, will also lead to a deepening of our understanding of "intelligent matter" and its mechanisms for information exchange between DNA and proteins, enzymatic activities, DNA mutational processes, neuronal activities and so forth. This will improve our understanding of the basic mechanisms of the living world, which in turn could foster the exploration of revolutionary, bio-inspired concepts for ICT systems.

Other options at the 1-10 nm scale to develop new devices or functions include single-electron transistors, molecular electronics, spintronics, etc. While these developments do not appear as promising today as those based on 1D structures, further research would be needed to explore their true potential in greater depth. Among the conceptual and design issues linked to these developments towards miniaturisation and new functions, the crucial issue of heat generation, conduction and dissipation must be considered in parallel to enable practical realisations of large-scale integration.

Besides their contribution to ultimate shrinking of devices, new materials will also enable the development of devices and circuits in currently unexploited THz frequency bands and in high-power applications.

3.2 Combining and interfacing a growing diversity of materials, functions, devices and information carriers

The CMOS circuits manufactured today already include tens of different materials. The physical media for future information systems will increasingly rely on combinations of many different types of materials, inorganic with organic, bio-molecular materials and living systems. They will also rely on different means to encode information into electrons, photons, ions, spin, new collective states of charge or energy or momentum carriers (e.g. phonons). These combinations will require novel schemes for computation but also to transfer information among hybrid components without disrupting their behaviour or operating conditions. The grand challenge will hence be to ***master interfaces at unprecedented levels:*** between different types of nanoscale components and quasi-particles, including interfacing among different materials and with living systems. For example, interfaces would have to be precisely designed to guarantee reproducible and efficient injection and collection of charges/spins/photons. They would need to mitigate dephasing mechanisms in terms of energy, quantum coherence, spin control, etc. Interfaces must also bridge the gap between nanometre components, micrometer circuits and the macro-world. Finally, interfaces between information systems and human beings are also a key area for future research, including autonomous complex microsystems that perform sensing and actuating functions combined with cognition and processing.

Master the interfaces between different nanoscale components, materials and information carriers; interfacing with the living

Manipulation and engineering of bio-molecules can bring about novel exciting and practical opportunities for the development of integrated hybrid bio-electronic interfaces and systems. By investigating the fields of biomimetics, completely new technologies for material synthesis and manufacturing based on natural nanofabrication could be implemented. In this area also, the controlled transfer of information between completely different materials and media might be a central issue to take full advantage of the interfacing between inorganic and complex living matter.

Biomimetics may inspire new ways for material synthesis and manufacturing based on natural nanofabrication

Most discussions at the workshop converged on the challenges raised by the discovery of future nanoscale components with characteristic dimensions at the 10 nm scale. At this scale, the boundaries between inorganic and organic matter disappear, and various sciences and disciplines are merging. Interdisciplinary research combining electrical engineering, physics, chemistry, material science, biology, computer science and mathematics will be necessary to progress on the challenges at this scale. It will drive progress in strategic nano-scale science, nanoelectronics and nanophotonics, applied quantum physics, and will stimulate many biomedical applications.

3.3 Cost-effective fabrication methods for complex systems with deep nanometre scale devices

Another grand challenge is the development of ***novel unconventional fabrication technologies.*** These could exploit bottom-up, self-organized, bio-inspired, combined bottom-up and top-down, heterogeneous micro and nanosystem fabrication. Fabrication methods are intimately linked with device and circuit architectures. The crucial requirement is to grow and shape novel components at around and below 10 nm through technologies with a potential for mass manufacturing. These should aim to go far beyond the known limitations of lithography. A key enabling phenomenon is the self-assembling of nano-objects mediated by (bio)-chemical interactions. It provides a promising route to a sustainable upscaling of performance of components with downsizing devices. Self-assembling processes offer a promising alternative for the manufacturing of storage components, in particular for magnetic storage and for sensors, including links to biological elements.

Current directions for self-assembling of nano-components include Chemical Vapour Deposition (CVD) growth techniques and electric field directed or chemically-assisted selective deposition and localization of nano-components onto functionalized templates. Advanced chemically assisted deposition could exploit DNA self-recognition and assembling rules, chemical affinity, genetic engineering of viruses, etc. For both chemical assembly and CVD, the substrate has to be prepared to allow self-assembling and precision positioning of a very large number of nanoscale objects. Inducing self-organized growth and functionalisation at the wafer-scale is a fundamental step, complementary to 1D growth approaches.

New promising fabrication methods explore self-assembling of nano-components

Other new investigation paths include bio-inspired and biologically-mediated fabrication

Unconventional fabrication might also help in the realisation of novel substrate and template designs, such as taking advantage from crystalline lattices or special material designs such as quasi-periodic, twisted substrates, etc. These would allow the positioning of building block precursors such as nanodot catalysts, or the localization of templates for further chemically driven selective deposition of nano-components. In particular, for mass storage materials, self-organisation may be the only solution to reach magnetic media densities of 50 Tbit/in2. Finally, nanofabrication should also explore ways of harnessing bio-inspired or even biologically mediated fabrication. These methods would exploit biological templates but could even consider harnessing bacteria and viruses as “device factories”, while taking into account considerations on societal acceptance. Biologically inspired fabrication methods may be necessary to develop characteristics of living systems such as 3D architectures and the related interconnect issues and self-repair as an answer to defect increases.

New fabrication methods such as chemically-driven self-assembly may favour the practical integration on silicon platforms of novel functional units based on new materials and nano-components. The merging of bottom-up with top-down fabrication approaches appears to be an attractive opportunity to complement the development of silicon-based manufacturing techniques for the forthcoming decade.

3.4 Pushing the limits of miniaturisation to the nanometre scale

Pushing further miniaturisation would require methods and tools to model, manipulate, fabricate, characterise and exchange information with objects at the atomic scale

Beyond the multidisciplinary nanotechnology developments at dimensions of 1 to 10 nm discussed above, researchers and engineers are likely to push size reduction further ahead. This would require methods and tools to model, manipulate, fabricate, characterise and exchange information with objects down to the atomic scale. This, in turn, will require pursuing the improvement and use of manipulation tools such as scanning tunnelling microscopes in extreme conditions, and ultra-high vacuum or scanning tunnelling microscopes with multiple heads. These developments would pave the way for an atomic scale technology. The transfer of information to and from atomic scale elements is also a crucial issue. Information transfer may be ultimately conveyed by very small current densities, the injection and collection of which will require high precision measurement tools. Other techniques to communicate information with atomic scale objects include vibrations or optical free space radiation, in the near field or in the far field.

One of the directions of this atomic scale research is to investigate the potential of "computation" inside a single molecule or of computation by means of interacting (supra)-molecular objects, as new long-term approaches for data processing. Indeed, molecules as well as self-assembled molecular architectures encode a wealth of intrinsic electrochemical-based information, with a specific way to react to and process external perturbations. In contrast to inorganic bulk matter, isolated molecules are electronically defined by a small discrete set of energy levels which are modified under external perturbations (electrostatic, photonic, …), leading to energy transitions. Molecular units could be used as computational building blocks for processing or storing external information.

New computing approaches are based on molecular and quantum computing

Quantum computing is a different approach to information processing that would take advantage from quantum entanglement of electronic wave functions, to handle data processing beyond the binary scheme. It could offer unprecedented computational opportunities. However, its reliability and scalability are strongly dependent on controlling quantum decoherence and dephasing/dissipative mechanisms. Currently, basic units of quantum computing, known as qubits are tentatively implemented by using inorganic bulk materials, with the challenge of maintaining quantum coherence at an operational level. Appropriately designed molecules could provide intrinsic localised quantum entanglement and, when combined with quantum theories, could bring about computing inside a single molecule.

3.5 Mastering the giga-complexity of systems and architectures in a nano-scale world

Current downscaling of CMOS into the nanometre scale already has a strong impact on the complexity of design processes and computational architectures. In the coming years, complexity will be further exacerbated by the integration onto CMOS platforms of many different materials, elements and functions, and of top-down, bottom-up and self-organised structures. The related grand challenge is to establish ***methods and tools to master giga-complexity ICT systems and architectures***, which arise from the integration of billions of devices with nanoscale dimensions, mitigating the effects of variability, defects and energy-dissipation issues. A collaborative effort between process technologists, component providers, platform architects and system and service designers is crucially needed to address this major roadblock and lead to a sustainable development of ICT systems during the next decades. The major issues concern the "power-software" conflict, the abstraction of digital information from nanoscale physics, and the design productivity.

The ***power-software conflict*** faced by designers relates to the contradicting requirements to increase both system processing power and (re-)programmability, while reducing power consumption. While planned developments of future ambient intelligent systems will require computing power increasing faster than Moore's law, at the same time, they would require more programmability and reconfigurability to adapt to evolving standards and to allow mass-manufactured components to be used in different end-products. Software-defined systems usually require at least 3 orders of magnitude more energy than their "hard-wired" counterparts, so a simple shift to software to define the functionality of ambient systems will not be a solution. In particular, ambient intelligence applications call for battery-operated (100mW) or "no-battery" (100µW) systems. Ultra low power systems could emerge from a combination of very-low energy-dissipating devices and power-saving architectures. For example, architectures could tolerate individual devices with lower performance but reach higher aggregate power through massive parallelism, with local storage and low-power on-chip networking. Other solutions could come from the synthesis and simultaneous compilation of circuits and software, and/or from power-optimising operating systems. Solutions developed for low-power systems could also be used to mitigate the increasing power dissipation densities of the highest-performance processors. Other avenues could explore phonon engineering, i.e. the tailoring of crystal vibration waves as carriers of thermal energy. These might also be a promising way to channel thermal energy inside a device and reuse dissipated energy.

A second aspect of the complexity challenge is related to the ***complexity of physical phenomena*** determining and limiting the behaviour of nanoscale devices and circuits. Today's digital design tools and methods are based on the abstraction of physical phenomena in devices into digital data processing models used in designing systems. However, when processing information with nanoscale devices, additional considerations have to be taken into account. They include the dominant leakage power for nanoscale CMOS platforms, limitations in today's continuous and semi-classical physics approaches to model downscaled transistors, and fluctuations of doping levels at interfaces. All these issues cause unstable performance in current modelling schemes, making them inefficient. System architectures also need to be developed to mitigate the effects of defects, errors and stochastic behaviour of devices. Bottom-up modelling allows a better simulation of nanoscale devices, material-related interface issues, as well as charge injection regimes, accounting for novel physical phenomena and material constraints. Building the architectures of novel components would thus require novel multi-scale simulation approaches, to help assessing performances and operational modes of basic computing units, as well as power consumption perspectives. Modelling techniques are also required to deal with the combination of novel nano- and bio-based devices with various materials in a micro- or nano-system, and to understand their thermal, mechanical, and electrical behaviour, as a product, but also during the fabrication process. The discussions did not extend much beyond the scope of components, corresponding to today's integrated circuits, packages, including basic software, and to their likely evolution. Important additional challenges arise from the further conception, design and integration of such components as part of complete products and applications, but these were not covered in the meeting.

Dealing with the integration of billions of nano-devices into ICT architectures would require addressing:

- **the power-software conflict that designers face**
- **the complexity of digital phenomena characterising the behaviour of nano- circuits and nano-devices**
- **the design complexity of ICs and the design gap between the scale of manufacturable ICs and the productivity of design teams**

Another challenge already present today is the increasing ***design gap*** between the scale of manufacturable integrated circuits and the productivity of design teams that define their configuration to deliver product-level behaviour. While incremental improvements in design productivity mitigate part of this increase, major breakthroughs will be necessary in the coming two decades. The economic value of further downscaling of CMOS would be limited if the design time and cost of the circuits would become prohibitive. Design productivity must be increased fifty-fold by 2014 (32nm node) to keep design costs acceptable.

In summary, architectures and design methods for novel nano-components will demand new concepts and system designs, addressing scaling, power dissipation, variability, defects and reliability issues.

4. Research in Complex Systems

System complexity, deriving from the interactions of large numbers of highly interdependent system components, is becoming an obstacle to further progress in the design and deployment of large scale systems. Communication networks, large databases and software systems, the Internet, large distributed control systems, businesses and the global economy, are examples of huge, interdependent, open, information-processing systems with behaviour that is increasingly difficult to predict and control.

– Harness the system complexity and the efficient handling of huge data sets in large scale ICT systems

– Modelling, simulation, design and control of complex systems are central issues to address

No less important, the huge amount of data to be handled today in many areas of science and the increase of information flow in novel communication and computation systems – like the next generation Internet, the Grid, and a myriad interconnected nomadic wireless devices – confront us with unprecedented challenges.

Modelling, simulation, design and control of such large-scale systems in technology, business and the sciences are major issues to be addressed. The workshop participants have therefore focussed on the following two main subjects:

1. Design and modelling of complex information and communication systems, and

2. The modelling and simulation of complex systems in other domains, such as biological systems and social systems.

Today however, ICT systems can no longer be considered in isolation: they are embedded in larger, and typically complex, technical and social systems (that may themselves be considered information and communication systems). So, there is a need to consider also ‘conventional’ ICT systems in the context of the wider-scale systems in which they must operate. Finally, the experts also considered the impact of awareness of complex systems behaviour, and emerging results from complexity science, on the fundamentals of computer science and software engineering.

Vision

Recent scientific studies on the principles of functioning of complex systems – like living organisms and ecosystems, as well as societies – suggest that lessons on efficiency and reliability can be learned from such systems. Ideally, new system theories that are informed by the scientific study of such systems in other domains will identify architectural, algorithmic and functional foundations of systems that incorporate vast numbers of adaptive and interacting elements.

In turn, such theories will inform and underpin:

- The design of scalable ICT systems with novel functionalities and substantially higher autonomy, performance, and reliability.

- The effective use of IT systems in modelling, simulating and ultimately managing highly complex processes (for instance in biological or social processes), thus helping to understand their complex behaviour and making their complexity more 'tolerable'.

The study of living organisms, ecosystems and the society can inspire new system theories for building the functional foundations of systems incorporating vast numbers of adaptive and interacting elements

Prospective examples include *autonomic computing and communication* that embody self-configuring and repairing computation; *self- and context-aware communications*; and *self-modifying software*, with reduced cost of building and maintenance.

Scalable tools for analysing and understanding large amounts of data from living systems could provide the basis for a new era in the life sciences. And in social systems the capacity to handle large amounts of data will open a new era of social simulation and prediction.

Research challenges

Five priority challenges for research were identified at the workshop. The first two, on *'Inferring systems models from incomplete information'* and on *'Human-Responsive Systems'* were quite discrete. The remaining three all addressed the aim for complex man-made systems to have the properties that we desire. *'Foundations for Software-Intensive System Development'* seeks a transformation of software engineering techniques so that the properties of such systems can be guaranteed. The other two – *'Control and Integrated Design of Complex Systems'* and *'Many level, Many Unit, Many Purpose Systems'* – both seek to learn from complex natural, social, technological and economic systems: the former to establish engineering guidelines that draw inspiration from such systems; the latter to establish an underpinning framework of formal techniques for analysis and reasoning about such systems.

Since these challenges were developed by sub-groups of the workshop, operating independently, there is some overlap in the associated research priorities that they identified.

4.1 Inferring systems models from incomplete information

The Challenge

The ambition is to be able to model and simulate many systems for which there is at present insufficient direct knowledge. Such systems occur especially in ecology, molecular biology, certain technological-information processes (internet, etc), systems with the human in the loop (management, finance, economics) and in medicine. To achieve this will require techniques for inferring models – dynamics, laws governing their interaction and dynamics and describing their behaviour – that may be used as the basis of simulation, even in the absence of full information and in the presence of inconsistent and partially false information.

The Research Challenge:

Model and simulate systems for which we have incomplete or inconsistent information

Develop techniques for inferring models (dynamics & laws describing their interaction and their behaviour) from vast sets of data

Rationale

An implicit assumption in modelling of systems, as they occur in nature, society or technology, has always been that we know, or could in principle know, the individual elements and their interactions in great detail, or we know the evolutionary process that underlies the changing mechanism. For many complex systems in the real world this is definitely not the case: we lack a full description of the relevant components of the system; there is uncertainty in the values of parameters of the relevant components of the system; and there is incomplete information about their interactions (interconnection topology) and about the influence of the system's environment.

The explosion of dynamical data is now, for the first time, providing a basis for reconstruction of the dynamics of highly complex systems. But the research community faces a fundamental challenge in dealing with the volume and form of this data, in managing its storage, and in using it to build real understanding of the system being modelled. Deriving useful information and then knowledge from vast sets of data is prerequisite to development methods and techniques for solving real life problems in many domains.

The construction of long-term databases on complex systems must begin now and must be supported by methodologies and tools for managing and extracting information from them. Such databases must include information on the dynamic evolution of systems, not only on their structure. This means that data will be programs inferred from incomplete data and queries will act upon the semantics of the programs. Visualisation tools must be equipped with (stochastic) run-time support showing the execution of programs according to the quantities driving the interactions.

The information revolution has vastly improved our ability to gather, store and process data. As a result, contemporary science in many areas is struggling to deal with an overwhelming explosion of raw data. This is true in biology (in the so-called ‘post genome’ era) and in modern communications networks, as modern technology gathers data automatically, offering a rich storehouse of information on the dynamics of these systems. Progress on this challenge will offer Europe an ability to harvest this information explosion to the benefit of basic science, as well as in the service of important technological applications.

Research priorities

Research is required in order to:

- ***Describe systems at different levels of ‘granularity’ (accuracy), e.g., from a qualitative to quantitative level.*** Methodologies for robust computations on models with uncertainty are essential for breakthroughs in this area.
- ***Enable the extraction of meaning from heterogeneous, incomplete, inconsistent, partially faulty data sets.*** This involves development of concepts and computational tools that allow the systematic transition from data to information and then knowledge.
- ***Infer models to describe the dynamics of complex systems from incomplete and inconsistent data sets, and repositories for these descriptions.*** This will require development of experimental as well mathematical methods for the description of systems. An example would be the classification of topologies (spatio-temporal structures) in such systems.
- ***Enable automated maintenance of system models, drawing on data-mining of public databases of relevant information, or even from the open literature.*** This requires elaboration and application of formal compositional description techniques so that new knowledge can simply be composed with existing knowledge in order to refine a behavioural model.

The suggested research requires contributions from a rich mix of disciplines - computer science, mathematics, physics, statistics and design of experiments, control theory, information, systems identification and communications systems. And, in addition, contributions would be required from the targeted disciplines of biology, the social sciences, and so on.

A first step would be to make all the data from the present information explosion available to the entire scientific community in an appropriate form. For this we need to develop a platform for achieving and guaranteeing the free sharing of data. This is a social and a technical challenge.

4.2 Human-Responsive ICT Systems

The Challenge

The workshop participants envisaged a new era of human-responsive systems that actively consider the user's perspective, whether designing, implementing or executing complex systems. Such systems will significantly augment human capabilities, rather than replace them with technology.

We can no longer treat ICT systems as separate from their human users and others affected by them. An ICT system and the human context in which it is deployed together form a system. By shifting the emphasis to increased human productivity, people will no longer be viewed as simply input to a complex system, but rather as the object of system development.

> **The Research Challenge:**
>
> ***Design human responsive systems where ICT systems together with their users are forming a new system***
>
> **Develop new design principles taking into account the changing needs and desires of people participating in complex systems**

Rationale

On-going advances in technology have produced a stream of innovations, resulting in technology that is cheaper, better and faster. However, instead of a corresponding increase in human productivity, users are often over-whelmed and less productive. By recognizing that complex systems incorporate both human and technological components, we aim to ensure that such systems are responsive to people and that they increase human productivity.

Today's systems have reached the limits of current tools and techniques for supporting human-computer interaction. As we begin to explore the new possibilities offered by ubiquitous computing and mixed reality, which merge physical and virtual information, we will need to move beyond the desktop metaphor and take advantage of the full range of human sensory and motor capabilities.

Progress toward this vision will enable us to take optimal advantage of both human and technological strengths, enhancing human skills, such as judgment, handling unpredictability, social interaction and decision-making, while profiting from technological strengths, such as calculation and information management. The participation of human users in decision-making will then increase, resulting in increased overall effectiveness and greater satisfaction.

This human-responsive approach reinforces Europe's existing leadership role in participatory design, by demanding greater participation of users in the design, implementation and operation of complex systems.

Research priorities

We need new design principles that accommodate the changing needs and desires of human participants in complex systems, rather than treating them as outside the system, and rather than presuming to know what they need.

New processes, measures and techniques are required to ensure that the human element of complex systems is considered as an important aspect of design. Specifically, research is required in order to enable development of:

- ***Multi-disciplinary design processes for system designers*** to enable them to respond to human needs and capabilities when designing and controlling complex systems
- ***New design patterns that allow complex systems to be responsive to the human participants within them***

- ***Technological tools and interaction techniques that increase human capacity for handling complex data and making effective decisions***
- ***Metrics for measuring the effectiveness of complex systems*** in both human and technological terms

We also need better understanding of human behaviour in order to develop generative theories that should inform the organisation of architectures to support and sustain participation, including participative co-design of the systems themselves.

This research requires multi-disciplinary design teams who are able to cross boundaries and address design questions from various perspectives. The disciplines to contribute are the social sciences, including psychology, sociology and anthropology; computer science; software engineering; hardware engineering; and various design disciplines such as industrial engineering, graphic design and architecture.

Significant progress should be achieved within 5 to 10 years. However, in order to affect a paradigm shift that values human as well as technological performance within a system, we will need to make changes in the design process, in the interaction paradigms, and in the metrics used to determine success. For example, we need a measure of the simplicity of a solution relative to the complexity of the problem and a measure of effectiveness and productivity of human decision-makers.

4.3 Foundations for Software-Intensive System Development

The Challenge

A fundamental breakthrough is sought for the scientific basis of computer science and software engineering technologies so as to capture evolution and dynamics, selfish interests of individual entities, various levels of bounded rationality, learning aspects and self-emerging behaviour, in a strict, yet tractable way.

In particular, we need to understand how the attributes of systems that are often regarded as 'non-functional' and that have typically been treated as emergent – such as security, safety, scalability, resource optimisation, quality of service, maintainability, flexibility, and efficiency - might be designed-in, and guaranteed by construction.

This would drastically improve the ability to meet industrial and consumer expectations regarding quality and functionality for software-intensive systems, and to reduce the effort required for their development.

The Research Challenge:

Strengthen the scientific basis of computer science and SW engineering technologies

Develop new theories for capturing the evolution & dynamics, selfish interests of individual entities, various levels of bounded rationality, learning aspects and self-emerging behaviour

Rationale

Software technologies are of crucial importance for the development of all advanced products and services in modern economies. The relative weight of software in the value of these products and services is constantly expanding to the point where it a strong factor for differentiation and competitiveness. More than 59% of software in Europe is developed internally by enterprises. Software development is thus at the heart of European productivity and competitiveness, the fundamental Lisbon objectives.

Competitiveness in software intensive systems is starting to depend heavily on the capacity to produce high quality, complex software at a reasonable cost. This objective contrasts with the relative low level of the techniques currently in use for software development, debugging, and composition. A major step forward is urgently needed to meet the requirements arising from the following technological trends:

- Sensors, embedded systems (avionics, automotive, space), wireless telecommunication (mobile phones and wireless services), and pervasive computing.
- Large-scale distributed systems (Internet, with emphasis on security and resource awareness).
- Large-scale software systems and applications (telecommunications, air traffic control, enterprise operations, banking and e-commerce with emphasis on security, interoperability, and compositionality).

Maintaining and extending Europe's lead in some sectors such as embedded systems and telecommunications and services, improving the productivity of European industry (which, as mentioned, relies highly on internal software development), and acquiring the lead in other software-related sectors requires significant advancements in software development technologies in order to enable the production of very high-quality software with the least effort possible. Europe is in a unique position to make a contribution in this area by building on its strong traditions for foundational work and applying them to systems problems.

Research priorities

Research is required for:

- ***Guaranteeing non functional system properties*** (i.e., security, safety, scalability, resource optimisation, quality of service, etc).
- ***Devising new, high-level paradigms and languages for programming*** that encompass distribution, mobility, dynamic evolution, and that take into account non-functional properties
- ***Developing new algorithmic techniques for distributed systems,*** taking into account non-functional properties
- ***Conceiving and implementing modelling theory, methods, and tools for complex software systems,*** encompassing heterogeneous levels of abstraction
- ***Property-aware compilation and implementation techniques,*** especially for non-functional properties, with automatic verification
- ***Establishing the foundations for component-based development, especially theory, methods, and tools for building of software intensive systems that are correct by construction*** (compositionality, component-based techniques, modularity, etc.).

4.4 Control and Integrated Design of Complex Systems

The Challenge

The aim is to develop modelling and computational tools that will enable understanding of emergence of complex types of behaviour in systems, and then permit the formulation of integrated design strategies and techniques for the synthesis of complex processes, the structuring of their organization (centralized-decentralized-hierarchical etc), the design of measurement and control structures, and finally their control design.

Such complex systems come from many diverse domains and disciplines: they may be the result of a design process; they may have been formed at a given instance; or they may be the result of an evolutionary process. They include traditional complex engineering processes, energy systems, financial systems, new technological processes (micro-, nano-systems etc), biological and social sciences, and management systems, including systems for the intelligent management of communications and computation applications (the Internet, mobile networks, etc.) It is important to note that complexity in such systems is not due to our inability to act upon them, but the result of their properties and history.

The Research Challenge:

Understand the emergence of complex types of behaviours in systems

Develop modelling & design techniques for the synthesis of complex processes, the structuring of their properties, their organisation and dynamic behaviour and their emergence at higher, collective levels of activity

Rationale

For systems comprising many interacting elements we currently lack a framework of formal or mathematical techniques for modelling with which to predict the types of structures, the dynamic behaviour and properties that are likely to emerge at higher, collective levels of activity, or to clarify the conditions that will support such emergence. In other words, we lack a basic theoretical understanding of how properties of elements and element interactions at the micro level produce system properties at the macro and aggregate level.

Contemporary science has crossed an important threshold. In many areas, science has progressed to the point where we know the individual elements that make up important systems, as well as the nature of the interactions between those elements. This is true in materials science, micro-nano systems, for example, and increasingly in biology. It is also true for large scale engineering systems (power, chemical processes etc), communications and computational systems, where we have designed the components and engineered their connections, as well as integrated management problems (from a firm to networks of suppliers etc). But we now face the task of understanding how complex functions emerge in such collections of interacting elements and how to design or redesign such systems to achieve desired behaviours. Complexity is the next great barrier to technological progress and research to improve understanding and management of complexity is timely and challenging.

At the same time we now have the tools that enable researchers to attempt to breach this barrier. In particular, we are now able to carry out powerful and realistic simulations of complex systems. While simulations themselves cannot yield formal insight directly, they do make it possible to explore the behaviour of complex systems in an experimental way, complementing and verifying theoretical studies and thereby making fundamental progress more likely. Hence the emerging field of integration between simulation techniques and verification techniques could enable new insights towards the solution of the challenge.

Furthermore, theory for modelling dynamic, distributed and mobile complex systems is now well developed and can be exported to other areas: the major field of application seems to be that of biological systems or artificial bio-inspired systems.

Fundamental insight into the functioning of complex systems and the relevant modelling, simulation and computational tools will offer many economic benefits, as many economically important technologies must overcome the barrier of complexity in moving toward the next generation. Furthermore, the emerging conceptual framework and tools will allow better management of resources and will enable us to control technological and biological processes, which sometimes risk becoming autonomous under the pressure of progress.

Research priorities

To meet this challenge, research is required to:

- ***Develop modelling tools*** based on logical and mathematical insights ***that will enable*** researchers and designers ***to understand the process of emergence and the nature of related system properties.*** They will then be able to explore their potential for tackling problems of integrated design (synthesis, design of measurement-control structures, organizational issues etc) and the consequences for stability, controllability, observability (reconstructibility) system efficiency (performance) and resilience, etc.

- ***Establish new computational paradigms and primitives to model and control complex systems.*** These should hide the complexity and provide tools to assess qualitative as well as quantitative properties affecting the structure and the behaviour of these systems.
- ***Inform the development of a sophisticated, freely available and easy to use platform for the computational simulation of complex systems and tools*** for evaluating the emergent properties and carrying out design.

Achieving these breakthroughs will require expertise from mathematics, operational research, computer science, statistics, physics, control theory and information theory. Knowledge from particular application fields is also required. In particular, expertise in biology, economics, management and social science will be required so that the resulting insight might be applied to important applications.

To realise this vision, it is best to focus first on relatively 'simple' complex systems, (that is, systems for which we understand in detail the nature of the individual elements and the interactions between them) and then specify clusters of generic (discipline independent) problems such as problems emerging from technological processes, before moving to biological, man-machine, and social systems. The idea is to first tune the formal framework over known systems so as to reproduce known behaviour, and then use it in a predictive fashion to control and design much more complex systems.

Significant progress on this challenge could be achieved within 5 to 10 years. The nature of application areas influences the rate of progress, since many of the required tools will be domain-specific.

4.5 M3P – Many Level, Many Unit, Many Purpose Systems

The Challenge

A new paradigm for computational systems was proposed that draws inspiration from complex natural, social, technological and economic systems, and on existing modelling work (swarm computing, evolutionary computing, cellular automata, formal modelling methods for hybrid and heterogeneous processes etc.). It does not however limit itself either to studying the factors that make these systems successful or to simply exploring what emerges from such systems. Rather it aims to define engineering guidelines that will enable us to find cost-effective solutions to problems that cannot be solved with current techniques.

> **The Research Challenge:**
>
> ***Draw a new paradigm for computational M3P systems***
>
> **Develop a theory and define engineering guidelines for the design and control of M3P evolutionary systems by drawing inspiration from biology and sociology**

Examples include:

- Enterprise systems, value-chain networks, telecommunications networks, energy distribution networks, traffic networks, air traffic control systems, and complex industrial plant that are resilient, adaptive systems in the face of unpredictable failures and attacks.
- Naturally resilient, self-repairing systems for peer-to-peer telecommunications, data sharing and knowledge management.
- Large scale simulation models for biological, social, economic and artificial systems and support systems for decision makers operating with or inside such systems.
- Technological support for effective decision-making by competing and collaborating agents in political systems (e-democracy), industrial companies (e-management and value-chain management) and other large organizations (e.g. the internet).
- Mission-critical emergency warning systems including systems for ecological, epidemiological, space, industrial and security applications.
- Knowledge capture (growable) and data-mining in very large information spaces where individual 'agents' obey a central purpose but have access to only part of the relevant data.

- Novel approaches to 'hard' computing problems (e.g., weather forecasting, molecular modelling, hard optimisation problems, and scheduling problems) based on very large numbers of interacting units (perhaps confined in a small physical space – 'a computer in a glass').
- Evolutionary computing systems that self-organise into subpopulations and sub-layers.

Rationale

A key characteristic of many systems is that they involve components with uncertain operation and interactions which are at least partially unpredictable or hard to formalise in algorithmic terms (e.g., complex interactions with human users, interactions with the physical world, interactions with human-designed complex systems). Systems should be adaptable, malleable and resilient in the face of such unpredictability.

A number of biological, social, management and economic systems exhibit these desired properties. These systems are made up of many units, have a given organisational form of management and information structures that can be seen as performing 'computations' with local - and possibly global - performance criteria. These systems solve a class of problems that resist attacks by traditional mathematical methods and computing techniques. At present we do not know how they do it.

Although many natural, social and economic systems have been modelled by researchers (e.g., in *ALife* modelling) and a large research community has dedicated itself to the construction of Multi-agent Systems, the majority of modelling approaches suffer from one or more of the following defects:

- The number of units or agents (usually hundreds or thousands) in the system is many orders of magnitude smaller than the number of units (millions, billions, trillions) in the natural, social or economic processes the system is attempting to emulate.

- Models and systems are often organised at a single level. Even where systems do consist of multiple levels, these are deliberately designed. Only very rarely do they emerge naturally from lower-level interactions as occurs in natural, social and economic systems. Emergent behaviour is critically dependent on architecture in a way which is not considered at present.

- In many models, such as those used in multi-agent systems, the knowledge they contain is explicitly programmed. As a general rule, current models have no way of incorporating new knowledge during their evolution or development.

- Many models (such as those produced by ALife modelling) have no "purpose": while this kind of model may well exhibit interesting behaviour this has no 'use'; there is no way to program the model, even when we define programming in the broadest possible sense.

- System models and design in the past have been done without economic, business or social objectives, and this has resulted in inflexible systems that have to be constantly reprogrammed or rebuilt in order to satisfy newer objectives. The levels of programmability have always been an issue, and almost every ICT system implemented anywhere has to be reprogrammed to handle new kinds of applications, new entrants, and new economic demands.

- Most models in the past have focussed on homogenous systems, where agents or agent-like environments only function in homogenous environments in relative terms. In reality, systems are very heterogeneous, for example, ICT systems in large enterprises are multi-vendor, with very different behavioural characteristics internally, but externally have some level of programmability that could be utilized to create order.

However, there are already in circulation many concepts and techniques which could contribute to M3P – Multiple Agent Systems, complex system theory, analyses of specific complex systems, systems biology, agent-based economics, swarm computing, evolutionary computing, large scale P2P applications, distributed systems. It is time to attempt a synthesis.

The development of computing technology means it is now technologically feasible to produce very large numbers of the highly sophisticated components required for implementation of the paradigm and with the Internet it is possible to practically test concepts involving thousands, tens of thousands or even millions of computational units

Foreseeable parallel developments in nano- and bio-technology offer the prospect of novel possibilities for implementation.

Work in this area would provide European industry with a head-start in a new area of hardware and software that is likely to be of great importance. This kind of head-start, similar to the US head-start in personal computing or the European advantage in 2nd generation cellular telecommunications, can translate into long-term strategic advantage.

At the same time, the systems made possible by the M3P approach could facilitate decision-making at all levels of European society. This would be especially important if Europe took the lead in the adoption of such systems (as the US took the lead in take-up of previous generations of computing technology).

Research priorities

Several research priorities and breakthroughs are required to meet this challenge:

- ***Develop a theory to guide the design of M3P systems by formulating a set of generic conditions under which a real many-units purposeful system has to operat***e (typically, limited computational communication and computational resources) and devising a methodology that allows optimisation of their elements under these constraints.
- ***Find ways to 'steer' systems comprising very large numbers*** (perhaps millions, billions or even trillions) ***of autonomous heterogeneous computational units that exhibit spontaneously emergent levels of organization so as to satisfy some objective*** (social, economic or business).
- ***Find approaches to design systems so that they are aware of the environment they are operating in:*** this awareness will provide better intelligence to react accordingly.
- ***Find approaches for optimization so as to enable such systems to perform under tight physical constraints*** (e.g. limitations on the complexity of individual computational units, limitations on communications among units etc.)
- ***Establish a design paradigm for the design of evolutionary systems.*** The purposes of M3P systems will be not be completely expressed as an explicit program. Like natural systems, M3P systems will evolve and develop, and in the process they will automatically incorporate information from the environment. This ability will provide them with flexibility and malleability unheard of in current multiple-agent systems. In particular such systems might evolve their structure: at least partially they will be self-assembling, self-programming systems. Structural methodologies and methods for aggregating behaviour will also be required.
- ***Formulate in rigorous terms the inspiration coming from biology and sociology and operationalise it in methods and tools:*** metaphor is not enough.
- ***Develop new methodologies required by the large dimensionality of such systems and their heterogeneous nature for reducing the designing burden to manageable levels.*** Design problem decomposition, sequencing of design, decentralised and hierarchical control will be challenging issues in this new paradigm.

This wide range of research will require contributions from mathematics and computer science, statistical physics, complexity science, information theory, control theory and optimisation, theoretical and experimental biology, economics, sociology, materials science, nano- and bio-technology. A multidisciplinary approach that goes beyond the traditional computer science is required where modelling, control theory, operational research and optimisation have to be deployed.

4.6 Conclusion

A clear need was identified for radical thinking about how we should design complex systems, recognising that 'complex' means much more than merely 'complicated'.

While the Holy Grail of complexity science is to understand how to engineer micro-properties so as to cause desired macro-behaviour, the first step – acknowledged in several of the independently devised 'research challenges' – is to harness the power of existing computational technology to simulate such complex systems, so as to gain insight into their operation, to inform and test man-made complex systems, and to explore the effects of man-made intervention in existing systems.

The ramifications are extensive. At one end of the scale, our whole approach to understanding our 'requirements' will require revision to move away from 'specification' of 'the system to be procured' (with, maybe, vague hopes for flexibility) to take proper, rigorous, account of the need for evolvability. At the other end of the scale, we may expect fundamental changes in the nature of computer science, as it moves from dealing with 'the bits' to dealing with the qualitative expectations for the effects of those bits.

The phrase 'paradigm change' is much over-used. But it is difficult to find an alternative characterisation of the outcome of this workshop. Europe must seize the opportunity – not shrink from the uncertainty that this new way of thinking will create.

5. Research in Intelligence and Cognition

Toward Natural Cognition

Rationale

Traditional Cognitive Science, Cognitive Psychology and Artificial Intelligence (AI) make no commitment to the form of a cognitive system's implementation. Both intelligence and cognition have largely been seen as independent of the actual substrate on which they occur, i.e. the body of a cognitive system, its morphology and its biological realisation. Cognition has been viewed mainly as a process of inference that is built on objective world knowledge based on conceptual ontologies. These approaches to artificial cognition have been relatively successful in dealing with limited, structured, symbolic problems, such as expert systems, knowledge bases for the semantic web, game-playing programs, etc. Overall, there has been less success with respect to real-world interaction, such as reliable perception, fully autonomous navigation, and so on. This ability, however, is central for future Ambient Intelligence systems.

– Intelligence & cognition have been seen as independent of the body, morphology and biological realisation of a cognitive system

– The body and its substrate are crucial to understand cognition

Today, especially in Cognitive Neuroscience and robotics the body and its substrate are considered much more crucial in order to understand cognition. One obvious difference between IT systems and biological cognition is the extent to which biology is self-programming, has adaptive configuration of sensors and effectors, and has extendable processing. There is much evidence that cognition is not, or only partially, a process of classical computation of inputs into outputs based on internal representation, but rather a highly dynamic and analogue process, which can not be separated from the morphology of the actual components in which it occurs.

Therefore, it was considered to take a radical step away from classical AI-based IT approaches to cognition, toward research on self-organisation and development as a natural framework for cognition. In this context, cognition is seen as more than only an inferential process. It is a property that results from interaction of an organism with its environment.

Vision

The vision is to build artificial cognitive systems that are inspired by biology, in particular neuroscience, under the following assumptions:

– Cognition in systems that must interact with the real world depends on, and is facilitated by, the embodiment of the system.

– The structure of the body, the environment and body-environment interaction must be seen as inseparable from each other when building artificial cognitive systems

> **The new Vision:**
>
> ***Build artificial bio-inspired cognitive systems***
>
> **Focus on the morphology of a body, the development of system structure and the coupling of embodied interaction with its physical implementation**

More precisely, the vision is that through focusing on issues like a body's morphology and its interaction with processing, the development of a system's structure, and the close coupling of embodied interaction with its physical implementation, a decisive step forward can be taken in building artificial systems that are to attain naturally cognitive behaviour.

Benefits

Many European research groups already have a long tradition in exploring alternative routes to artificial cognition, be it in neuroscience, neuromorphic engineering or robotics. Previous and ongoing FET initiatives have been successful in forming important interdisciplinary nuclei for enabling large-scale research along the lines envisioned here. "Toward natural cognition" would build on this foundation and likely spur a strong European research community aimed at building innovative systems toward truly cognitive artefacts. This new vision will provide a platform to enable a critical mass of researchers to seriously explore promising new routes with an application potential on some larger time scale.

Research priorities and breakthroughs required to achieve the vision

The following research challenges will need to be addressed in order to attain "natural" cognition in artefacts:

- ***The exploration of non-classical computation:***
  Can new paradigms of "computation" or signal processing be designed that are more suitable for mimicking natural processes? Can dynamical systems theory help us in understanding cognition? What does more morphology play as role in natural processing?

- ***The development of robust scalable self-constructing/repairing architectures:***
  Is some form of self-construction essential to the elaboration of systems complex enough to achieve cognition? Can natural cognitive systems be reverse engineered? What can we learn from simulation and where do we need actual physical substrate, such as in-vitro biological tissue or polymers?

- ***The exploitation of phylogenetic and ontogenetic development:***
  How much understanding of phylogenetic (i.e., evolutionary) development do we need to understand cognitive systems? What artificial mechanisms are there that mimic it? What role does structural change in ontogenetic (i.e., individual) development play in building cognitive systems? What principles drive developmental stages?

- ***The development of systems of self-regulation and self-maintenance (homeostasis) for cognitive systems:***
  What principles guide a complex, hierarchical and modular system of self-regulation and homeostasis? How can we ensure its stability? How does self-regulation emerge from systems of more simple components?
- ***The investigation and subsequent exploitation of emergent properties of large-scale structures:***
  How can principles borrowed from biology be implemented in large-scale systems? Is it possible to build cognitive systems by extrapolation from simpler implementations? Can emergence be predicted or controlled? What role does scale play in achieving cognition?
- ***The achievement of high-level cognition coming from this bottom-up direction:***
  Can the approach advocated here actually result in high-level cognition, such as reasoning, planning or language? Can we come from a purely bottom-up direction or is side-stepping the approach and top-down design necessary?

For addressing the above, we must take some inspiration and innovation from biology (such as neuroscience), explore the relationship between cognition and architecture, take a decisive step forward without having to result in a fully embodied or fully cognitive system, and be transdisciplinary, offering a synergistic interaction of informatics, cognitive psychology and systems sciences with neuro- or, more generally, life-science. Inspiration from biology can take place in one of several levels, ranging from a faithful replication of biological mechanisms to a rather generic implementation of biological principles leaving room for other (e.g. sensory-motor) dynamics that are intrinsic to artefacts but might not be found in biology per se.

The following is a, by no means complete, list of possible topics that need to be explored:

- New forms of biology-inspired analogue processing
- Materials issues (e.g. growing tissues or polymers)
- Body construction or development (in a real embodied system or in simulation)
- Morphology issues and their relationship to processing
- Programming and configuration tools for understanding and building layered systems
- Investigating the question: Is embodiment crucial, and how much embodiment is sufficient?
- Nature vs. Nurture: the relationship between top-down knowledge, innateness and learning
- Large scale implementation of biology-inspired intelligent systems
- Representations for analogy making as a basic ingredient for cognition

Why now? Needs and opportunities from recent breakthroughs

The time is ripe for innovative biology-inspired research on cognitive systems. Previous and ongoing FET programmes have paved the way for the next step of breakthroughs. Advances in new electronic circuits, in-vitro tissue cultures, biology-inspired robots and the like, hold the promise for a medium to long term success of the research endeavour. Further increasing European networking in this trans-disciplinary area will ensure a long-lasting impact with great future exploitation potentials.

Disciplines involved

In order to realise the vision above, highly inter- and, in particular, trans-disciplinary research cooperation is required. This involves at least the following disciplines:

- Computer science (e.g. artificial intelligence, computer vision) and robotics
- Electronic and materials engineering
- Mathematics and systems science
- Physics
- Neuroscience
- Biology
- Cognitive psychology and cognitive science
- Philosophy of mind
- Anthropology and behavioural sciences

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