FET Research Roadmaps

Pointing the Way to Future ICTs

March 2009

Future and Emerging Technologies Proactive

SEVENTH FRAMEWORK PROGRAMME

European Commission
Information Society and Media

LEGAL NOTICE

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Foreword

The Future and Emerging Technologies activities (FET) within the Information and Communication Technologies (ICT) Programme of the European Commission serve as an essential pathfinder for identifying and shaping radically new information technologies. FET supports research into new and emerging scientific ideas and thereby acts as a catalyst for the creation and development of new visions for Information and Communication Technologies. With a community funding of about 100 M€/year, it rallies Europe's best scientists and engineers to venture into uncharted areas beyond the frontiers of traditional ICT, by fostering multi-disciplinary research collaboration around novel research themes. This research leads to a radical transformation of ICT research agendas and seeds major technological, industrial and societal innovations in Europe. It fosters new research practices that change the way in which research is carried out.

To further these objectives FET supports the elaboration of research roadmaps that expose future ICT visions and research challenges to be tackled. They also identify the impacts, both at scientific and socio-economic level, which are likely to emerge from the pursuit of the research marked out. The roadmaps are laid down by specific European research communities, supported by FET Coordination Actions that facilitate the collaboration among research teams across Europe and beyond. The roadmaps point the way on how to align efforts and facilitate focusing research resources in an optimal way in Europe. They are used by the researchers themselves to orient their visions, and by national funding agencies as well as the EU Framework Programme to establish research initiatives and programmes.

This brochure presents the highlights of FET roadmaps from five different areas; it is not exhaustive, and covers only a subset of FET activities. This brochure is to be considered a first issue of a series of FET research roadmaps, due to be expanded upon as further roadmaps are elaborated and become available for publication. For further updates and new roadmaps please visit our website[1].

The specific roadmaps covered in this first issue, listed along with the Coordination Action responsible, are as follows:

1. **Presence Research in Action** (PEACH)
2. **Quantum Information Processing and Communication in Europe** (QUROPE)
3. **Complex Systems Science** (ONCE-CS)
4. **Neuro-IT** (Neuro-IT.net)
5. **Nature-inspired Smart Information Systems** (NiSIS)

I am grateful for and highly appreciate the significant efforts that have been engaged, involving broad consultations among Europe's best scientists under the leadership of the various Coordination Actions.

I hope that this roadmaps brochure will inspire others to participate in these joint European endeavours, enable a consolidation of research agendas at the European level, ease collaboration at international levels, and ultimately contribute towards a more coherent European Research landscape in ICT FET-like research

Wolfgang Boch
Head of Unit
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[1] http://cordis.europa.eu/fp7/ict/fet-proactive/press_en.html#roadmaps

Introduction

The continued pace of ICT development faces significant challenges. Today's systems have become so complex that traditional means for their design and management can no longer guarantee reliable operation. Device technology is also running up against limits to the miniaturization of electronics. Many areas of science and technology, from biology and artificial intelligence through economics, are also struggling to keep up with and find meaning within overwhelming streams of data, the collection of which has been made possible by ICT. But all these challenges also point to new opportunities if ICT research and development can pursue promising avenues which break radically with the methods and designs of traditional ICT.

The rapidly growing depth of our knowledge of biological systems, for example, points to a tremendous potential for building powerful ICTs using bio-inspired approaches, including the explicit modelling of computational systems along the lines of the human brain. Scientists increasingly see the potential of virtual reality technology to aid knowledge discovery -- by harnessing the power of human pattern recognition, for example, to find meaning in massive data sets. In a wide variety of problems, from ecosystem management to economics, it has also become clear that a focus on the holistic or collective properties of entire systems will be required for intelligent interventions, and the same is true for modern distributed ICT networks. And we may find the route to revolutionary new ICTs by learning to exploit quantum phenomena in the new field of quantum information science.

The six essays in this brochure offer a brief summary of the principal recent advances and future challenges in each of these areas, as based on detailed roadmap documents developed by experts in these fields. The essays summarise some of the key opportunities and challenges for ICT development over the next 10-15 years. In brief, the six areas are:

1. Presence Research in Action PEACH

Presence research aims to understand how and why technology can exert such strong influences on human perception, creating the feeling of "being there" in some virtual environment. This feeling is the result of a complex interaction of many technological, non-technological and personal factors, a fundamental understanding of which will enable the creation of more realistic experiences with applications in areas such as scientific visualization, for example, or simulation-enhanced learning. Building on advances in modern cognitive neuroscience and psychology, Presence research will lead to many new technologies and enable powerful applications at home, in school and on the move.

2. Quantum Information Processing and Communication in Europe QUROPE

Quantum information is a revolutionary new area of physics and technology based on counter-intuitive quantum mechanical phenomena. Technologies exploiting these phenomena have no analogies in classical science or engineering, and connect a fundamental physical theory, quantum mechanics, with cutting-edge experiments and novel technological applications. These technologies have the potential to revolutionize many areas of science and technology. The principal opportunity is to realise quantum computers with computing power beyond the capabilities of any classical computer, and quantum cryptography, which can in principle guarantee absolutely secure communication.

3. Complex Systems Science
ONCE-CS

Many of mankind's most difficult and pressing problems flow out of complex webs of interactions -- among myriad physical processes in the oceans and atmosphere, for example, which influence climate change, or among many firms and individuals in the global economy. Understanding such systems requires much more than an understanding of the parts -- it demands insight into collective system function in a more holistic sense. The science of complex systems aims to bridge the gap between the individual and the collective and to provide radical new ways of understanding collective systems of all kinds. Its insights will be at the heart of the future Worldwide Knowledge Society, and its pursuit will likely have enormous implications for European well-being in the future

4. Neuroscience meets information science
Neuro-IT.net

Understanding the biological functioning of thinking and consciousness, in both humans and other animals, remains one of the great scientific challenges. How does the brain encode memories, and act as the seat of awareness? Insight into these basic scientific mysteries promises powerful new avenues for developing information technology, especially as living organisms still easily outperform computers on many tasks. Recent developments in the neuro-sciences have made it possible to begin tackling research challenges that couldn't have been described even five years ago. These developments promise key advances in basic brain science, as well as potentially revolutionary new information technologies.

5. Nature-inspired Smart Information Systems
NiSIS

The study of nature has inspired mankind for countless generations, both in the pure and applied sciences. In recent decades, biological science has advanced at an unprecedented pace, and its research has vastly improved our understanding of the complexity and principles of living organisms. We have learned that living systems are "smart" in the sense of being adaptive, self-healing, fault tolerant and robust, and have begun to grasp the design principles that underlie these properties. ICT has an obvious opportunity to transfer some of the techniques and principles that biology uses into the design of artificial technologies for our modern information-rich society.

1 PEACH: Presence Research in Action

Why do people smile at an avatar that is smiling at them, when they know full well that no one is there, and no one can see their smile? Why do they become anxious when standing in front of a deep virtual hole in the ground, while knowing for sure there's no hole there? Since the advent of virtual reality in the 1980s it has been well known that not only do people have a feeling of being transported to the place depicted by a virtual environment, but they also tend to act as if they were really there. Why? Presence research aims to understand why, and to develop technology for achieving realistic feelings and experiences when immersed in a technologically mediated environment. The feeling of being there is the result of a complex interaction of many technological, non-technological and personal factors, a fundamental understanding of which will allow for construction of virtual and augmented environments with greater effectiveness.

To create a more realistic experience -- for technology for scientific visualization, for example, or for learning how to drive in a driving simulation -- we must understand fundamental issues in cognitive neuroscience and psychology, as well as social interactions. Presence research will lead to many new technologies and enable powerful applications—communications, learning, robotics, etc.—that are more affordable and usable in the workplace, at home, in school and even on the move. It will clearly be linked to a number of other technologies, such as mobile telephones, augmented reality, instant messaging, video conferencing, and consequently will likely have major social repercussions in the near future.

Recent Achievements and Future Challenges

Presence can be thought of as technology which can provide means for people to act and behave in a virtual world as they do in the real world.' There have been two broad streams in recent technology for realising it. The first, Physical Presence, seeks to understand the way we build our understanding of reality and self from sensory input and how we can make subjects feel and act as if their experiences were real. The second stream, Social Presence, focuses on media, and the impact of media on social interaction. What is the role of technological media in altering, enhancing or lessening human experience and human communication? This stream has growing importance of social networks and the evolution of "metaverses" such as Second Life.

While collaborative virtual environments, video-conferencing and other presence technologies have been in development for two decades, recent studies have shown that our notions of authenticity depend as much on emotional psychological plausibility as on the accuracy of physical representation. Another issue eliciting increased attention is the effect of the sense of touch -- generated by so-called "haptic" technologies -- on Presence, especially in the social context.

Modern neuroscience experiments based on the recording of EEG and fMRI activity of the brain have been very successful for exploring various stimulation technologies (audio, video for visual and aural stimulation). Computer and graphic performances now available, and advances in technologies for head-mounted displays and virtual reality, make it now potentially possible to develop flexible, modular stimulation platforms to conduct cognitive neurophysiology investigations. Research in this area may provide fundamental clues to answer to one of the central questions of Presence: what constitutes a "convincing data stream"?

All these avenues of research are helping to advance capability toward a number of key applications:

Therapy

Presence technology is being used to support exposure therapy for a variety of anxiety disorders including Post Traumatic Stress Disorder, fear of flying, heights or speaking in public, as well as of related conditions such as acrophobia, spider phobia, or panic disorders. Presence technologies are also being applied for stroke rehabilitation, Parkinson's disease, orthopedic rehabilitation, and other related issues.

Training

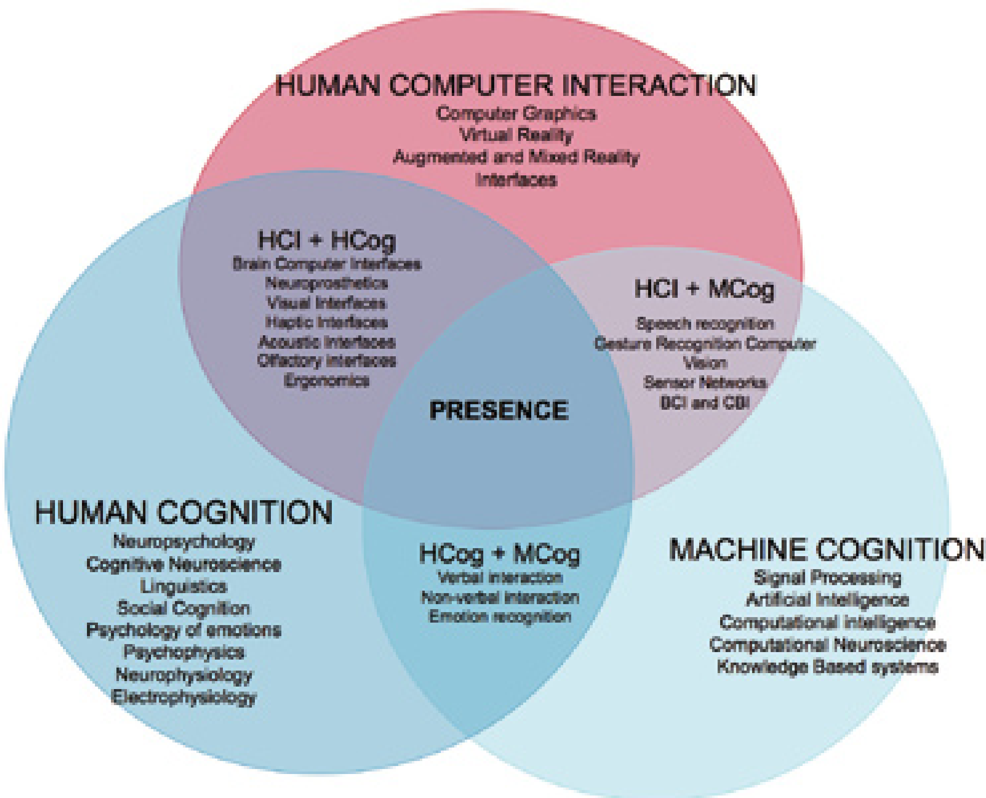
The use of Presence technologies in training has been established for a long time through various kinds of vehicle simulators used to train people in operating vehicles that are prohibitively expensive and/or impractical for real-life training. Simulators greatly reduce the cost of such training for airplanes, ships and other vehicles. In addition to cost reduction, simulation offers extended functionality that would not be possible in real life. It is thus possible to switch training situations on demand – weather, position, traffic situation, location. The case of training in military scenarios should perhaps be especially stressed, and has been a major source of funding for Presence research in the United States.

Entertainment

High-end entertainment centres (such as Disney World, Universal Studios theme park etc.) use Presence technologies very effectively in numerous attractions. The norm is to use completely scripted scenarios designed to take a large number of people through the attraction in a standardised manner. Typically the complete experience is precisely timed and generated in advance.

Online communities

Text based chat systems as are now giving way to systems using 3D desktop VR. For example ActiveWorlds30 and the more advanced Second Life both offer their users alternatives to everyday life and let them assume new personas. Such systems allow people to take part in communities which may not normally be popular in mainstream society, such as those seeking alternative online



The three pillars of Presence, their disciplines and intersections. Presence is a scientific and technological multi-disciplinary field requiring joint work in Human Cognition (including social cognitive aspects), Human-Machine interaction and Machine Cognition. The sub-disciplines listed are an illustrative subset.

lifestyles. This is evident from the relationships which are now being formed online and the fact that people regularly visit their chosen communities to socialise, trade or just explore. Online communities are gaining in popularity with over 1,000,000 registered users of SecondLife. The growing popularity of such systems has led to well known retailers setting up virtual shops, and people paying real money for virtual land and objects, and the economy within SecondLife has a daily turnover of around $500,000USD. The increase in the virtual economy points to a gradual blurring of the line between real and virtual life, which is likely to grow more pervasive in future.

A next-level development of such mediated communication can be the increasing adoption of technologies for Virtual Meetings. While the globalization of business combined with increasing cost and inconvenience of travel is clearly pushing towards remote meetings as a viable replacement for real meetings, the classical solutions (telephone conferences, videoconferencing) do not provide the level of social interaction of a real meeting. Companies such as ATK Services, Cisco, Destiny Conferencing, Digital Video Enterprises, HP, MedPresence, Polycom, Telanetix, Teliris and others are expanding into telePresence – the conferencing solutions that address the human factors of the participants and duplicate, as closely as possible, an in-person experience.

Expected Impacts

People often respond to virtually generated sensory data as if it were real data. Presence research aims to explore and characterise how and why this happens in quantitative, scientific terms, and to learn how engineers can design and influence the process, as well as protecting individuals. This research will likely have wide ramifications across many dimensions: Presence research will help us understand what it is about the way the brain processes sensory signals that makes it possible for relatively poor simulations of reality to spark such a high degree of realistic activity, and how we can use this understanding to make better designed environments. Even the very notion of the human body and our relationship to our own bodies may be transformed.

There are fundamental opportunities for the construction of new systems, and their emergence out of the laboratory into businesses and homes. This research may initiate entire new fields of endeavour in psychotherapy, neuro-rehabilitation, quality of life technologies, ergonomics, mission training, industrial prototyping, future urban environments and dwellings, and education, to name but a few. When we add the capability for such virtual environments to be shared by many people, we also add a vast range of additional applications, such as remote negotiations and meetings, virtual travel, virtual conferences, and so on.

2 QUROPE: Quantum Information Processing and Communication

Quantum information is a revolutionary new area of physics and technology based on counter-intuitive quantum mechanical phenomena. Technologies exploiting these phenomena have no analogies in classical science or engineering, and connect our most fundamental physical theory, quantum mechanics, with cutting-edge experiments and novel technological applications. These technologies have the potential to revolutionize many areas of science and technology, principally by putting quantum entanglement -- the entirely non-classical linking together of the properties of distinct particles -- to work.

Quantum information devices hold the promise of immense computing power beyond the capabilities of any classical computer, and may offer a "Beyond Moore" route to continuing Moore's Law on the basis of entirely novel modes of computing and communication. Another key opportunity lies in the area of secure communications, as quantum technologies can in principle guarantee absolutely secure transfer of information though the technique of quantum cryptography. However, making these possibilities real requires delicate hardware platforms able to achieve the highly precise coherent manipulation of quantum entangled and superposition states. While it is not yet known which technologies will be best suited for quantum information technologies at large, a number of distinct technologies show promise.

Recent Achievements and Future Challenges

Quantum information science is advancing rapidly toward several milestone technologies:

Quantum Computation

The technological exploitation of quantum phenomena requires new kinds of processing devices, such as quantum logic gates, quantum registers, etc. At present, a number of physical systems are under investigations for their suitability to implement a quantum computer. These include trapped ions and neutral atoms, cavity quantum electrodynamics (CQED), solid state devices (such as superconducting qubits, possibly in combination with circuit CQED, and spin qubits), all-optical devices, as well as impurity spins in solids, single molecular magnets etc. During the last few years remarkable progress towards demonstrating the basic building blocks of a quantum computer have been reported in these systems, and no fundamental roadblocks seem evident that would prevent building a scalable quantum computer.

The key future challenge is to develop the scalability of qubits well beyond the current state of the art, while improving methods for fault tolerance and error correction. Many sources of errors, including device imperfections and coupling to a thermal environment, presently hinder the development of large-scale quantum information applications. Research should progress on a broad front across all physical disciplines which studies these systems in view of scalability, coherence and speed of QIP, in particular also concerning their reliability, fault tolerance and use of error correction. Finally, development of a computer architecture must be complemented by interfacing with quantum communication to allow building of quantum networks. Major international companies have shown interest and support for developing a new quantum systems industry based on systems suitable for quantum manipulation.

Quantum Communication

Quantum Communication is the art of transferring quantum states from one place to another, and will be required for the "wiring" inside a quantum computer. Already now, one of its outstanding results is the emerging technology of quantum cryptography, which promises absolute secure transmission of the key codes that are essential to encrypt messages with tamper proof security. The laws of quantum mechanics imply that the mere act of observing a quantum bit will in general modify it, causing a change in its quantum state. Hence, an eavesdropper's attempt to intercept the secret key made of qubits will therefore be manifest to both parties. Quantum cryptography is now developing from the initial approach known as point-to-point Quantum Key Distribution (QKD), towards the management of quantum-based security over many-nodes networks, that are being built in various places worldwide (USA, Europe, Japan).

At present the technical problems are controlled well enough so that secure transmissions over a few tens of kilometers can be implemented. However, non-trivial problems emerge for really long-distance communication (hundreds to thousands of kilometers), and in the quest for higher bit rates. High-flux single photon sources as well as entangled photon sources should be developed in order to enhance the secure medium range quantum communication. At present photons are the only suitable system for medium-distance quantum communication, as they maintain a robust quantum state throughout transmission, can be detected efficiently and with low levels of noise (other systems, such as atoms or ions, can be used for building quantum memories but not to propagate qubits over long distances).

The main future challenge facing quantum key distribution, the fundamental basis for quantum cryptography, is a distance limitation of approximately 500km. Establishing cryptographic links beyond this distance demands improved single-photon detectors, and also devices called quantum repeaters. Once these are realised, quantum key distribution will become feasible over continental distances will have an enormous commercial impact.

Engineering Quantum Entanglement

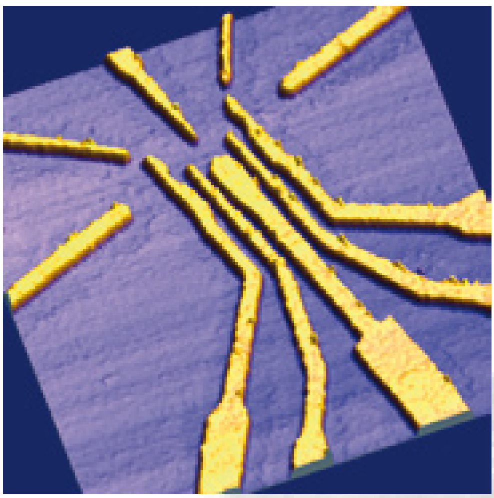
Quantum entanglement is the fundamental basis for all quantum information technologies. Hence, a key practical goal is to develop flexible and powerful means for the precise creation and control of entanglement. The control of entanglement offers a unique opportunity to surpass standard quantum limits and to perform measurements with unprecedented accuracy. A roadblock to such advances is the lack of a coherent control. Removing this roadblock will allow the exploitation of a few qubits in quantum sensors, quantum metrology, quantum imaging and quantum random number generators.

Quantum Information Science

Our conception of computation has been altered drastically during history, since the times of Leibniz, Babbage and Turing, and computers as we know them today have transformed our society. The development of computation and communications through quantum technology with take another step, triggering a potentially profound transition in human history. Alongside the development of engineering techniques, physicists, computer scientists and other researchers in recent years have begin developing a deep theoretical framework for quantum information science, which outlines its fundamental principles and capacities, and offers guidelines for practical engineering development. Specific challenges for the future include he development of new quantum algorithms able to bring quantum computation to a variety of problems, as well as new protocols for quantum communication.

Expected Impacts

Quantum information research will lead to a deeper and broader understanding of the fundamental laws of the quantum world, including the nature of information and the principle of causality.



An atomic force microscope image of a double quantum dot nanostructure.
Using a pattern of gold electrodes on the surface of a semiconductor substrate, individual electrons can be locked up in electrical traps. The spins of the electrons can be operated as quantum bits.

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In scientific terms, fast entanglement-enabled coprocessors and quantum simulators will allow researchers to find solutions to problems ranging from many-body physics to quantum field theory, and to model new materials with unprecedented accuracy. Meeting the above challenges will create a pool of powerful quantum information technologies deployable in the real world.

Quantum information technology holds the promise of immense computing power beyond the capabilities of any classical computer. The realization of fault-tolerant quantum computers would have tremendous impact on science and also on technology, economics and society. Their applications, already possible with quantum simulators even before the realization of a full-fledged quantum computer, include efficient simulation of systems of importance for nanotechnology, materials science, biotechnology (drug design) and elsewhere. In addition, single-photon detectors developed for QIPC have applications in many optical-sensoring and metrology applications, for example, in the more precise determination of fundamental constants.

Another major impact will be for encryption of communication links and networks. This is of central strategic importance, given the enormous importance of information in our society.

3 ONCE-CS: Complex Systems Science

Many of mankind's most difficult and pressing problems flow out of complex webs of interactions -- among myriad physical processes in the oceans and atmosphere, influencing climate change, among many firms and individuals in the global economy, among diverse cells in the human body. Understanding in every case, either for scientific purposes or to inform management interventions, requires much more than an understanding of the parts -- it demands insight into system function in a more holistic sense. In biology, for example, the activity of almost any gene depends on that of many others through complex cascades of interaction; even if we knew the exact nature of each biochemical component in every cell of an organism, we'd still know very little about how the organism works as a whole or how to intervene to treat a disease. Similarly, while the Internet and World Wide Web have altered the very way we work and organize our lives, our understanding of its function remains scientifically primitive, based on ad hoc rules. We understand hardware and software components in isolation, but face a challenge in learning how to design systems which are robust and adaptive, and not afflicted by widespread dysfunctions such as SPAM. In coming years we will witness the emergence and deployment of ever more massively distributed, interdependent and complex ICT systems composed of billions of interacting components whether fixed or mobile. The ever-growing scale and complexity of such ICT systems poses fundamental challenges to their evolution and control.

Traditional science and engineering have always sought to understand and design systems by breaking problems into smaller component parts, and nothing in these disciplines has prepared us to manage today's huge and ever-expanding systems. Our intuition offers little or no guidance, but within the past few decades, scientists have begin building a science of such complex systems, which aims to bridge the gap between the individual and the collective -- going from psychology to sociology, from organism to ecosystems, from genes to protein networks, from atoms to materials, from citizens to societies. Complex systems in general exhibit so-called "emergent phenomena" -- collective order and processes which cannot be linked in any obvious way to the properties of system components alone.

The greatest challenge in building a science of such systems is understanding this "micro to macro" link – how low level properties give rise to higher level order and organization.

Our current lack of understanding presents a huge obstacle in managing such systems, knowing what to expect from them, and it in designing systems with specified behaviour. The Science of Complex Systems has forged bonds between researchers from across the spectrum of engineering and ICT disciplines on one side, and those in natural and social sciences on the other side. It accepts the frequent irreducibility of system behaviour and seeks to understand coherence of function and organisation in a new way.

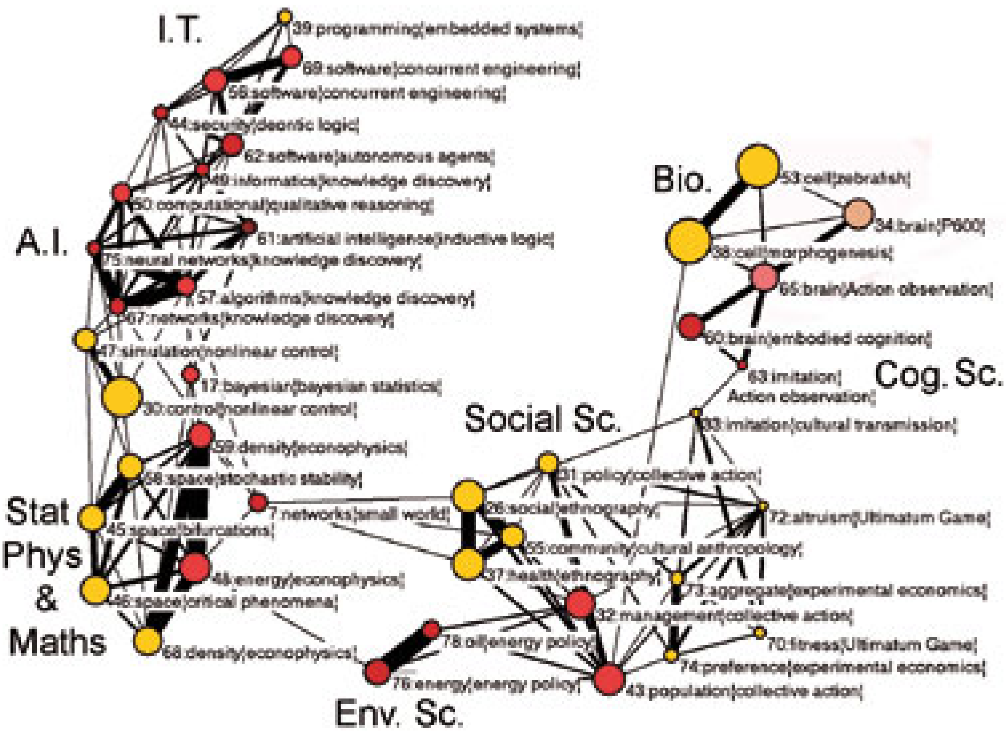
Recent Achievements and Future Challenges

Complex systems science has already made striking contributions in many areas of fundamental and applied science, ranging from artificial intelligence and robotics to computer science, physics and biology. One major advance in the past decade has been the discovery of deep similarities in the architecture of many complex real world networks, including the Internet, social networks and food webs, as well as biochemical interaction networks, i.e. among proteins and genes in the cell. Complexity science has contributed to the development of powerful new modelling techniques now used in the study of issues ranging from ecosystem stability to the nature of fluctuations and volatility in financial markets. Its techniques and insights are being used in traffic management, in the design of complex manufacturing lines, and in devising efficient strategies for drug discovery.

The new science of complex systems is providing radical new ways of understanding the physical, biological, ecological, and social universe, and cuts across traditional scientific boundaries, creating new and shorter paths between scientists and accelerating the flow of scientific knowledge. Complex systems science bridges the natural and social sciences, enriching both, and reduces the gap between science, engineering, and policy. It will also help reduce the gap between pure and applied science, establishing new foundations for the design, management and control of systems with levels of complexity exceeding the capacity of current approaches. The economic regions that lead this science and its engineering will dominate the twenty first century by their wealth and influence. Funding this fundamental scientific research will be popular because its applications will impact on everyone's life in many obvious ways including medicine, health, welfare, food, environment, transportation, web services. Thus Complex Systems Science will enhance long-term harmony between science and societal needs.

Pushing complex systems research ahead in Europe will require the creation of European platforms with massive computer power for data processing, reconstruction, modelling and simulation of system dynamics. This will require new generations of multiprocessor clusters to support new technologies such as grid computing. These platforms have to be understood as big instruments in the same sense as for research in physics. In view of the exponential increase in data and information, and the complexity of the systems studied, it can be expected that this need for big instruments will be even much more demanding than for physics.

Complex systems research emphasises, in particular, the fact that components and organisational structures are able to adapt their function to novel conditions and tasks. To discover the laws that likely govern emergent properties, we need to collect as much experimental evidence as possible on the dynamics of complex systems and undertake focused efforts to analyze this data. In this respect, information technologies are now allowing us to acquire and to store extraordinary amounts of data. In biology, we are currently creating a wealth of empirical data on living systems that was simply not available only 10 years ago. The resulting radical increase in data and information causes novel challenges and has led to a



Network space of scientists' interests: work done within ONCE-CS showing the inter-relationship between the scientists' interests.

surge of interest in Complex System Studies to better understand how behaviour of systems as a whole is related to characteristics at a molecular/neuronal level. Together with progress in computation this opens up radically new avenues for many sciences.

There is also a need for creating open observatories for all kinds of complex systems (at least at the European level) for collecting and sharing data. Complex systems are all different and seen in multidisciplinary ways. There is a strong need to organise data in a homogeneous way from these heterogeneous point of views. Networked centres of European data repositories are needed to receive and archive the gigantic data streams produced by European projects, and to index those data, making them available on-line to European researchers through high capacity Internet links. In the United States, vocal advocates are pushing for a new emphasis on distributed databases and distributed query facilities on a medium scale. The assumption is that carefully gathered, curated scientific data will start to pool up in hundreds or thousands of research centres, and these data are too large to ship around the world in response to simple analytical questions. Therefore there is a need for community-wide work on metadata standards, local access methods, and smart ways of collecting the extracted observations from multiple types of science, cross-correlating them, visualizing them etc.

Expected Impacts

Complex systems are studied on the basis of increasingly large quantities of data, and this science will develop in the same way that physics developed over the three last centuries -- through a continually renewed process of reconstructing models from constantly improving data. This reconstruction of the multi-level dynamics will be possible through a new family of European platforms, similar to the big instruments used for physics. The resulting science and the insights it yields will be at the heart of the future Worldwide Knowledge Society, and its pursuit will likely have enormous implications for European well being in the future, impacting everything from health to agriculture, information and communication technologies, nano-science and materials sciences, energy and environment (including climate change), transport, socio-economic sciences, security and governance.

Because complex systems science respects the organization of whole systems much more than the science of today, it will be particularly important also in aiding human response to climate change, and in finding a sustainable approach to managing the Earth System. We are now living in an era in which human-engineered systems have an enormous impact on our terrestrial environment, so that natural systems no longer operate independently of human processes. Insights from complex systems science will be required to manage this interaction on a scientific basis.

4 Neuro-IT.net : Neuroscience meets information science

Understanding the biological functioning of thinking and consciousness, in both humans and other animals, remains one of the great scientific challenges. How does the brain perceive, control action, encode memories, and act as the seat of awareness? Insight into these basic scientific mysteries promises powerful new avenues for the development of information technology, especially as living organisms still easily outperform computers on many tasks, even those we consider to be "simple." Computer scientists can only dream of engineering systems with the object-recognition skills of humans, or robots able to learn and adapt as well as an ant. The relatively slow progress in the creation of bio-inspired artifacts and IT applications in recent decades has been a source of frustration for policy makers, scientists, and engineers alike.

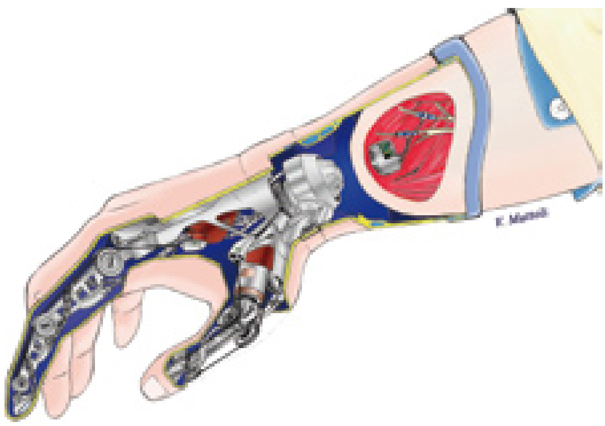
However, recent developments in the neurosciences have made it possible to begin tackling research challenges that couldn't have been described even five years ago. Researchers increasingly have the means to gather an unprecedented quantity of high-quality data, and in recognition of these opportunities, large scientific collaborations are emerging throughout the world. Biologists, neuroscientists and computer scientists are finding new ways to share their data, models and analysis tools across laboratories and national boundaries. Such data promise key advances in basic brain science, as well as potentially revolutionary new information technologies.

Neuro-IT.net aimed to bring together within the European Union researchers at the interface between Neurosciences (NS) and Information Technology (IT), and to stimulate and foster research benefiting both the NS and IT communities by helping to solve problems linked to the emergence and modelling of cognitive and awareness processes.

Recent Achievements and Future Challenges

Neuro-IT Interfaces

Recent research suggests that a popular subject of science fiction -- the direct interfacing of the human brain with computers -- may soon be technically possible. Better interfaces and fast-signal processing techniques have spurred incredible breakthroughs in research using rodents and monkeys. But all current demonstrations are one-directional using signals from motor cortical areas to control virtual devices. For real-life applications, such as re-establishing a patient's control of paralysed limbs, bi-directional interfacing will be necessary. The Brainship idea seeks to develop an awake animal model where the brain interacts with the environment through such bi-directional techniques.



Cyberhand

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Bio-Inspired Hardware

Technological progress has rapidly increased the number of transistors on a single chip. But most computing systems remain limited by their dependence on clocked digital processing units with little parallelism. Bio-inspired hardware may outperform conventional solutions and enable a broad range of applications including the real-time control of robots, the implantation of artificial cochleas and retinas, and large-scale simulation of complex systems, including the brain itself.

Humanoid Robots

Further work in the emerging fields of epigenetic robots and embodied systems, which develop through interaction with their physical and social environments, may soon lead to the realisation of "humanoid" robots. These would be able to evolve their own cognition and motor control based on multi-modal and multi-sensory feedback, effectively developing and learning like people. It is no longer science fiction to work towards a fully functional robot able to grow its body and IQ autonomously, by a factor of 10, over a period of, say, 10 months.

Machine Consciousness

There is now serious interest in Europe in the topic of 'Machine Consciousness,' which even 10 years ago would have been dismissed as 'crackpot' science. Thanks to progress in brain science we now understand that the human brain sifts through a huge amount of information before selecting the elements that influence behaviour. Achieving similar behaviour in machines would improve the efficiency of technological infrastructures, such as power grids, which need to co-operate with other applications in order to monitor their own performance.

Evolvable Systems

Traditional Artificial Intelligence (AI) has failed to scale up to real-world applications. But new design techniques inspired by evolution and Complex Adaptive Systems (CAS) may allow the design of highly evolvable structures and behaviours, adaptable to different environments. This could lead to 'generic' autonomic (self-managing) robots whose body plans, sensor configuration and processing capabilities can be trained to do specific tasks. Hybrid chemical-computerised environments could be created for the evolution of "complex-ware," making this close to creating artificial life.

Medicine

Brain research is important for information systems and technology, but it obviously also offers tremendous opportunities for developing new medical techniques. Some 35% of all disease in Western Europe is linked in some way to brain disease. Ongoing work in this field aims to record neural activity from a thousand electrodes in five different brain regions to obtain high-resolution images, which will greatly aid the understanding of the link between micro and macro brain behaviour.

Expected Impacts

The neuro-sciences are currently making rapid progress, producing high-quality databases, and increasing the quality and the quantity of input for successful reverse engineering of neuronal circuits. Technology for building such circuits, such as deep sub-micron CMOS technology or nano-scale switches, are increasingly available and await new applications in artificial neural circuits. The resulting novel information processing devices will be used both as a research tool in studying neural information processing, the dynamics of brain plasticity and learning, and also as new technology for information processing, especially in the study of low power consumption and self-organisation.

These challenges are very ambitious and will occupy the minds of researchers for many years to come. Indeed, we need further development of knowledge and skills even to initiate specific projects toward some of these goals. But the ambition of these challenges and the scope of the research being attempted take Europe to the very forefront of this important work, which will have a dramatic impact on the way we live our lives..

The potential is enormous. The more we understand brain function and construction, the better able we are to treat brain disorders and illness and prolong life. The development of robotics, cyborgs and humanoids towards self-aware, learning, adapting machines will lead to any number of commercial applications and subsequent economic benefits will surely follow. By creating Neuro-IT.net and forming a completely new area of research at the interface between neuro-sciences and information technology, we have given Europe the lead globally in a field that will have direct benefits for IT generally, as well as helping to discover completely new research domains.

5 NiSIS: Nature-inspired Smart Information Systems

The study of nature has inspired mankind for countless generations, both in the pure and applied sciences. In recent decades, biological science has advanced at an unprecedented pace, and research has vastly improved our understanding of the complexity and principles of living organisms. We have learned that Living systems are "smart" in the sense of being adaptive, self-healing, fault tolerant and robust. ICT has an obvious opportunity to transfer some of the techniques and principles that biology uses into the design of artificial technologies for our modern information-rich society. With this in mind, NiSIS has aimed to build closer links between the life and information sciences.

Several areas offer particular promise as inspiration for the design and creation of new ICT artifacts. First, we can learn new nature-inspired algorithms by adapting strategies and designs already utilized, developed and proven by nature. Second, we can learn to mimic, in the next generation of ICT devices, desirable features of natural systems, such as the self-repairing and autonomous behavior of cells and organisms. Third, we may be able to create hybrid technologies that bridge between the natural and synthetic world, bringing "wet" biology together with our own technology to realise artificial organs, sensing aids, and other new technologies. In general, we can seek to reproduce the desirable qualities, features and capabilities of the natural systems both in their distinct functionalities and in their aggregated actions.

Recent Achievements and Future Challenges

Nature-inspired techniques such as genetic algorithms, particle swarm optimization and ant colony foraging already play key roles in state-of-the-art methods for handling some problems in emerging computing environments, including autonomic and ubiquitous computing, P2P systems, the Grid and the Semantic Web. These novel algorithms succeed in demanding environments involving the interaction of large numbers of de-centralised, parallel, asynchronous, and distributed software or hardware components. Artificial organisms are also being investigated with attempts to separate ”body“ and ”mind“ components in a manner analogous to biological functions. For example, British Telecom's traffic management scheme now separates gene-like coding concepts and phenotype- like organism components. ICT engineers are also increasingly learning to "reverse engineer" the statics and dynamics of biological gene regulatory systems, signal transduction and metabolic pathways, which give insight into the behaviour of cells, organisms and populations, to find new ideas for advanced information systems.

The current applications and emerging trends only begin to illustrate the kinds of technologies that may evolve from nature inspired ideas. The NiSIS Roadmap has identified a number of specific grand challenges for the future:

Building a Computational Nervous System and Brain-like Computing

By mimicking the design and function of biological nervous systems, it should be possible to develop "sensing capabilities" for artificial information systems. The ultimate goal will be to provide an information system with a central nervous system able to acquire data and information in a robust way and, at the same time, able to adapt and repair itself, as happens in biological systems. The expected benefits would include increased ability to acquire information, additional safety provided by self-assessing mechanisms and, therefore, better information quality and robustness to system failure or performance degradation.

A similar aim is to realise what might be called Brain-like Computing (BlC) by mapping brain functionalities into conventional computer systems, and building next-generation computing systems with a complexity comparable to biological systems. The payoff would be information systems able to take real-time decisions, to extract, maintain, manage and memorize valuable information efficiently, to perform associations between problems and solutions and, eventually, to build new solutions to unknown problems through computational processes akin to human creativity.

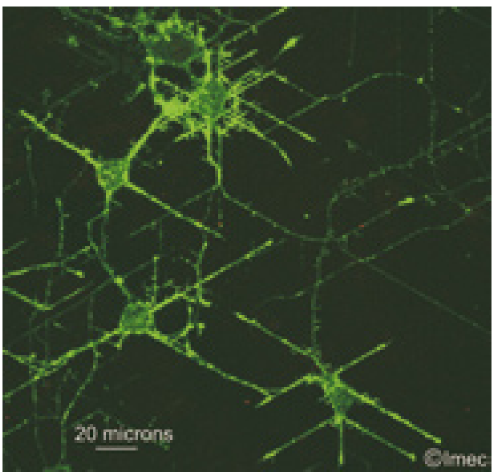
Distributed Cooperative Intelligence

The increasing complexity of today's information systems demands management through non-centralized mechanisms, as in biological systems. The ultimate goal is to develop information systems able to survive and improve their fitness through time by the distributed optimization and adaptation of their components, with vastly increased robustness to failure or network communication faults.

Device, Communications and Transportation Networks

Advances in micro-electronics have led to a vast increase in the processing power and/or sensing abilities of many everyday objects. At the same time, advances in communication technologies make it much easier to transfer data faster and more efficiently than before. Together these advances are leading to complex networks of enormous scale and heterogeneity, such as telecommunications networks and pervasive computing systems. A looming challenge is to automate control and management of these processes by emulating the way the body regulates and controls itself.

The same technology would have major applications in other settings too. For example, modern economies thrive on increased trade amongst different regions, countries and continents, and in the era of globalization, logistic and transport networks have become much larger and more complex. People are also more mobile. Effective control of such networks could decrease idle times and increase road utilization, and such networks should ideally be self-managing. An additional challenge is that humans are in the loop, for example, choosing which route to take, and hence optimal decisions cannot be imposed. It will be crucial to develop advanced design mechanisms for managing systems in which humans take part.



Fluorescence image of mouse hippocampal neurons on micronail patterns
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Advanced Information Networks

The "Information Society" envisaged by European leaders requires easy access to enormous amounts of information, as well as powerful and effective means for processing such information. Both capabilities demands advanced information and communication technologies. However, we increasingly face serious problems in our interaction with the huge "information spaces" creating by gathering and storing such information. People find it difficult to find the information they need, in sorting through vast quantities of information, or in merely keeping up with the continual updating of information sources. In finding a solution, we may find inspiration in the human brain which has a tremendous capacity for visual or metaphorical recognition of meaning. Future information systems should be able to find previously unknown connections, and be able to filter out the meaningless from the meaningful with little human assistance, and nature-inspired techniques may provide solutions.

Nature inspired modelling

We face a huge challenge in learning to model high-dimensional non-linear processes. The analysis of genetic data, for example, poses statistical problems in the form of high dimensionality with small sample sizes. The identification of key variables, or feature selection, is a key task to simplify such modelling. Large scale systems such as 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 issues to address in the coming years.

Nature inspired optimisation and control

Bio-mimetic solutions in evolutionary algorithms that mimic not only micro-evolution but also macro-evolutionary strategies are grand challenges in nature-inspired optimization and control. In computing, for example, multitasking is a method by which multiple tasks, also known as processes, share common processing resources such as a CPU. Its optimization concerns CPU usage by the scheduling strategy. It is not known if biological multitasking — as occurs, for example, in the liver — can be a model for multitasking in computing. Other areas to exploit include algorithms inspired by the function of the immune system, and able to mimic its capability of pattern recognition, memory and clonal selection for anomaly detection, data filtering and feature extraction selection, for use in data mining and knowledge discovery, for example.

Expected Impacts

Smart information systems draw inspiration from natural systems, and would exhibit their desirable qualities, features and capabilities, being adaptive, robust, and efficient in interaction with the external world. Already, successful cases along this line exist such as evolutionary computation and swarm intelligence. The development of new and advanced Smart Information Systems will have innumerable applications, and contribute enormously to the scientific and economic success of European society.

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FET Research Roadmaps

Pointing the Way to Future ICTs

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