# FET Consultations 2009-2010

## Shaping the future

••• Future and Emerging Technologies
Proactive

European Commission
Information Society and Media

SEVENTH FRAMEWORK
PROGRAMME

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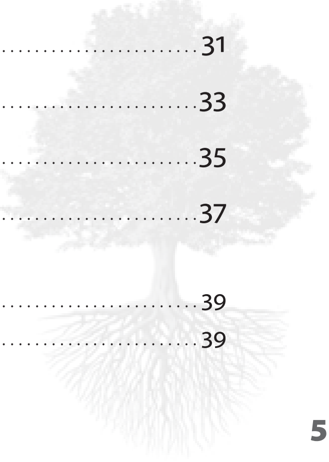

# Foreword

Information and communication technology (ICT) now has an essential role in our society. From political events driven by social networking, to simulations of climate change used to determine energy policy, to advanced medical diagnostics – ICT plays a crucial role in shaping our society and our lives. In order to advance ICT even further we increasingly have to look into new domains to find inspiration, to master the way that nature deals with complexity and concurrency, to understand how societies can join their forces to achieve more than an individual can, and to gain control at the level of atoms and quantum forces.

In preparation for the second update to the ICT workprogramme in FP7 to cover the period 2011-2012, FET continued its practice of consulting the research community through a series of workshops on topics related to long term research in ICT. Overall, these workshops have confirmed that many of the topics discussed during earlier workshops in 2007 continue to be of great interest to researchers and still hold the promise of delivering impressive contributions to the development of ICT. However, even in the space of 2 years science has progressed and new ideas have emerged that also deserve investigation. The workshops have highlighted important topics for future ICT research, and have been an invaluable source of ideas for updating the FET sections in the ICT workprogramme.

Future and Emerging Technologies (FET) acts as the pathfinder of the ICT programme of the European Commission, fostering frontier research across the full breadth of information technologies. It promotes the exploration of radically new ideas and trends for future research and innovation, opening up new avenues of research. It aims to go beyond the conventional boundaries of ICT and ventures into uncharted areas, often inspired by and in close collaboration with other scientific disciplines.

As part of the wider FET scheme, FET Proactive operates through initiatives grouped around emerging topics, and so striving to identify new topics and trends is at the very heart of FET. Scientists and technologists, selected from academia and industry, have provided FET with highly valuable suggestions, visions, and discussion during a series of encounters in the second half of 2009 and the beginning of 2010. FET has challenged them to re-think or revolutionise entire disciplines, shape new ones and disrupt established technologies, thus helping to create a home for transformative research. They have challenged FET to support entirely new areas, and at the same time to provide sustained support to emerging areas that require long-term fundamental research.

The topics that have been elaborated show how FET serves to act as a catalyst for change in interdisciplinary research. Radical breakthroughs in ICT increasingly rely on fresh synergies, cross-pollination and convergence with different scientific disciplines (for instance, biology, chemistry, nanoscience, neuro- and cognitive science, ethology, social science, economics) and with the arts and humanities. FET Proactive has a crucial role and the means to kick start and to build new communities, in order to enhance Europe's innovation potential around those fundamental challenges in ICT that will be key to the long-term sustainability of a technological future in Europe.

I am very grateful to the researchers that have contributed so much of their time and effort to these workshops. I hope that their enthusiasm for seeking new ways to overcome the barriers to better ICT that is reflected in the reports will inspire you in your future work.

Wolfgang Boch
Head of Unit
Future and Emerging Technologies - Proactive

# Introduction

Early in 2011, the famous American quiz show Jeopardy! returned to TV screens for a one-off contest. The program pitted the show's two most successful winners against a newcomer: a supercomputer called Watson built by a research team at IBM.

The battle quickly caught the attention of the world's media who watched with baited breath as Watson first matched its human opponents and then overtook them to finish as the clear winner. The victory was heralded as a landmark in computing performance.

And yet, much as Watson's victory showcases the enormous advances made in computer science in recent years, so it brings into sharp relief the limitations of today's most powerful computing machines.

Watson is finely honed for the task of answering quiz questions. When it springs into action, it uses 2880 cores with a combined RAM of 1TB. It can search its own 1 petabyte database, all of it intricately categorised and structured by algorithms that IBM developed specifically for the task (no connection to the web is allowed). And it comes to its conclusions in an average of three seconds, at least as good as most humans.

But there is a price for this computing extravaganza: it requires an 80 KW power supply; enough to power an entire village. By contrast, a human brain uses a paltry 20 Watts and as well as answering questions, can easily turn its hand to other complex tasks. But ask Watson to negotiate a flight of stairs or to pick out Albert Einstein in a photograph or to tell a joke and it'll be stumped. Despite IBM's undeniable achievement, there's clearly something important about the way the human brain works that we've yet to understand.

The European Commission has a strategic initiative for exploring visionary ideas in information and computing technology (ICT) and for promoting high risk research with the potential to transform society. Part of this strategic initiative is called Future and Emerging Technologies-Proactive, which promotes foundational research and non-conventional approaches to emerging societal and industrial needs.

In preparation for the next work programme (2011-2012), FET-Proactive invited researchers from key fields of science and technology to a series of brainstorming meetings. The goal was to help the Commission identify strategic areas, especially those going beyond traditional lines of research and those presenting novel opportunities for collaboration with other scientific communities.

The problem of understanding, harnessing and improving on the human brains' extraordinary abilities throws up many important challenges identified in these meetings. For a start, there is the issue of power consumption. Nobody is quite sure how the brain does so much on so little juice, but clues are emerging from various branches of science.

Neuroscientists point out that information travels along nerve fibres in pulses or spikes. This ensures that only a small section of the fibre needs to be charged at any instant, unlike conventional power lines. Computer scientists are exploring the possibility that the brain exploits exotic forms of computation to work more efficiently. And as they study these other forms of computation, it is becoming clear that conventional computing may not be the best way of tackling many types of problem.

Even more intriguing is the growing evidence that the precise control we have over our bodies comes not just from the brain but from the shape, structure and properties of the materials from which we are made. It's as if the brain outsources much of its control to our morphology, a conclusion that has profound implications for robotics.

The growing interest in emergent behaviour and the profound effects it can have on our world is another topic identified in the brainstorming meetings. At 2.42pm on 2 May 2010, the Dow Jones stock market index suddenly dropped by 600 points, wiping $1,000 billion off the value of US shares in less than five minutes. Within 20 minutes, however, the prices had rebounded and the shares regained most of their value.

This so-called "flash crash" puzzled financial investigators. How could such a wild variation be possible in market that is seemingly so well controlled?

The investigation found that the crash began when a large institutional investor attempted to sell off $4.1 billion of shares in just 20 minutes. But although it is possible to trace the chain of events that followed, nobody is quite sure why they occurred on such a huge scale.

The problem appears to have been exacerbated by high frequency traders who use automated programs to buy and sell on timescales measured in microseconds. These in turn use computer algorithms to model the market and make predictions about how it will move. Clearly these "systems within a system" interact with each other in a way that produces complex behaviours that are hard to predict. It may be that flash crashes are just one aspect of this natural emergent behaviour.

The goal of complexity science and the study of collective adaptive systems is to better understand this kind of emergent behaviour and to manipulate it in ways that can benefit society. It will not be an easy task. Researchers currently lack even a way of describing the way complex behaviour emerges from these systems. Developing such a formalism is an urgent challenge.

But there is also a consensus that significant progress is possible. Computer systems are becoming powerful enough to rival the complexity of the systems they are modelling. The hope is that they can be used to better understand the full consequences of emergent behaviour in areas such as transport and economics, health care and climate change.

At the other end of the spectrum is the study of the very small. Biologists have long admired the process of photosynthesis, the molecular mechanism in plants that converts sunlight into chemical energy. This process begins when light-harvesting antenna molecules absorb photons which then excite electrons. This excitation energy has to travel across a giant matrix of biological molecules to reaction centres where it is converted into chemical energy which can be stored and transported to other parts of the cell.

One problem is how the excitation energy makes the long journey from the antenna molecules to the reaction centres with an efficiency that is close to 100 per cent. Classical energy transfer theory predicts that the energy hops from one part of the molecular matrix to another, making its way across it more or less at random. But calculations show that such a random walk would take too long and allow too much energy to leak away.

In the last few years, evidence for another explanation has begun to emerge. This exploits the quantum properties of energy excitations, which allow them to explore more than one route at the same time. In this model, the excitation exists in a superposition of states that explore different routes through the landscape simultaneously. When the superposition collapses, however, it leaves the excitation at the reaction centre, where it is converted to chemical energy.

One way to think of this is as a kind of quantum computation which calculates the shortest route and allows the excitation to make the journey with almost perfect efficiency.

The idea that quantum processes can play a role in the hot and wet environment inside cells is revolutionary. And a growing number of physicists and biologists are exploring the implications of operating at the boundary between the quantum and the classical worlds. Their goal is to exploit the full range of quantum and classical properties of atoms, molecules and biomolecules in areas such as information storage, information processing and computing efficiency. There is also potential to revolutionise other areas such as materials science, drug design and manufacture.

The FET-proactive brainstorming sessions identified these and many other areas of high-risk research with high potential pay-off. The essays that follow in this brochure offer a brief summary of the principle conclusions from these sessions. Each section sets out the motivations for an area of research, describes the challenges that arise and the transformative impacts that breakthroughs in this area can expect to have.

The essays are organised as follows (in chronological order):

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# Atomic & Molecular Scale Devices and Systems and Bio-Chemistry Based Information Systems

## Motivation

Atomic, molecular and bio-chemistry-based information systems are expected to lead to a new generation of information and communication technologies that exploit both quantum and biological effects.

## Challenges

Designing and building information and communication technology (ICT) systems that exploit the properties of atomic, molecular and bio-chemical systems is laced with significant challenges. One example is the difficulty in working out how to design ICT functionality using a top-down approach involving guided assembly of atoms and molecules. Just as hard is the bottom-up approach that exploits biomolecules realized by nature to process information. A third option for future ICT technology is a combination of both approaches. The resultant ICT components then have to be characterized and a cost effective method of fabrication developed.

A second challenging area is in working out how to embed atoms and molecules in a controlled environment, achieving stable configurations that can then be interconnected and linked to the outside world. These devices will need to exploit coherence to take advantage of a system's quantum behaviour but they will also need enhanced decoherence to turn the system classical in the shortest possible time. This will require a better understanding of how to operate at the quantum-classical boundary.

In the area of bio-chemistry, self-organisation is an important process. Exploiting this process to design and program self-organising construction systems at the molecular scale will require new theories, methods, tools, languages, architectures and simulations. It will also require ways of implementing these ideas in real self-organising systems, such as supra-molecular systems, reaction networks, sub-cellular/cellular systems, organism (single robots), and swarm robots. And it will require biology-inspired strategies of information coding and exchanging

## Expected Impact

Breakthroughs in this area offer the potential for ICT disruptive technology. New devices that should become possible are novel sensors, interfaces, recognition systems and actuators. These have clear applications for human health, the environment and security. This research also points to new paradigms and architectures for computer science, of embodied decentralised pervasive information processing. It should have an important impact on robotics and its applications which play such an important role in our society. This field of work promises a range of completely novel “smart” materials that combine and exploit both physical properties and information processing capabilities. It provides a radical new outlook on sustainability of products that can be locally constructed and then sustainably dismantled when no longer needed.

# Quantum Information Foundations & Technologies

## Motivation

Applying the ideas from information science in a quantum setting makes possible complex calculations and tasks that cannot be achieved with classical systems. In recent years, this approach has led to secure methods of communication and to the development of the basic building blocks of quantum computation. This is a rapidly moving field and further significant developments are expected in the future.

## Challenges

The first special purpose quantum computers will be quantum simulators capable of modelling other quantum systems. The challenge here will be to improve the simulation capabilities of such devices, moving from condensed-matter theoretical models towards the simulation of materials and chemical compounds.

Beyond that, we are currently witnessing the birth of a new quantum paradigm that exploits the advantages of atomic, molecular, optical and condensed matter physics to develop the building blocks of more complex quantum devices. There is therefore a clear need to bring hybrid technologies past the proof-of-principle stage. Potential applications include a working quantum repeater that will be a key component of a 'quantum internet' and devices connecting quantum memories and quantum information carriers.

Researchers will have to learn how to handle large numbers of qubits. Dealing with qubits in high densities is challenging because of the more complex and noisy environment for quantum operations which is caused by factors such as cross-talk from nearby qubits and their control, coupling, and readout systems. These problems have to be identified, explored and solved.

Novel practical devices need to be investigated for exploiting entanglement as a resource. Potential applications include quantum sensing, imaging, measurement, and communication technologies.

## Expected Impact

Quantum communication technologies can be embedded in the current telecom fiber infrastructure and will transform present-day point-to-point communication networks into absolutely secure quantum ones. Entanglement assisted sensors and metrology will enable sub-micron imaging, sub-shot noise measurements and single-spin sensing as well as the development of ultra-precise clocks. Quantum simulators will help us design new drugs and artificial quantum materials with tailored properties and better understand the dynamics of complex systems and phenomena. And quantum computers will become the next generation of processors beyond micro- and nano-electronics while bypassing various roadblocks towards more energy efficient computing. Their remarkable power should help us better tackle complex problems such as climate change and protein folding.

# Web Science

## Motivation

For sheer size, growth and impact, the World Wide Web is hard to beat. Google currently indexes some 10 billion pages and 1.5 billion images and the web has helped to drive the development of entirely new approaches to health, science, business and even social interactions. These in turn have spurred the development of the web in a complex feedback process.

In studying this process, researchers are discovering a complex interplay of scales, timescales, subjects and conceptualisations of the web.

Describing the dynamics of this interplay, analysing its effects and engineering its future development in a controlled way will require a huge range of expertise. That means there is a growing need to support research into the web so that a clearer focus can emerge, with consistent and well-understood methods, vocabularies and datasets.

This area of research is called Web Science. It is expected to become a discipline in its own right with characteristic methodologies linking engineering and science, synthesis and analysis, in a principled, directed and efficient way.

## Challenges

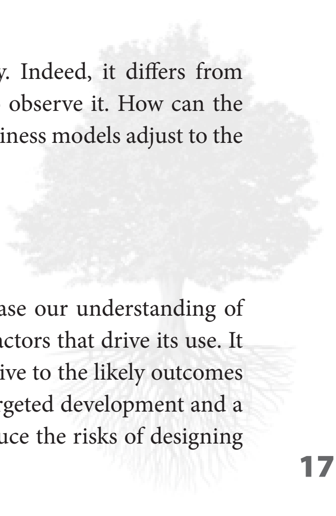
The world of online collaboration is extremely novel and sufficiently different from offline collaboration that understanding how it occurs is a significant problem. The collective intelligence involved in collaborative endeavour and innovation can lead to the emergence of large-scale, coherent resources such as Wikipedia, Digg and Google.

This kind of collaborative production raises a number of important questions. How, from a technical point of view, can collaborative innovation and collective intelligence be enabled? How can these qualities be predictably engineered? What are the socio-economic reasons why individuals participate in collective endeavour? What legal framework governs, or should govern, the resources created? How can the risks and problems arising from community-generated information resources be managed? What role is there for policy-makers to engage in and facilitate collaborative endeavour?

Another set of challenges relate to the web's ability to evolve quickly. Indeed, it differs from previously-studied systems because it evolves faster than our ability to observe it. How can the web be instrumented to monitor it effectively? And how can existing business models adjust to the rapid pace of change?

## Expected Impact

The development of Web Science as a standalone discipline will increase our understanding of the web, its growth, its relation to its socioeconomic contexts and the factors that drive its use. It will allow web technologies to be developed in a way that is more sensitive to the likely outcomes of their widespread deployment. This will allow more intelligent and targeted development and a greater ability to avoid unintended consequences. This should help reduce the risks of designing and deploying web technologies.



The academic impact will be considerable. The areas of collective intelligence and web dynamics present such large and novel problems as to have genuinely revolutionary potential, bringing together a large and new interdisciplinary constituency with innovative methods and foundations.

Beyond that, the impact of Web Science will be felt throughout society, or at least in those areas of social interaction where the web plays a prominent role. The economy and the digital economy, in particular, will benefit as well as related areas such as e-science, e-social science and e-health.

# Collective Adaptive Systems

## Motivation

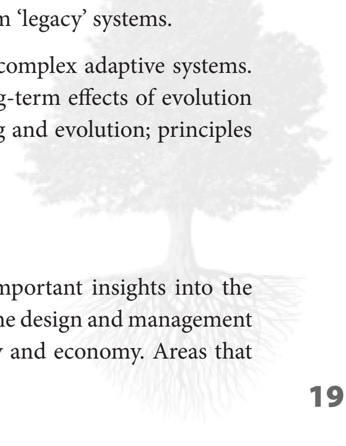
Digital systems have become part of the socio-technical fabric of society. Examples of these ‘systems of systems’ include city-wide transportation infrastructures, mobile communications networks and smart energy networks. These systems are increasingly made up from large numbers of autonomous units with their own individual properties and actions operating at different spatial and temporal scales and with objectives that sometimes conflict. They are becoming so critical for the effective function of our societies that we urgently need to understand their highly complex and dynamic behaviours.

## Challenges

The study of collective adaptive systems is beset with numerous challenges. Key among them are the problems of describing systems which work on multiple scales in time and space and working out the principles by which collective adaptive systems operate. Answering these questions will be crucial if we are to go further and determine how to build collective adaptive systems in a way that ensures purposeful and secure behaviour. It has become abundantly clear that these systems demonstrate emergent behaviour that is not easy to predict. Just how to design in and exploit this behaviour is an increasingly important challenge.

These challenges point to a number of key priorities for research, which fall into the following categories

1. Operating principles: research into the principles by which complex adaptive systems operate. This includes issues such as: the representation and reasoning about multi-level and multi-scale objectives; the ability to learn, adapt and/or evolve new policies and functionality; ability to reason in the presence of partial, inaccurate and noisy information, and principles of ‘lifetime unlimited’ systems.
2. Design Principles: Research into the design and engineering principles necessary to build and manage complex adaptive systems. This includes developing: models and design principles that allow for the creation of emergent behaviours; tools and methods that support such development; and principled approaches to incremental development starting from ‘legacy’ systems.
3. Developmental Systems: Research into the evolutionary nature of complex adaptive systems. This includes: open-ended (unbounded) evolutionary systems; long-term effects of evolution on the system; a better understanding of trade-off between learning and evolution; principles and effects of replication; and design for emergence.



## Expected Impact

A better understanding of collective adaptive systems should yield important insights into the ‘socio-technical fabric’ underlying 21st century society. It will facilitate the design and management of the growing number of complex, multi-level systems in our society and economy. Areas that

Øwould benefit include urban transportation, in which the emergent behaviour of large numbers of travellers could be understood and exploited, and microenergy production systems in which individual residents and factories are producers as well as users of energy

# Shaping the future

FET-Proactive asked experts to identify key challenges in the field of information and communication technology (ICT), which go beyond traditional lines of research. They came up with a list of 11 potentially transformative initiatives:

## 1. Socially benevolent ICT

### Motivation

Peer production has led to the emergence of a remarkable body of work including Wikipedia, various open source software projects and decentralised finance and lending initiatives. Consequently, peer-production now appears to be a persuasive alternative to the market and government-oriented modes of economic production which have dominated society for the last 20 years. There is a clear motivation to understand this phenomenon and to study the radically new organising principles that social ICT allows.

### Challenges

The challenges fall into two broad areas. First, we need a new theory for the design of ICT protocols and infrastructures that will encourage and support socially benevolent behaviour. Second, we need new ICT tools for developing and testing new economic theory.

### Expected Impact

Success would establish a new economic vision for society and make clear the broader transformative potential of social self-organization.

## 2. Beyond von Neumann Computational Facilities

### Motivation

The modern information age is based on the classical computing architecture originally laid down by John von Neumann in 1945. But this approach appears to be limited by low fault tolerance, high power consumption per elementary operation, the increasing complexity of software and the potential for catastrophic failure.

There are alternative computational systems, such as the brain. Unlike von Neumann machines, brains make no spatial distinction between memory and computation. Neurons and synapses are both involved in computing and memory operations in a way that is not yet fully understood. Similarly, brains do not make a clear distinction between hardware and software, between the device and the program running on it. Neural systems process information, even in complex environments, by learning relevant features and using them to craft future decisions. Understanding the way the brain does this and exploiting it will be one of the keys to success for artificial neural systems.

## Challenges

The principle challenge is to demonstrate a working hardware system that solves a computational benchmark problem not accessible to any high-performance von Neumann computer. This will involve learning to exploit the self-organising features of complex systems and to use this knowledge to build a real device able to carry out a brain-like computation.

## Expected Impact

Being able to produce a real brain-like device would contribute to our fundamental understanding of the brain, with potentially vast implications for the future of ICT. In particular, this would change the way we store, distribute, compress and interpret information. Such a device would likely form the basis for the next generation of truly novel computing devices.

# 3. Developmental Dynamics for Cognitive and Information Processing Systems

## Motivation

Neuroscientists know a great deal about the operations of individual neurons and synapses but the secret to brain function appears to lie in the collective behaviour of thousands or millions of them. Little is known about this behaviour.

## Challenges

If structural plasticity and fast remodelling are so crucial to brain function, then a crucial question is how the dynamics of these evolving brain structures play a role in cognition. Hence, a main thrust of research in this area should be to understand if it is the developmental processes in the brain that allow the emergence of high-level cognition, and, if so, precisely how they do so.

## Expected Impact

A breakthrough in this area would allow the exploitation of brain-like dynamics for the creation of new ICT tools and devices. For example, it may be possible to let machines devise their own methods for attacking a problem, working more along the lines of human insight and creative exploration from which truly new surprises may emerge. If machines can generate ideas and hypotheses as well as the means for testing them, it may even be possible to automate the process of scientific research itself.

# 4. Interfacing between single-molecule and CMOS Technologies

## Motivation

The potential of microchip technology could be vastly multiplied if it could interact in a reliable way with molecular or biological systems, which function along very different chemical and physical lines.

## Challenges

The challenge is to learn how to assemble nanoscale components such as molecules and biomolecules into a functional electronic circuit, to place such circuitry in defined patterns on a CMOS surface and to form a reliable electronic contact between the two systems.

## Expected Impact

This method would have a major impact on our ability to explore and exploit electronic properties of molecules for information processing, storage and communication. Applications would include rapid medical diagnostics, ultra sensitive sensors for toxic chemical, biological and explosive agents, and high-throughput biomolecular screening. Another potential application could be the rapid detection of single DNA sequences and proteins that would allow identification of a single cell, spore or virus.

# 5. Methods for Automated Development of Large-Scale Models

## Motivation

One of the few ways of gaining insight into large-scale complex systems such as ecosystems, economies and entire biological organisms, is through large-scale computational models. Such models are approaching a “tipping point” where their complexity will soon match that of the systems they are meant to represent. When that happens, the behaviour of the model and modelled system will be indistinguishable. Yet current methods for building such models are labour intensive and time consuming. Worse, they often fail to produce useful results.

## Challenges

Many systems are simply too complex to model by hand. Hence, a key challenge is to develop ICT tools that allow the rapid generation and prototyping of large-scale models using the known laws of physics and data gathered about the system in question. These models will themselves be highly complex so finding new ways for scientists to gain insight from them will also be important.

### Expected Impact

The ability to construct and scientifically evaluate complex models for systems such as economies, organizations, ecosystems, whole organisms, global climate and so on, will have a major impact on science, society and ICT.

## 6. Information Processing at the Quantum/Classic Interface

### Motivation

There is a growing body of evidence that some biological systems can exploit quantum information. If so, then systems in nature may already be using a hybrid dynamics that straddles the divide between quantum mechanics and classical mechanics. We stand to gain immensely by learning this trick.

### Challenges

A key challenge for future research is to learn how to build large-scale interacting systems using both classical and quantum dynamics.

### Expected Impact

A hybrid device that uses both classical and quantum dynamics could be more efficient than a classical information processor and at the same time much more realisable than a full and purely quantum information device, which may yet be many years in the making. We may discover the outlines of such a device from systems in biology.

## 7. Augmenting Real-Time Mediated Human Interaction

### Motivation

Europe includes many diverse cultures, their differing histories reflected in unique languages, customs, social norms and expectations. These differences pose challenges when Europeans of distinct cultures interact, whether in a professional or social context.

### Challenges

The challenge is to develop tools for mediating and improving human interactions in real time. This will require building for each interacting user an accurate model of the other users. That will require a detailed picture of the other users' potential meanings and intentions based on knowledge of their likely affiliation (from language, cultural display rules and so on).

### Expected Impact

A practical technology that can mediate human interactions in real time would have enormous implications for society in improving business relations, cultural understanding, tourism, and so on. It could also help autistic people sense emotions, blind people sense nonverbal cues and be a powerful tool for training and negotiation

## 8. Empowering Creativity

### Motivation

Story telling, music, visual arts, opera, theatre and games help give meaning to our lives and maintain cohesion in our societies. Yet the process of artistic creation and how it helps us make sense of our world, remains largely mysterious. What's more, only a small minority of people create artistic content.

### Challenges

The challenge is to give professionals tools to create content with fewer resources and to give nonprofessionals the power to become creative easily. In general, that will require meaning-oriented tools that can describe artistic work at multiple levels and a new generation of authoring tools that give support at the level of information processing. We also require fundamental research on support technologies such as pattern recognition and constraint-based design and construction grammar.

### Expected Impact

Developing tools for empowering humans creativity will improve peoples' lives by changing the nature of activities such as interactive story telling, live improvisation and games. It should also help to catalyse social and scientific change

## 9. Moving Away from Charge

### Motivation

Information processing technology works almost exclusively by controlling and manipulating information stored in electric charge. The next-generation of novel ICT systems may be able to exploit a wide range of new properties other than charge, including surface plasmon polaritons, spin, fluxons and magnetic monopoles. This could greatly extending the spectrum of possible ICT devices and systems.

### Challenges

There are three main challenges. The first is to discover new materials able to carry information in novel forms, for example as surface plasmon polaritons, controllable electronic spins or emergent magnetic monopoles. The second challenge is to learn how to process and control the fabrication of these novel materials. The third challenge is the development of algorithms that can exploit these new physical properties to process information.

### Expected Impact

This research would be embryonic and foundational and the impact of its success would be internationally pervasive. Advances in exploiting novel physical degrees of freedom may well uncover new ways of sidestepping traditional road blocks to the development of current ICT technology, especially limitations on heat dissipation.

## 10. Quantum Decisions

### Motivation

The mathematical structure of quantum theory may be more generally useful for finding meaning in text and other related problems than classical logic, because quantum logic somehow captures important aspects of the way people organize information and meaning. Why the mathematics of quantum theory should be so relevant to human thinking remains unknown but this discovery is ripe for practical exploitation.

### Challenges

The challenge is to explore the relevance to ICT of quantum structures and other related contextual theories and non-traditional systems of logic.

### Expected Impact

The aim is to develop novel ICT models of human thought and human decision making processes. This could lead to fundamental breakthroughs in the modelling of cognitive systems and yield promising new approaches to long-standing problems in artificial intelligence. The work could contribute to novel data-mining and search techniques for the web.

## 11. Towards the Subjective Machine

### Motivation

A major barrier to the development of truly artificially intelligent ICT is our profound lack of understanding of what it takes for a device to have a ‘self’; that is, a point of view from which it judges and moderates its interactions with the environment and other agents, whether human or artificial.

## Challenges

One important challenge will be to move beyond the standard view of embodiment in which intelligence emerges from an interaction between brain, body and environment. Instead, we need to understand how the phenomenon of subjectivity emerges from this interaction.

This will come by developing an integrated model of physical and subjective self which is sensitive to time and place as well as to individual history and memory.

## Expected Impact

Machines with subjective qualities would be able to adapt to their environments, such as social environments populated by other agents, by humans from different cultures and by other machines. This would enable things such as hybrid human/machine collaborations which would have applications across society.

# Neuro-Bio-ICT

## Motivation

Brains are remarkable computing devices which clearly outperform conventional architectures in real-world tasks. Computational neuroscience has made tremendous progress in uncovering the key principles that neural systems use to compute. But while information and communication technology (ICT) has advanced to a point where it is possible to integrate almost as many transistors in modern chips as there are neurons in a brain, we are still unable to develop artificial neural systems with basic computing abilities that parallel even simple insect brains. The goal of neuro-Bio-ICT is to match this ability using innovative approaches to ICT inspired by the amazing processing capabilities found in nature and above all in the human brain.

## Challenges

The crucial breakthrough needed in this area is to understand the computational principles used by the brain, how they are exploited for processing, and how to implement them in hardware. This can be broken down into three areas

> Challenge 1: To learn more about the relationship between structure, dynamics and function in neuronal circuits and assemblies, and how information is represented or "coded" in patterns of neuronal activation.
>
> Challenge 2: To develop deeper and more comprehensive theories of neural processing, in particular those based on paradigms from dynamic and complex systems.
>
> Challenge 3: To close the gap between neuroscience and engineering with interdisciplinary work that ties data with theories, models and implementations.

## Expected Impact

The expected impact of Neuro-Bio-ICT on science and engineering is potentially huge and wide-ranging. Neurocomputers built on the principles of information processing in nature should be capable beyond the limits of conventional computers. They should find widespread use in areas such as complex object and scene recognition, autonomous robot navigation, complex problem solving and inference based on rich sensory stimuli. Application areas include medicine (neural prostheses, therapy of neuronal disorders, etc.), robot engineering, real-time autonomous processing, embedded systems and many more.

# Unconventional Formalisms for Computation

## Motivation

Conventional computation is based on the mathematical abstraction of Turing machines with exact provable results. It has been incredibly successful. However, there is a growing sense that it encompasses only a small subset of all computational possibilities and there is increasing evidence that it may not work well in certain domains.

Unconventional computing is a broad term for other forms of computation. These include hypercomputation, quantum computing, analogue computing, chemical computing, biocomputing and so on,

The very breadth of this field means that coverage is spotty. In some areas, excellent progress is being made while other fields remain isolated. In some fields, theory lags implementation and in others, implementation lags theory. In general, however, most approaches have not yet been scaled up to engineering or industrial-strength levels. And that means that the full potential of unconventional computation is not yet close to being realised.

## Challenges

Hypercomputation exploits new areas of physics for computation such as quantum mechanics and general relativity. It uses real numbers for computing rather than discrete and finite symbol sets and allows computing with physical oracles.

Current challenges fall into two categories. The first is discovering what can be accomplished theoretically if real numbers (all of them or even just one classically uncomputable real) are included in a model. This could lead to novel complexity and computability classes beyond the Turing capability. Second, what can be accomplished practically in implementations that exploit the laws of physics--how much of that extra computing power is actually accessible? In particular, the study of real world oracles is promising. These are physical systems that supply possibly uncomputable inputs for a classical computational system.

Bio-inspired computation is a rich source of novel forms of computation and some of these might be characterised as “hypocomputational”: there is not always a requirement for universality in the Turing sense. Various areas of biology are being mined for computational analogues such as the brain (artificial neural networks), evolution (a variety of evolutionary search algorithms), the immune system (a wide range of artificial immune algorithms), swarms and flocks (particle swarm optimisation), social insects (ant colony optimisation, brood sorting, colony defence mechanisms) and so on. There are also combinations of these approaches, for example, neuro-endocrine-immune computing; “evo-devo” algorithms incorporating evolutionary search with a developmental process generating a computational phenotype.

Parallelism has finally become a mainstream technology in the “standard” computer and a few more generations of Moore’s law would lead to 1000-core processors as standard. However, the current approaches to parallelism will not scale. A major issue with exploiting parallelism is the serial mindset (reinforced through education), and a lack of appropriate high-level abstractions.

Classical computation is not embodied: it is so far abstracted from the physical properties of the underlying material that it can be implemented on a wide range of diverse substrates. This implies that the physical properties of the substrate cannot be used directly to perform classical computation: a “virtual machine” layer is built to implement the abstract computational model. Embodied computation, on the other hand, directly exploits the physics of the material to perform the computation (the physics “just does it”, rather than the system needing to be driven), and can be much more efficient. (We have a vivid recent example in the transition to digital radio and the complaints it has generated about the order of magnitude more power it takes.)

Analogue computing is an example of such embodiment. In its widest form, it covers a diverse range of substrates. Examples include: mechanical orreries, wooden slide rules, soap films, DNA, quantum simulations and so on. It is important to be able to define and compare the computational power of such devices. Recent research has started to focus on generic ways to characterise these resources, assessing input and output encoding as well as the core computation itself.

Both biological information processing and amorphous computing emphasise the intimate link between the computation and the physico-chemical properties of the material substrate in which it is embodied.

## Expected Impact

Unconventional computation is a relatively immature domain. Many of the research examples are “toy” devices: theoretical devices or small, laboratory bench implementations. Scaling up to engineering or industrial-strength approaches is non-trivial, requiring novel approaches and significant resources. Achieving these goals may help to unify aspects of unconventional computing, novel mathematics and information theory under a single umbrella. New forms of computation could be applied to a wide range of problems such as systems biology, artificial intelligence, web dynamics and so on.

# Complex Systems Science

## Motivation

Information and communication technology (ICT) systems are socio-technical systems, in which the behaviour of the whole emerges from and coevolves with the behaviour of individuals, groups and the mass of people worldwide.

These systems are complex at every scale. At the microlevel of a program running on a single processor, enormous complexity can emerge from interactions between the data and the dynamics of the computation. At this level, there are also major problems of robustness, adaptation, self-configuration and self-repair. At higher levels of aggregation, wired and wireless networks create systems of the immense complexity exemplified by the Internet.

The internet economy is a good example of a complex system. It has no centralized control - its global behaviour emerges from the interaction of local behaviours of agents and is deterministically unpredictable. For example, the system exhibits cyclic increases and decreases of economic output but predicting the timing or severity of the next slowdown is not possible. Contrary to conventional economic theory, the internet economy is frequently disturbed and is permanently "far from equilibrium" - it has no time to return to equilibrium. The system is nonlinear, so small disturbances can be amplified and cause very large disruptions. And the system is capable of self-organising and changing its dynamics. In common with all social systems, its constituent agents have declared and undeclared objectives and pursue these objectives in competition or co-operation with other agents.

A system of enormous complexity emerges from all these interacting factors. But current ICT is based on conventional software, which is based on a rigid structure of algorithms calling algorithms. Because of this, it cannot adequately support businesses, governments and social institutions that operate in an increasingly complex environment

So there is an urgent need to develop a new ICT that is adaptable and capable of providing autonomous real-rime management of business, administrative and social processes. This will only be possible by designing complexity into ICT systems.

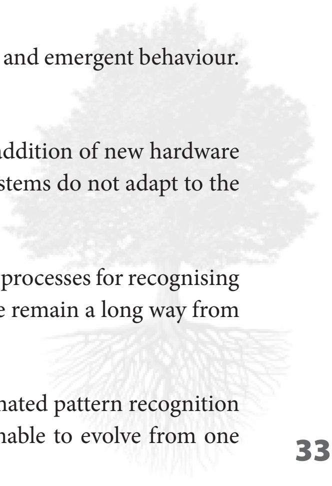
## Challenges

The challenge is to design future ICT systems that can exploit complexity and emergent behaviour. There are numerous bottleneck problems in achieving these goals.

For start, ICT systems often fail when new parts are added because the addition of new hardware and software can lead to unpredicted and undesirable behaviour. ICT systems do not adapt to the changing requirements of users. Neither do they self-repair.

Search remains highly limited and non-humanlike. The human cognitive processes for recognising patterns are not well understood and not implemented in computers. We remain a long way from The Ultimate Google identified by the FET Evergrow project.

Despite being the key to many high-added value ICT applications, automated pattern recognition remains primitive. For example, current machine vision systems are unable to evolve from one



application such as recognising car number plates, to other applications like recognising rocks on Mars.

ICT systems generally have poor human-computer interfaces partly because massive amounts of data cannot be synthesised and presented to users in useful ways. 'Visual analytics', the use of computer graphics to present information in ways that human can see complex patterns, remains a pragmatic second best.

## Expected Impact

Solutions to any of the bottleneck problems mentioned above would have enormous commercial and social value. All of them have been the subject of intense research over many decades. Clearly, solving them requires new thinking.

From the perspective of complex systems science, it is striking that these problems all have the same characteristic: they are systems of systems of systems. We have no scientific formalism for representing either the bottom-up or top-down dynamics of these multilevel systems.

This is a problem that extends across the sciences. In biology, there is no formalism able to integrate the dynamics of cells with the dynamics of organs or the dynamics of the whole body. Instead we have many partial models that fit together, at best, descriptively.

In geography and environmental planning, we have no formalism that can integrate the choices and behaviour of individuals with the emergence of cities across the globe. In social and political science, we have no formalism that can explain why the values and beliefs of individuals aggregate into mutually destructive policies at a national level, as illustrated by the recent inability of nations to agree a strategy on climate change.

And in ICT, we have no formalism that can integrate individual computers and their users at one level into the larger scale phenomenon of the internet.

Creating a formalism for multilevel systems of systems of systems and demonstrating its applicability will be critical for progress in these and other areas of science.

# Robotics & Embodied Systems

## Motivation

While Moore's law has led to an exponential increase in computing power over time, the same law does not seem to hold for robotic and embodied systems that have to interact with the real world. The reason is that intelligent and cognitive systems do not rely on computation alone and other factors play an important role. Understanding these factors is an important open challenge.

In recent years, FET has funded two major initiatives in the areas of robotic and embodied systems. The Beyond Robotics initiative (2004-2008) called for interdisciplinary work on three objectives:

- The development of cognitive robots whose "purpose in life" would be to serve humans as assistants or companions
- Hybrid bionic systems that would augment human capabilities such as perception of the environment, motion, interaction with other humans etc.
- The development of autonomous microrobot groups ('robot ecologies'), consisting of many heterogeneous members exhibiting collective behaviour and intelligence.

The Embodied Intelligence initiative (2009-2012) called for new technologies and design approaches for building physically embodied intelligent agents and artefacts, with emphasis on the relationship between shape, function and the physical and social environment. This initiative focused on three objectives:

- Mind-body co-development and co-evolution through the interaction of agents with the physical and social environment.
- Morphology and behaviour: new design principles for sensing, actuation and locomotion components and for robot architectures that are based on a deeper understanding of the role of form, material properties and the environment in shaping behaviour.
- Design for emergence: design paradigms and techniques for purposive agents where behaviour is not strictly programmed but robustly emerges from the interaction of the various components (each with local intelligence), the environment and its ubiquitous information resources.

While researchers have made much progress in these areas, many of the grand challenges remain open.

## Challenges

Research in this field faces many theoretical, conceptual and practical challenges.

One of the most important lies at the heart of the research efforts in morphological computation. In traditional control theory, there is a clear separation between the control and the controlled. However, this separation does not seem to apply to biological forms of intelligence, where shape and form are key elements of control.

How can morphological properties, such as shape, distribution of sensors and actuators in and on the organism, weight distribution, and material characteristics (such as elasticity, stiffness, symmetries, deformability) be exploited to achieve coherent stable behavior? A rigorous scientific treatment and understanding of this problem is still lacking.

A particularly challenging issue will be to understand the implications of morphological computing for learning.

One line of research aims at implementing the lowest functional level of intelligence that could be embedded in a robotic artefact by tightly merging the concepts of morphological computation and emerging behaviours.

Other important challenges lie in the areas of embodied intelligence, artificial metabolism, artificial consciousness, nano-robotics and molecular robotics, design methods and psychological, ethical, and societal issues.

## Expected Impact

Machines that perceive, understand and interact with their environment will have a profound impact in society, from the transport and manufacturing industries to research, education and health care. Extending the scope from the virtual world of Turing machines into the real one will open up entirely new design possibilities, conceptually and practically.

# Disruptive Solutions for Energy Efficient ICT

## Motivation

Some eight orders of magnitude separate the energy efficiency of conventional computers from what is theoretically possible. Closing this gap would lead to a significant improvement in the energy efficiency of information and communication technology (ICT). Achieving this goal will mean overcoming a number of serious hurdles in understanding the nature of computing, in exploiting unconventional ways of computing and in designing systems that exploit computers.

## Challenges

In the mid 20th century, computer scientists placed fundamental limits on the energy efficiency that is possible with computing devices. But there are still many aspects of computing where we lack a good conceptual understanding of energy efficiency. For example, it may never be possible to reach the theoretical limits of computing efficiency but an important, unanswered question is how close it is possible to get.

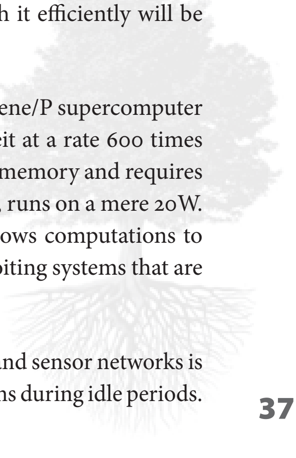
Today, the field effect transistor is the basic building block of the vast majority of computing machines. But there is a growing interest in other computing mechanisms that have the potential to be significantly more energy efficient. These include exotic switches consisting of simple atoms or large biomolecules and post-Boolean logic system in which data is represented in higher bases. Nano and microelectromechanical components have the potential to reduce the energy consumption of wireless radio devices by an order of magnitude.

In addition, there is much to be learned from biological systems. For example, by sending data in the form of spike-like solitons which mimic the way neurons carry information. The advantage here is that only a small section of the transmission line is charged rather than its entire length as in conventional devices. But understanding biological information processing is a major challenge.

As we improve the energy efficiency of computers, noise will play a greater role. The noise comes from sources such as thermal fluctuations and causes errors and uncertainty in calculations. Noise will also be an issue with future nanoelectronic CMOS technologies in which device properties will show signification variation. Understanding noise and how to deal with it efficiently will be essential if low-power computing is to be fully exploited.

Better systems architecture can also help to save power. In 2009, IBM's BlueGene/P supercomputer simulated the function of a cat's brain consisting of 1.6 billion neurons, albeit at a rate 600 times slower than real time. BlueGene/P has 146,456 processors with 147,000GB of memory and requires a 1.4MW power supply. By contrast, the human brain with 25 billion neurons, runs on a mere 20W. Among the keys to such energy efficiency is massive parallelism, which allows computations to proceed more slowly and therefore more efficiently. Understanding and exploiting systems that are massively parallel will yield substantial energy savings.

And there are simpler fixes too. One way to save energy in computing systems and sensor networks is to turn off parts of systems that are not being used, such as radio communications during idle periods.



But this inevitably leads to a trade off against the performance of the system. Maximising the benefits of such trade offs requires new ways of modelling a system's performance and activity.

Smart software will also be needed that understands the application and can determine when these trade offs can be made. This will require new ways of measuring efficiency that go beyond a simple measure of the number of operations per Watt.

Since the dissipation of some energy is unavoidable, steps should be taken to recover it. Such techniques are closely linked to the ability to harvest ambient energy. Examples include nanoelectromechanical devices which have the potential to harvest ambient energy and make ICT devices self sufficient.

## Expected Impact

Overcoming these challenges is expected to yield significant improvements in the energy efficiency of ICT. Estimates of the reduction in energy use range from 50 per cent to several orders of magnitude.

Among other things, this kind of improvement will allow an exponential increase in the performance of supercomputers with a constant power budget. Greater efficiencies should also make possible novel low-power devices, such as machines that can operate inside the body, energy efficient vision systems and energy harvesting devices that require zero power input.

# Annex

## Rapporteurs

The reports on the individual consultations were written by the following rapporteurs:
(in alphabetical order)

- Daniele Binosi, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento (IT)
- Mark Buchanan, Independent author & Science writer (UK)
- Georg Dorffner, Medical University of Vienna, (AT)
- Cecilia Laschi, Scuola Superiore Sant'Anna, Pisa, (IT)
- Justin Mullins, Independent author & Science writer (UK) (overall summaries)
- Yasser Omar, Technical University Lisbon (PT)
- Mike Sharpe, MS Consulting & Research Ltd (UK)
- Susan Stepney, University of York, (UK)

## List of consultations with links to full reports

(in chronological order)

At http://cordis.europa.eu/fp7/ict/fet-proactive/shapefetip-wp2011-12_en.html you can find the full reports for each individual consultation and written contributions or position papers where available.

The links to each full report are given below.

ATOMIC & MOLECULAR SCALE DEVICES AND SYSTEMS & BIO-CHEMISTRY BASED INFORMATION SYSTEMS
22-23 October 2009, Brussels
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-01_en.pdf

QUANTUM INFORMATION FOUNDATIONS AND TECHNOLOGIES
Autumn 2009 - online consultation
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-08_en.pdf

WEBSCIENCE
Autumn 2009 - online consultation
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-09_en.pdf

COLLECTIVE ADAPTIVE SYSTEMS
3-4 November 2009, Brussels
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-02_en.pdf

SHAPING THE FUTURE ("OPEN" CONSULTATION)
4-5 November 2009, Brussels
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-03_en.pdf

NEURO-BIO-ICT
9-10 November 2009, Brussels
ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-04_en.pdf

### UNCONVENTIONAL FORMALISMS FOR COMPUTATION

30 November 2009, Brussels

ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-05_en.pdf

### COMPLEX SYSTEMS SCIENCE

December 2009 - expert consultation report

ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/shapefetip-wp2011-12-06_en.pdf

### ROBOTICS & EMBODIED SYSTEMS

January 2010 - online consultation

http://cordis.europa.eu/fp7/ict/fet-proactive/docs/shapefetip-wp2011-12-07_en.pdf

### DISRUPTIVE SOLUTIONS FOR ENERGY EFFICIENT ICT

8-9 February 2010, Brussels

http://cordis.europa.eu/fp7/ict/fet-proactive/docs/shapefetip-wp2011-12-10_en.pdf

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