2. What is Complex Systems Science?

There are two kinds of interdisciplinarity that contribute to our understanding of complex systems. The first begins with a particular complex system and addresses a variety of questions coming from that particular domain and its points of view. The second addresses questions that are fundamental to complex systems in general, cutting across particular domains such as the earth and life sciences, economics, the social sciences and the sciences of the artificial.

The first leads to domain-specific interdisciplinary fields such as cognitive science. The new science of complex system belongs to the second kind of interdisciplinarity, by starting from fundamental open questions relevant to many domains, and searching for *methods* to deal with them. These two kinds of interdisciplinarity are complementary and interdependent: any advance in one makes a contribution to the other.

The Science of Complex Systems will develop in the same way that physics has developed during the three last centuries through a constant process of *reconstructing models from constantly improving data*. The reconstruction of the multi-level dynamics of complex systems presents a major challenge to modern science but it is becoming more and more accessible through the increasing power of computers. This allows orders of magnitude more data to be collected, of increasing quality and value. It also allows these data to be analysed over practical timescales and the results to be presented in more accessible ways through, for example, advanced computer graphics. This combination of data, processing, and representation is rapidly leading to theoretical advances in understanding.

Physics has used formalisms from mathematics elaborated over the three last centuries to express its dynamic constructs unambiguously. Similarly, Complex Systems Science has to create pertinent formalisms, depending on the particular types of complex system involved. It has to find the most useful description of complex system phenomenologies and their data. Generally these are the most elegant, consistent with both the theoretical viewpoint of Komolgorov complexity in computer science, and Occam's razor in epistemology.

In summary, Complex Systems Science is concerned with fundamental questions relating to the reconstruction of theory from data for particular systems, and fundamental questions about methods of scientific investigation across the domains. *These fundamental questions will be addressed by the Program "Ideas" of FP7.*

2.1 What are complex systems?

It would nice to be able to give a clear single sentence answer to the question "*what are complex systems?*". More than a decade ago Murray Gell-Mann wrote "A great many quantities have been proposed as measures of something like complexity. In fact, a variety of different measures would be required to capture all our intuitive ideas about what is meant by complexity and by its opposite, simplicity."[2] The literature contains many variants of definitions of complexity and complex systems.

To put this in perspective, despite the many variants of the definition of 'life', and the many examples lying on the edge of these definitions, this causes little trouble to the majority of biologists. We will not, therefore, attempt to give such a single-sentence definition of

[2] 'What Is Complexity?', *Complexity*, **1**(1), 1995. http://www.santafe.edu/sfi/People/mgm/complexity.html

‘complexity’ here. Rather, we have opted for a characterization that underlines four different aspects of complex systems research that permeate all research into complex systems.

Complex Systems Science bridges the gap between the individual and the collective: from psychology to sociology, from organism to ecosystems, from genes to protein networks, from atoms to materials, from the PC to the World Wide Web, from citizens to societies.

In multilevel complex systems, higher-level system processes result from lower-level interaction-induced co-operative emergence. Similarly, lower level system processes may be constrained or even determined by higher-level interactions, thus allowing the possibility of adaptation and co-evolutions between lower and higher level dynamics.

Thus, multiple-component systems evolve and adapt due to internal and external dynamic interactions. The system keeps becoming a different system. Simultaneously, the demarcation between the system and its surroundings evolves as well. When a multiple-component system is manipulated it reacts by feedback, with the manipulator and complex system inevitably becoming entangled.

Complex systems research attempts to understand the consequences of combining many internal and external multi-level system-environment dynamics.

The characterisation of complex systems given above covers most practical cases. From the perspective of this roadmap the important thing is the *science* of complex systems, and this can be characterised by a series of questions that cut across particular complex systems in particular domains.

2.2 What are the Fundamental Questions of Complex Systems Science?

Complex systems science is characterised by general scientific questions relating to *method* rather than questions about any particular system. These questions include but are not restricted to:

(1) How can we reconstruct multilevel dynamics from data, including bottom-up and top-down inter-level interactions. How do the reciprocal influences between individual parts and the whole operate?

(2) How can we characterise emergence? How can we think of the morphodynamics of emergent structures and their robustness when there is sensitivity to initial conditions, difficulty in boundary definition, and dependence on the history of interaction with the environment?

(3) How can we study dynamical attractors and their families of transient trajectories?

(4) What are the different levels of organisation in complex systems and what are their characteristic spatial and temporal scales (*e.g.* slow versus rapid dynamics)?

(5) What are the specific emergent properties characterising adaptive systems coevolving with changing environments? How do intra- and inter- systems links appear and disappear with changing strength? How does the fundamental interaction topology of systems evolve in continuous and discrete ways? Can we interpret the long-term logic of link creation as a rational adaptation of networks to the function they realise?

(6) How can we study systems of systems?

2.2.1 Questions about reconstructing and predicting multilevel dynamics

In complex systems, reconstruction is searching for a model that can be programmed as a computer simulation that reproduces the observed data 'well'. In this sense, reconstruction is the inverse problem of simulation.

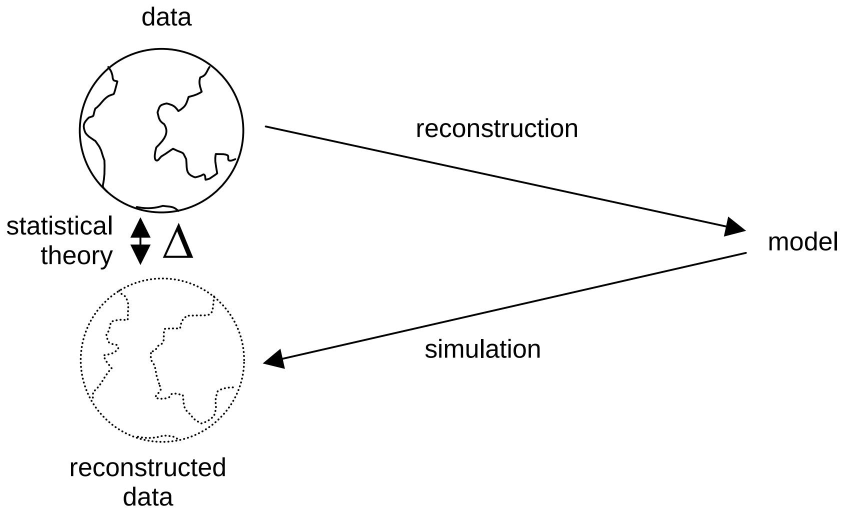

Figure 1. Reconstruction and Simulation as inverse problems in science

In general, even the reconstruction of the dynamics of a single complex system cannot be done in a deterministic way. The predictions from Complex Systems Science do not say what *will* happen, but what *can* happen. Indeed, the ideal of predicting the multi-level dynamics of complex systems can only be done in terms of probability distributions, *i.e.* under non-deterministic formalisms. *It means that reconstruction can only be done up to a certain level of 'noise'* and the nature of the noise has to be chosen very carefully.

In practice, predicting exactly a probabilistic law is generally an intractable task because of data incompleteness and computational complexity. *Only prediction within uncertainty of distribution laws can be attained*. Complex Systems Science even has to deal with 'radical uncertainty', *i.e.* uncertainty about the space of possible system states.

In all cases, the aim of Complex Systems Science is to reduce the uncertainty, by reasoning from first principles and using data. This means that even the dynamics of uncertainty have to be estimated.

An excellent definition of complex systems is "those systems without known tractable exact models", no matter whether they are deterministic or non deterministic. This definition is not intrinsic. It is an epistemic definition such that a system ceases to be complex if we can predict it without uncertainty, *i.e.* exactly in probability law.

Many formalisms for representing discrete or continuous dynamical models already exist. Following from these, mathematics, computer science and statistical physics can bring new formalisms for representing complex systems dynamics in an elegant and useful way. The choice of formalism for a particular class of complex systems will be increasingly determined by reasoning from first principles.

Given a formalism, methods already exist for reconstructing excellent predictive models from accumulated data. But reconstruction is a very difficult problem and there is a critical need for new methods. The first main difficulty comes from reconstruction as the inverse problem of simulation: given a model, simulation produces complex data and behaviour; given complex data and behaviour, reconstruction provides an admissible model. The second main difficulty is to find amongst the admissible models one with excellent "uncertain predictability". The theory of "uncertain predictability" is difficult, especially when it concerns multilevel dynamics at different level of emergence.

2.1.2 Questions on the epistemological cycle: assumptions -> protocols-> reconstruction

Scientific activity on complex systems typically obeys the epistemological cycle: (i) starting from scientific questions and assumptions (ii) looking at protocols for testing the assumptions (iii) reconstructing the multilevel dynamics according to the assumptions (iv) if the reconstructions are "bad", changing the assumptions.

The need for data in Complex Systems Science is unavoidable: there is no new science without new data. As for biology, data on complex systems can be sometimes obtained *in vitro* by controlling the experimental conditions. But as in biology, the ideal for all kind of complex systems consists of *in vivo* experiments. Many protocols producing multi-source, multimodal, high throughput data already exist. But a huge number of protocols remain to be designed for studying complex systems. Due to the epistemological cycle, they must be designed not only by experimentalists involved in a specific class of complex systems but also by theoreticians involved in the transverse cross-disciplinary questions.

New high throughput protocols will typically be candidates for becoming distributed European platforms, in the sense of big instruments for reinforcing the European scientific infrastructures. This is not only due to the importance of the investments, but also to the simple fact that data-bases on complex systems are gold mines for the knowledge economy.

A significant part of the data must be public, at least — for deontological scientific reasons — that part of the data for which the reconstruction of the dynamics involved has been published. The corresponding reconstruction has to be submitted to international competition to find the best possible one.

The storage capacity of data on complex systems is not infinite. It is very probable that storage will rapidly become a bottleneck. The only long term solution is precisely the reconstruction of the dynamics responsible for the data, which equals exactly the minimal program for reproducing these data.

2.1.3 Questions related to the design, control and management of complex systems

One of the major factors driving the Science of Complex Systems is the possibility of applying the new science to the design, control and management of existing and new systems. This includes the application of new scientific principles in engineering design, but it also includes the design of socio-technical systems such as the Internet and transportation systems, and it will increasingly include the design of social systems such as companies, health services, armed forces, and civil administration.

The Science of Complex Systems is increasingly enabling the 'Sciences of the Artificial'[3]. There can be no science of a human-made system before that system exists, *e.g.* there was no computer science before the invention of the computer. (WHAT DO YOU MEAN WITH THIS?)

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[3] Herbert Simon's book *The Sciences of the Artificial* (MIT Press, 1969) introduces the idea that design can be thought of as a 'science' of artificial human-made systems.

Complexity impinges on design in four major ways. First, many designed systems are complex, and the designers need a scientific theory on which to base their designs. Second, the construction of systems can be complex, involving many processes and inputs organised in complex supply and distribution chains. Thirdly, the socio-economic context of design is complex. Demand for products and systems can change rapidly for reasons as diverse as fashion and environmental sensitivity. Fourthly, the design process itself can be complex, involving many people distributed at many locations manipulating large heterogeneous data flows (www.complexityanddesign.net).

Understanding the nature of complexity in design is of crucial importance to Europe. Design is the interface between science and its value-added exploitation. Transfer of scientific knowledge into the commercial and industrial sectors is an established priority of the European Commission.

2.3 Methods, Algorithms and Tools for Complex Systems Science

In science, methods generally come before theory; theory is the synthesis of knowledge gained by the application of systematic or heuristic methods. This section will give a brief survey of the methods of Complex Systems Science. Real world systems will be a constant source of inspiration for novel concepts and methods in complex systems research, and the methods will be illustrated by examples from particular domains.

2.3.1 Modelling as reconstruction, a key tool in complexity science

In section 2.2.1 we presented the reconstruction of models as the inverse problem to simulation, *i.e. models* are generally *reconstructed* from data. Modelling complex systems is a very difficult inverse problem requiring a variety of methods.

Computers have opened new opportunities for system modelling. A *model*, once translated into a *program*, may be used to understand, measure, simulate, mimic, optimise, predict, and control.

Computer "experiments" are becoming increasingly important as a means of exploring the behaviour of complex systems, and for optimisation and sensitivity analysis. They are in a sense "*in vivo virtuale*". Computer simulation can often supplement experimentation in science and prototyping in engineering. During the *design and analysis* of complex systems in science and engineering, sophisticated and realistic numerical simulations are commonly used to limit the number of expensive prototypes or measurements. Simulations give insights into the behaviour of massively composed systems that are extremely large, distributed and function over very long time periods or at very fine time scales. The 'laws' of the simulated system are implicit in its program, but the consequences of those laws may only become visible after the simulation is run. Thus the simulation program is a 'theory' that generates the observed behaviour *in silico*.

Such simulations take data of diverse kinds and qualities that, through the process of creation of entities and then the generation of interactions among those entities, produce unimaginably large amounts of "synthetic" data. Doing so accurately often requires the integration of expertise and data ranging, for example, from molecular, genomic or proteomic levels, where the disease is evolving, to macroscopic disease dynamics in populations, analysis of economic consequences and so on.

Parametric computer experiments are becoming increasingly important as a means of exploring the behaviour of complex systems, and for optimisation and sensitivity analysis. Application areas include Bioinformatics, Operations Research, Network Simulation, Electronic Design Automation, Ecological Modelling etc. The user selects large parameter ranges, attempting to cover the whole design space. Despite the steady and continuing growth of computing power and speed, and despite the availability of high performance computers, clusters and grids, the computational cost of multivariate parametric computational experiments can still be prohibitive.

Autonomous, self-organizing exploration and modelling tools for parametric experiments on computer clusters and grids, which minimize the overall number of computational expensive simulations, are the ultimate goal.

2.3.2. Classes of inverse problems: Reconstruction of complex system multilevel dynamics

We are rapidly gathering enormous amounts of data on complex systems across many scientific and engineering disciplines. One of the purposes of Complex Systems Science is the comparison of such systems, in order to generate a better understanding of the structural dynamics inherent in various classes of system, and various kinds of system dynamics. The Science of Complex Systems will develop through a constantly renewed process of reconstructing models from data with a permanent interaction between models and data. The reconstruction of the dynamics of complex systems presents a major challenge to modern science but it is becoming increasingly accessible due to breakthroughs in computation.

The reconstruction of the dynamics constitutes a first class of inverse problems: finding the 'simplest' dynamical model representing a complex system. The control of the dynamics constitutes the next class of inverse problems: finding combination of a centralised control on the whole system and a distributed control on the network of its entities has the properties to keep its dynamics 'viable' or approximately 'optimal'. Finally the (re)design of a system constitutes the last and most difficult class of inverse problems, because its need some deep and precise ideas about the dynamics of the system and its control.

2.3.3. Discovering meaning in uncertain data

Western industrialized nations are overwhelmed by data (it is estimated that the US Department of Homeland Security receives 3 Terabytes of data *every week*). However, it is difficult to evaluate the validity and reliability these data, and to convert them into useful *information*. New methods are required to label data with indicators of its trustworthiness and then to process the data in ways that take account of its reliability. This *metadata* problem has direct relevance to the control of terrorism, where there is a vast mass of very unreliable data, while some, possibly very small, proportion of it is both true and of great importance. In another domain, more powerful means of exploiting this wealth of databases could advance our understanding of living systems, as well as our ability to design effective therapies, to entirely new levels. However, researchers face a fundamental challenge in learning how to extract useful information from large, and noisy, data sets.

To meet these needs requires sophisticated inference methods for modelling statistical dependencies between variables. One promising approach to this is through the development of so-called "probabilistic computing." Rational analysis based on logic is restricted to problems where information is both complete and certain. Alternatively, probability theory offers a framework for modelling reasoning in the presence of incompleteness and uncertainty. Probabilistic graphical models provide a powerful framework for modelling statistical dependencies between variables in sparsely connected systems. The price to be paid for the high degree of flexibility of these models is the vast increase in computational complexity for adapting the model parameters to data and for predicting unobserved causes (hidden variables) from observations.

To bring probabilistic or Bayesian computing to bear on practical problems, we require a new modelling methodology based on inference algorithms to automate probabilistic calculus, programming languages to implement these models on computers, and finally, we require new hardware to run these Bayesian programs efficiently. Important progress has already been made lately on the first three subjects (methodology, algorithms, and languages) but a lot of work remains to be done. This highly multidisciplinary goal requires mathematicians and computer scientists, but also, for example, neuroscientists who are developing Bayesian models of the central nervous systems that can inspire future developments.

2.3.4. Scalability

Good scaling properties are rarely found where there is centralised hierarchical control, since such control leads to bottlenecks due to the increasing amounts of information need to be passed to central systems. In the context of distributed systems engineering, scaling costs that are linear or better (*e.g.* log) are often considered to be acceptable. However, inspiration from biological and social systems teaches us that zero or negative scaling costs should be possible – for example, economies of scale and division of labour in social systems, and distributed search in evolving systems. In these kinds of systems "bigger is better" - the larger a population, the cheaper it is to deliver the same performance.

Nevertheless, self-organised processes are not automatically scalable in the sense used in engineering. In biology, examples point on the one hand, to scalar regularities in the size, organization and life-span of organisms, but on the other to a change of behavioural mechanism according to the size of the colony of ants or bees. Scalability is not automatic in functional self-organized behaviour and hence must no be taken for granted by complex system based approaches.

In approaching this task, the "soft" communities (sociology, anthropology, etc. who want to understand existing systems) and the "hard" communities (engineers, computer scientist, robotics, who want to build systems that perform a task) have a shared interest: understanding the mechanisms of emergence to be able to control system behaviour. To meet this challenge we need to find laws, rules, and regularities concerning the behaviour of such many-unit emergent systems. We will also need to better understand the conditions under which these regularities occur, so that gradually more abstract calculi can be built on top of each other in order to produce multi-layered models, each one grounded in the emergence capacity of the other. This, in turn, will be key to a methodology for 'emergence engineering' in large-scale complex systems.

2.3.5. Understanding and Engineering Emergence

In general, complex systems have many autonomous units (agents, actors, individuals) with adaptive capabilities (evolution, learning, etc), and show important emergent phenomena that cannot be derived in any simple way from knowledge of their components alone. Yet one of the greatest challenges in building a science of such systems is precisely to understand this link – how it is that micro level properties determine or at least influence those on the macro level. Our current lack of understanding presents a huge obstacle in designing systems with specified behaviour – to design the units of a system, their interactions and adaptive features, so as to achieve a targeted behaviour from the whole.

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. Technically this requires massively scaleable data analysis (data mining) methods, which should work “on-the-fly” so that the data generated by running the system do not have to be stored first and analysed off-line after the run has ended. The challenge is to find generic laws governing functional self-organization in both natural and artificial systems, and to find ways to classify such functional self-organization according to the type of problem is solved in the context of specific constraints.

Besides this systemic approach leading to classification, there is also a need for benchmarking of functional self-organization compared to other types of problem solving technology. For each class of problem an experimental approach should be developed to assess whether technology based on Complex Systems Science is, or is not, the optimal choice.

2.3.6. The Science of Complex Networks

Large and complex networks arise at many levels of the natural world. The Internet is a vast network of computers linked by transmission lines, and the living cell depends for its function on a staggeringly complex web of interactions among a great number of genes, proteins and other small molecules. Economically, a global network of trade links the world’s nations together. Ten years ago, science had very little to say about the architecture of these networks. They were, traditionally, viewed as random networks – that is, as sets of elements linked together at random, with any pair being connected with equal probability.

This understanding has been dramatically revised in the past years, as seminal work has led to a far deeper understanding of the architecture of both natural and man-made complex networks, and its impact on network behaviour. This work has revealed surprising similarities between networks that have emerged in diverse settings. In particular, food webs, social networks, the Internet and the World Wide Web, even the wiring diagrams of microprocessors, all share important topological properties; for example, these and other networks reveal the “small-world” property, as it takes only a handful of steps to go from any one element to any other, even in networks comprised of an enormous number of elements. Current research is actively pursuing an understanding of the relationship between the topology of complex networks and their functional properties such as stability and information-processing efficiency. Some network architectures in ICT are more readily “searchable” than others, leading to more efficient information storage and retrieval. These insights have influenced technologies relevant to Peer-to-Peer (P2P) networks and structured databases.

The work of the past few years represents only an initial foray into an area that looks certain to have profound implications across science. More than anything, the science of networks has begun to establish a conceptual language for describing and comparing complex networks in a meaningful way. Further work now underway, especially within the complex systems community, aims to address a number of fundamental questions. For example, what accounts for the emergence of similarly structured networks in so many distinct settings, where one might expect different factors to be at work? What is the link between architecture and network stability? How does network architecture influence the dynamics of processes taking place within that network? Answering these questions will have an immense impact on a wide range of scientific problems, as well as influencing engineering practice in ICT and elsewhere.

2.3.7. Message-passing to address “Computational Complexity”

Many complex problems of general interest have natural “non-deterministic” solutions *i.e.* if one can guess an answer then the verification that the answer is a solution is easy to do using today’s computing devices. Thus, it is important to understand how quickly a “deterministic” (or predictable) computing device can determine the outcome of a non-deterministic computation. So far, we have no general techniques that work any better than trying all step-by-step simulations.

Solving hard combinatorial optimisation problems is a fundamental task in many disciplines in the natural and engineering sciences. By transferring knowledge and techniques from information theory and statistical physics to computer science and the study of optimisation, researchers have recently discovered a new class of probabilistic Message Passing (MP) algorithms that solve combinatorial optimisation benchmark problems efficiently. Imagine students in a classroom trying to solve a hard problem via exchange of secret messages that express their belief regarding the answer to a subpart of the overall problem. The final answer they would give is some sort of common agreement of all their beliefs. This strategy of 'belief propagation' is at the heart of a recent breakthrough to find fast distributed algorithms for combinatorial optimization. This illustrates how a multidisciplinary effort between physicists and computer scientist led to an important breakthrough in algorithmics. These procedures generalise and extend the algorithms that currently set the state of the art, and therefore promise many important applications:

Regulatory Networks: The genome and proteome are highly interactive systems as the expression of a gene depends on the activity of others through complex cascades of local events that result in non-local interactions involving different factors. Systemic and network perspectives are thus becoming increasingly important for understanding their behaviour. Interactions between genes can be analysed in terms of genetic networks where nodes represent individual genes, and links represent regulatory interactions. The wealth of new data requires new concepts and tools of analysis. In this context, MP algorithms can be used to predict and analyse the gene expression variables, and to face the reconstruction problems of Regulatory Networks from the available (very noisy) data.

Neural Computation: Networks of biological neurons (*e.g.* in cerebral cortex) consist of a diluted directed graph. Communication in these networks occurs through discrete messages (spikes) travelling along the directed edges. Given the apparent similarity between biological neural network dynamics and MP algorithms, it is an exciting perspective to investigate whether such algorithms can be physically implemented in networks of biological neurons. This will necessitate a reformulation of MP algorithms as a stochastic dynamical system describing the time evolution of the neuronal and synaptic variables. Overall, these investigations can potentially shed new light on how biological neural circuits compute.

Decision making in complex social systems: Many economic, but also other kinds of decisions made by individuals are just as dependent on many different factors of context, among them how others in a community, or other communities, decide. In a competitive agricultural system, for example, individuals will evaluate how decisions made by others will affect the price they may be able to get for their crops. Everyone looks at everyone, until a 'decision' emerges. As such decisions are made in a wider economic and political context, the same kinds of multi-level hierarchical dynamics are essentially involved in agricultural decisions, as are in many other kinds of networks. Allowing authorities to anticipate such decision-making processes would permit them to calculate much better the outcome of their incentives, and dispense with a number of interdictions. MP algorithms would allow such calculations. They would also be of great importance in industry for anticipating the spread of innovations,

2.3.8. Algorithms, Tools and Problems Inspired by Economics and the Social Sciences

One of the most fundamental problems in the social sciences is the study of communication, decision-making and coordination structures. Throughout human history, different kinds of structures have emerged for these purposes, as the size, aggregation and means of communication among human populations have changed. The efficiency of these structures determines many aspects of our life, including security, wealth and wellbeing, power, governance and many more. In the science of organizations, this has been approached in a rather simplistic way by looking at different qualities of hierarchical, heterarchical and distributed control structures. Hierarchies, for example, transmit information more rapidly, but have inherent size limitations, whereas distributed structures are more adaptable, can accommodate larger groups, but are slower in responding to changes in external circumstances. Network approaches begin to develop new tools to tackle this fundamental issue. But we are a very long way from an approach that is sufficiently powerful to anticipate the social changes of the coming century with peace of mind.

To manage large networked systems effectively, we may adopt metaphors from Economics. For example, one can define the total network welfare as a global (perhaps imaginary and hard to compute) measure involving information from all the autonomous systems. A long-term goal would be to design new network management protocols that can adjust themselves in a dynamic way so as to ensure overall system “welfare”. Achieving a socially optimal (or close to optimal) choice in a complex system generally requires either some form of external intervention or some way of cooperation.

Individual actors should benefit only when their actions benefit everyone. One promising idea lies in devising a suitable system of tolls, which would make an autonomous system internalize the social effects of its choices. This approach suggests the need for the implementation of some kind of “virtual digital money” (VDM), which would allow for wider interpretations of exchange and accumulation of value; for example, the “money” could be in the form of access rights to routes, digital resources, temporary permission rights to elite peer-to-peer systems, etc. Only a thoroughly interdisciplinary, complex systems approach, integrating the expertise of researchers in social science and computer science, will permit the discovery of stable solutions and make the Internet a resource for all.

But such approaches conceive societies as relatively homogeneous, and the individuals in them as mainly driven by rational decision-making, and responding to the same sets of values. The problem becomes much less tractable when cultural and social diversity, are taken into account, as these increase the degrees of freedom of the individuals, and of the system, exponentially. The new means of communication offered by the Web technically allow for innovative approaches, but solving some of these problems is a necessary towards harnessing it to allow for a more diverse world to live together in relative harmony.

2.4. ICT Enabled Science for Complex Systems

There is no doubt that one of the main characteristics of the new Science of Complex Systems is that it is *computer enabled*. It is possible to perform science if new and different ways thanks to the possibilities opened up by our ability to store huge data sets and to perform massive calculations on those data to create usable *information*. Furthermore data and processing are increasingly distributed over many machines in many places worldwide, with modern *communications* technology enabling them to be brought together. Thus ICT has a special and generic role in the Science of Complex Systems not shared by other technologies.

The crucial importance played in Complex Systems Science by ICT can be understood by looking back at the older science before the first computers appeared in the middle of the last century. Before this the established paradigm was to represent observations as points in Cartesian space, and establish relationship between them using mathematical equations to express ‘laws’. These equations, many of them PDEs, were difficult to manipulate and difficult to solve. In the nineteenth century a great deal of effort was expended to finding ways of making equations more tractable in order to manipulate and solve them. Thus, for example, the Laplace Transform maps differential equations into different symbolic forms making them easier to manipulate and solve. Earlier, Napier’s Bones gave a practical way to perform complicated multiplications and divisions by mapping them to the much easier operations of addition and subtraction of logarithms. Of course these two examples are embedded in deeper mathematical theory but, arguably, the driving force was the need to calculate to solve real problems.

This intractability of formulae has gone two ways. First, mathematicians and scientists now have computer aids to handle formulae using computer algebra systems such as MathCad and Mathematica. This assists in symbolic manipulation that may lead to the reconstruction of generic characterisations of the dynamics of systems as collections of equations. From these, any particular set of boundary conditions leads to a specific point solution by substitution.

The other way involves calculation from the original equations to produce a single point prediction for a given set of boundary conditions. The example *par excellence* is Finite Element Analysis in which complicated physical objects have their irregular forms and their dynamics mapped to collections of simple polyhedra, and functions on the polyhedra and their faces. Then, given any particular set of boundary conditions, a particular consequent state can be calculated without there being a mathematical formalisation of all consequent states. In this case, the dynamics of the system are reconstructed from sampling many points in state space by calculating from particular boundary conditions.

The new Science of Complex Systems goes one step beyond this. Generally, scientists do not expect to formulate theories of complex systems in the form of exact solutions to systems of equations. Furthermore, scientists do not believe that there is necessarily one-one or many-one correspondence between data on current states of systems and the future states of those systems. For example, deterministic systems which are very sensitive to initial conditions may evolve to radically different states from the ‘same’ initial state, the point being that inevitable measurement errors effectively make the systems dynamics one-many. In such cases the concept of a point prediction is not applicable. When traditional many-one and one-one analytic mathematics breaks down, the best that can be done may be to find the *distribution* of outcomes for a given set of initial conditions – by calculation!

Thus the computer becomes an essential part of the scientific process in Complex Systems Science. This kind of science is impossible without ICT. Conversely there is a pressing need for fundamental complex systems research in ICT in FP7. Thus research into ICT is as important as research into Complex Systems Science to the future wealth of all nations. To summarise, ICT and the Science of Complex Systems are inextricably bound together. ICT is essential for the future development science of complex systems, and the Science of Complex Systems is essential for the future development of ICT. Funding in FP7 must recognise this interdependence.

3. Thematic Areas and Grand Challenges for Complex Systems Science

The Science of Complex Systems will enter into all domains of the Cooperation Programme FP7:

1. Health
2. Food, agriculture and biotechnology
3. Information and Communication Technologies
4. Nanosciences, nanotechnologies, materials and new production technologies
5. Energy
6. Environment (including climate change)
7. Transport (including aeronautics)
8. Socio-economic sciences and the humanities
9. Governance, institutions and law

9 Security and space

There is a need for complex systems research programmes in each of these domains, and also a crucial programme inside ICT to integrate the information dimension across them all. Taking health as an example — but it will be the same for the other domains — *personalized health* will need distributed databases for a huge number of patients about their specific genotype, phenotype and medical and general history. Then this distributed data base will be used for reconstructing the dynamics of patient health under different treatments and will provide, through time, what seems to be the "best" treatments or design of new treatments or new drugs on an individual basis.

Each kind of complex system will need such huge distributed databases. These will be directly useful to practitioners, but they are also crucial for constructing new scientific theories of the dynamics. This construction will be done through European platforms — understood as big infrastructure instruments such as those used in physics — with widely shared usage of each distributed data-base. That requires the implementation of a crucial programme inside ICT for Complex Systems Science, radically changing our ways of constructing formalisms, theories and models of complex systems in the different domains concerned. These platforms will be the place for 'coopetitive' (cooperative competitive) activity of scientists comparing their models and abstractions from data. Because coopetition is one of the main mechanisms in sport, and also occurs in scientific domains, this crucial programme in ICT can take the name of "Olympiads in modelling complex systems".

The "Olympiads in modelling complex systems" will constitute an important dimension in future ERA-NET and ERA-NET+ initiatives, enabling resources to be shared across European countries for scientific research and its exploitation.

The distributed databases and their associated modelling platforms will represent a massive potential resource for all social actors and the new science complex systems will allow it to be exploited for very high added-value commercial and civil applications. Thus Complex Systems Science will play a significant strategic role across all the nine areas listed above.

The European Commission has identified Joint Technology Initiatives (JTIs) as a way of realising public-private research partnerships at European Level. The idea is that bringing public and private interests together into new implementation structures will ensure that the research programmes are jointly defined and better match industry's needs and expectations, accelerating the technology acquisition process. In this context, it can be expected that Complex Systems research will play a significant role in many JTIs.

European Technology Platforms are intended to provide a framework for stakeholders, led by industry, to define research and development priorities, timeframes and action plans on a number of strategically important medium to major long term research and technological issues for achieving Europe's future growth, competitiveness and sustainability objectives. They are intended to play a key role in ensuring an adequate focus of research funding on areas with a high degree of industrial relevance, by covering the whole economic value chain and by mobilising public authorities at national and regional levels. In fostering effective public-private partnerships, technology platforms have the potential to contribute significantly to the renewed Lisbon strategy and to the development of a European Research Area of knowledge for growth.

As such, they will prove to be powerful actors in the development of European research policy, in particular in orienting the Seventh Research Framework Programme to better meet the needs of industry. European Technology Platforms can address technological challenges that can potentially contribute to a number of key policy objectives which are essential for Europe's future competitiveness, including the timely development and deployment of new technologies, technology development with a view to sustainable development, new technology-based public goods and services, technological breakthroughs necessary to remain at the leading edge in high technology sectors and the restructuring of traditional industrial sectors.

Complex Systems Science plays a fundamental strategic role unpinning such technology platforms, and it is imperative that we establish European Science Platforms to support the new kinds of fundamental research enabled by e-databases, e-content, and e-modelling.

To understand the huge scientific challenge of complex systems, consider the current very large project to simulate the physics of the atomic bomb. In this case five hundred years research in physics reconstructed the models and equations needed by scientists and engineers. There are no such models or equation in complex systems, a science that is less than fifty years old. Therefore it is impossible to build technology platforms for complex systems analogous to those used to simulate the behaviour of the atomic bomb.

Section 3 of this roadmap identifies what the complex systems community considers to be the key areas of strategic importance in Complex Systems Science, and what are considered to be the Grand Challenges in each area. Some seventy five scientists contributed to the Orientation Paper (http://complexsystems.lri.fr/portal/tiki-index.php?/page=Living+Roadmap) that forms the basis of this section (see Appendix A). This set of Grand Challenges can be synthesised to produce a 'living' list of Strategic Research Areas, as will be explained.

Thus the strategic areas identified here reflect a vision of the complexity science community on the key opportunities presented for Complex Systems Research. Many areas of science and technology now demand alternative methods for analysis and design. Below, we identify some of these areas, along with ways in which complexity science could help tackling the challenges faced.

3.1. The Internet and World Wide Web as Complex Systems

Information is as central to today's society as it has been to any other society throughout history, and the World Wide Web is its main repository; its vast resources have altered the very way we think and organize our lives. Yet navigating this immense world of information and services requires an ever more sophisticated set of tools and technical instruments. As use of the Web expands, and we become more dependent on its resources, we need not only to find information but also to ensure that it can be trusted. Gathering and managing large data sets is a fundamental issue in many aspects of society including individuals, industries, and governments, and will grow more problematic in the future as diverse computing entities (phone, laptops, PDA, sensors, digital cameras, etc.) will interact in distributed networks, gathering, relaying and storing vast quantities of information for later use.

The key challenge is to learn how to design systems that can adapt and optimize their topologies according to use, exploiting diverse sources of information to label data (in semantic terms, or with geographic or temporal markers) and to organize them within easily searchable networks. As the relative success of the Google search engine illustrates, basic research relevant to this field has immense potential for developing new applications and services that, quite literally, change the world.

3.1.1 Information Infrastructures: Internet as a socio-technological community

Major efforts are required to keep track of the full spectrum of digital material on the Internet, discovering who participates in creating and using them, and providing a means of devising novel and improved means of information exchange and processing, entertainment, and commerce. In the coming decades, the Internet will not only connect each of us to each other and to the world's knowledge, but much of business, consumer and scholarly activity will increasingly flow through it. The Internet will continue to be a main medium for interaction across European cultures.

Measuring the topology of and dynamics on the Internet

Internet efficiency currently suffers from an inadequate understanding of Internet topology and traffic flow. In theory, better algorithms and heuristics exist for service discovery, content distribution, and managing interactive services between groups of people, but these rely on (real-time) information about structure of the Internet. The FET funded project EVERGROW initiated an effort to map the Internet with distributed autonomous agents – the DIMES distributed measurement client – which has already created the most detailed map ever of the Internet's elements and is steadily compiling information on its rate of change. Its data is unique in the world, and focuses on monitoring the connections between people, not simply on exploring the high-speed backbone of the world's networks

DIMES is the first example of something that will become commonplace in the future – facilities that allow the network to measure itself and to use such knowledge to make decisions that are today made by standard rules. Such facilities would enable different parts of the Internet to share knowledge so that the Internet as a whole can be navigated more effectively, and manage itself gracefully, prerequisites to the network’s smooth assimilation of significant mobile and cellular information – such as voice, messages and pictures. A vision motivated by complexity science, and also inspired by biological analogy, is that all systems should devote a tiny fraction of resources to creating something equivalent to a nervous system – facilities that can learn about their local environment and make that information widely accessible throughout the network.

Keeping an Internet history

Projects now underway also aim to gather and store massive quantities of the information on the Internet to establish a history of Internet content. The European Digital Archive (EDA) stores a half-petabyte collection of a large fraction of the Internet as it has existed since 1996. By the start of 2006, that collection is expected to have doubled in size, and will be supplemented by several special collections and digitization efforts.

The Role of Complexity Science

Studying Internet topology, traffic flow and information content together feeds naturally into a complex systems perspective, as it recognizes that each influence cannot be understood adequately in isolation. Topology influences traffic, which affects content, and vice versa. The Internet is unlike any other man-made system in that it grows in absence of external control more like a living organism based on interaction between actors on the Internet. A more holistic approach is required, for example, to determine how wireless access and mobile telephony are beginning to influence the Internet. The greatest growth in the Internet's reach in the coming decade is already occurring in mobile clients on cell phones, and only a compound study of Internet topology, traffic and information can allow engineers and network operators to understand, evaluate, and better anticipate the dynamics of Mobile Internet growth.

3.1.2. Engineering Emergence in societies of information agents

Many information networks are examples of complex adaptive systems composed of agents that act autonomously and can adapt to their environment. Deployable mechanisms that produce the spontaneous emergence of cooperative and evolving communities in such agents systems are within our grasp and could produce a truly new kind of information-systems engineering, spanning the social and biological sciences and software engineering.

Emergence of socio-technological communities

Peer-to-Peer (P2P) systems are coming to dominate the Internet. As much as 35 percent of all Internet usage is now produced by just one peer-to-peer system – BitTorrent – and although most systems currently support user-level file swapping (often of an illegal nature), legitimate and successful P2P applications are now emerging. With the increasing speed of broadband domestic Internet connections, even television and media networks could become aspects of P2P technology.

As these networks illustrate, the Internet encourages the emergence of novel socio-technological communities, ranging from weblogs and distributed encyclopaedias (such as Wikipedia) to large and authoritative repositories of evolving scientific literature. Identifying “communities" – subsets of agents that are topologically highly connected and understanding their origin and their effect on function – is a crucial prerequisite to better use of the Internet. Key targets of current research range from developing automated algorithms for detecting significant communities, or for identifying how the dynamics of network growth – influenced by the possibilities of Internet-based communication – influence the characteristics of the communities that form.

Web-based resources implicitly create social networks of users, who produce, share and disseminate information in new ways, with human behaviour and technological development tightly intertwined. Understanding of such structures, which exist on top of the underlying Internet, will help to manage crucial services, facilitating, for example, the development of collaborative software, or enabling the early identification of communities of malicious actors. At the same time, such methods will be of increasing importance for consumers in guarding against unwanted privacy intrusions, and will help to realize the vision of an e-Society for all.

Efficient resource distribution through collaboration and cooperation

P2P technology also offers the potential to empower individuals and groups by redistributing computational resources dynamically on-demand from idle machines and servers to be utilized more effectively elsewhere. Many of the user machines on the "periphery" of the Internet are often idle or under-utilized. Efficient mechanisms for effectively redistributing these "latent resources" could, therefore, deliver very high returns at little cost. However, the problem of ensuring high levels of cooperation and coordination while suppressing selfish and malicious behaviour within P2P systems is holding back progress. Traditional engineering techniques cannot control massive decentralized systems. A complex system perspective emphasising means to achieve collaboration among individuals, both theoretical and practical, will be key for next-generation information systems engineering.

In this regard, recent work has drawn inspiration from the social sciences on strategies for encouraging the spontaneous evolution and maintenance of cooperative P2P "communities" or "tribes". These spontaneously emerging communities structure interactions, roles and resources in an on-going evolutionary process, and lead naturally to high levels of social cooperation and coordination. This is an example of how a strongly interdisciplinary complex systems perspective, integrating the ideas of biology and economics, the social and political sciences, and computer science, can help to improve the efficiency of key IT systems that affect all levels of the economy.

Similar difficulties in the engineering of cooperation within socio-technological communities affect the Internet at a higher level. The Internet is comprised of many Autonomous Systems (ASes), each of which is a sub-network administered by a single organization. The task of routing packets through different ASes within the Internet is currently achieved via the Border Gateway Protocol (BGP), which gives an AS the right to “advertise” routes it currently uses to neighbouring ASes. An autonomous system with many neighbours can choose routes from among many different possibilities, based on route length, perceived reliability, commercial relationships etc. Internet routing isn’t scripted by some social optimal performance, but is rather the outcome of many individual, self-interested decisions. Many other aspects of the distributed Internet arise out of similar situations – the balancing of load, for example. Understanding how such large and highly dynamical networks can be managed requires an interdisciplinary approach, adopting metaphors from economics, for example, as one might define the total network “welfare” as some global measure of the information “well being” of all autonomous systems. The long-term goal is to design network management protocols that tend naturally to improve the overall system “welfare”. One way to motivate the network autonomous entities to cooperate is through cost sharing, ensuring that the cost or benefit of some decision for an individual autonomous entity mirrors its collective social cost or benefit.

Network Security via adaptation

Every advance in technology of security – including issues of trust - naturally stimulates the co-evolution of new strategies for breaching that security. Hence, the most critical task is to engender a new mental attitude to system security among those responsible for its engineering. Complex systems, of which large software systems or distributed information networks offer prime examples, cannot be engineered to be “perfectly” secure, any more than an organism can be protected from all potential attackers. We need to begin from the belief that all defences will fail at some point. Hence, the aim of security engineering is to design for resilience and robustness, i.e. for the ability to withstand a broad spectrum of potential attacks and to fail gracefully – and hopefully in a recoverable way – to others. Inspiration can be taken from higher biological organisms, which based their security around a fully distributed and robust immune system. In this regard, recent developments suggest that self-organised distributed systems may be the best way to tackle seemingly insurmountable security problems, such as those stemming from SPAM. One approach to stopping SPAM that is currently proposed relies on the cooperative activity of millions of computers, sharing information, to act as a kind of “collaborative filter” or immune system against such unwanted messages.

3.1.3. Collaborative Information Discovery and Exchange

The information explosion poses tremendous challenges regarding the intelligent organization of data and the effective search for relevant information in business and industry (e.g., market analyses, logistic chains), society (e.g., health care), and all sciences that are more and more data-driven (e.g., gene expression data analyses and other areas of bio-informatics). The problems arise in intranets of large organizations, in federations of digital libraries, and in the largest and most amorphous of all data collections, the World Wide Web, including numerous databases that reside behind its pages. Complex systems research holds the promise to revolutionise the retrieval of useful data through emergent and collaborative approaches, which by their very nature will be better suited to face the heterogeneity and dynamics of the Web than current approaches around top-down ontologies. Progress in providing more flexible, dynamic ontologies has the potential to revolutionise our use of the Web and other information repositories.

Collaborative Web Search and semantic overlay networks

Search-engine technologies provide support for organizing and querying information. But for advanced information demands, search engines all too often require excessive manual intervention – manual classification of documents into a taxonomy for a good Web portal, or browsing through long lists of results with lots of irrelevant items. Current Web and intranet search engines fail when faced with questions of the kind we tend to ask naturally based on a context. Current technology fails because no single web site can offer a good match, or because the user can only interpret and sort through the results by using prior knowledge.

A promising approach to developing technologies that can handle natural queries is through collaborative Web search in an Internet-scale peer-to-peer (P2P) system. The idea is that every peer would have a full-fledged search engine that indexes a small portion of the Web reflecting the interests of that user. Such architecture has several advantages over a centralized server like Google. First, as the data volume and the query load per peer are much lighter, the peer's search engine can employ advanced techniques for concept-based rather than keyword-based search, leveraging background knowledge in the form of thesauri and ontologies and powerful mathematical and linguistic techniques such as spectral analysis. Second, peers can collaborate for finding better answers to difficult queries: if one peer does not have a good result locally it can contact a small number of judiciously chosen peers who are considered “knowledgeable” on the query topic. Third, a P2P system can gather data about user and community behaviour, including information on the reputation and trustworthiness of information sources.

Achieving collaboration among peers will require strategies for routing queries to other peers and for exchanging metadata, statistics, and background knowledge to form an evolving “semantic overlay network”. Understanding the dynamics and behaviour of such a network requires analyses at different levels and scales of the overall network. To be practically viable, a P2P approach needs good incentive mechanisms to limit the influence of egoistic or malicious peers. Successfully addressing this difficult issue requires combining expertise and methods from multiple scientific fields such as game theory, sociology and evolutionary biology, statistical physics, and computer science.

Emergent semantics via agreement among peers

Collaborative web search based around P2P systems should improve web searching. Collaboration can be taken one step further: encourage the establishing of mutual agreements on the interpretation of data that would permit widely dispersed sources of information, currently stored in the web under a multitude of incompatible formats, to be accessed and shared more easily. This is a very different from current approaches, which rely on imposed standards and are facing heterogeneity as a major problem.

The first principle of this idea is that agents equipped with local data representations, e.g. local ontologies, data schemes or categorizations, can build up categories for describing the data being offered for exchange on, say, a web site of potential interest. The category formation should not only be driven by the data itself but also by the user's interest. The second principle is that a communication system emerges through negotiation (rather than being a priori designed) among information agents. We face many fundamental questions before moving ahead to large-scale applications of self-organised emergent semantics. For example, we need to know how fast convergence can be reached, how robust such a system would be against in and outflow of agents, what the limitations are for emergent ontology coordination, etc. But the grand challenge is to conceive and design the mechanisms required for emergent semantics and put them into practice in large-scale experiments with human populations and realistic peer-to-peer information sources.

Among the benefits of such techniques will also be that they greatly reduce the economic costs and productivity losses associated with difficult problems of software interoperability. Semantic interoperability remains a key challenge in information system technology, and today constitutes a major fraction of IT costs. The key problem is that interpretation of data is inherently difficult to automate and requires costly human intervention. Recent progress in emergent management of peer-to-peer networks and information agent systems provides a framework to address this problem. Forming an agreement is a distributed reasoning and negotiation process in a network of agents that are able to relate their local data representations with each other. With such an approach, local knowledge can be shared through a network, the distributed agreement process allows agents to resolve ambiguities and disagreements in a scalable fashion, and by automating global agreement processes substantial human effort can be saved.

3.2. Design paradigms for artificial complex systems

A fundamental aim of today's IT research is to develop new mobile artefacts and extend the functionality of existing technological artefacts (mobile phone, WI-FI devices, etc.). Especially important in coming years will be the development of systems based on the interaction of billions of autonomously acting interconnected devices like sensors, actuators or even mobile robots.

Traditionally IT systems are designed using a careful methodology of specifying a valid region of operation for a system, followed by design, test, and deployment. But in systems where components act autonomously and where everything can have an impact on anything else, operation regions become ill defined and noisy. We need to come up with design techniques that can deal with uncertain situations where worst case performance estimates are probably more appropriate than a prediction of system behaviour in a well- defined environment and that allow a system structure to recover from a component failure or when the operating environment deviates too much from the specifications.

This is particularly true with system software, where we are beginning to deal with very large-scale systems whose behaviour can no longer be understood and tracked the way programs are debugged today. Also, despite the fact that software systems are developed in modules by different developers, there is currently no accepted science of design that acknowledges the collective character of software design process itself.

The ideas and tools necessary to tackle these and other critical engineering issues can come from the theory of complex adaptive systems. We need new ways to exploit bottom-up as well as top-down processes, to understand adaptability at all levels, to understand better the interaction between information systems and their evolving environments, and to understand how concepts like self-organisation or emergence are relevant to IT.

Defining a theory of systems-of-systems for efficient and safe artificial complex systems

The rapid development of ICT and its increasing pervasiveness in our society is encouraging the development of integrated systems. We are immersed in a complex web of interacting technologies and processes, where rapid change in technologies, practices and organizations has become the norm. Thus the aspiration to produce “capability” rather than just “equipment” is very strong and leads to a growing need of designing systems to fit with other systems within a “system-of-systems” approach. This trend occurs in civilian applications (banking industry, air-traffic system including everything from billing to airport and sky traffic management, public health warning and caring systems…), as well as in military applications (missile extended air defence, naval or air-land cooperative engagement capability…). There is a need for understanding, predicting and measuring the performance of such artificial complex systems, as well as for designing methods and tools yielding the ability to engineer efficient and safe systems.

It should be noted that systems engineering encompasses purely technical as well as cultural and social aspects: all these factors should be taken into account if we want to face the challenge ahead of us. This implies several (not necessarily independent) challenging questions: How do we measure the satisfaction of the objectives? How do we measure the quality and reliability of our artificial complex system? This necessitates a definition of what an acceptable behaviour of the system is, and of the relevant confidence level. How do we measure system risks? Indeed, integrated systems change the nature of the interactions between contributing parts and exhibit new complex behaviour due to lateral influences: unforeseen emergent properties and subsequently system failures might arise. How do we predict the overall behaviour and how do we influence and control it?

Complexity research yields potentially useful approaches and measures that have been observed for naturally occurring systems and could potentially be profitable for artificially engineered complex systems. For instance to control the system, by identifying the emergence of local behaviours, providing the way to compare vastly different kinds of behaviours, and synthesizing heuristics and schemes that effectively yield the means to obtain desired behaviours.

3.2.1. Swarm Engineering

Traditionally, the main goals in engineering, in particular industrial robotics, have been speed, precision, and cost-effectiveness. The theoretical underpinnings come from control theory, which is well-suited to optimally achieve these objectives. With the recent shift in focus to autonomous entities like mobile robots that have to function in the real world – in offices, homes, public spaces, disaster areas, the sea, outer-space – engineering is now moving towards applications that can be characterized as “collective ” or “swarm intelligence”.

Designing the individual behaviour of robots that, as a population, produce a desired collective behaviour is extremely difficult. Yet this is a crucial requirement for applications. Complex systems techniques such us evolutionary algorithms represent very promising methods for engineering emergent collective behaviour. Indeed, evolving a population of robots on the basis of their performance can sometimes discover solutions even if researchers cannot understand or model the relation between individual and group behaviours. Efforts within complex systems to develop an engineering science around this and other approaches will have an important impact on real world applications.

Case study: collective robotics for rescue operations in hazardous environments

The exploration of dangerous environments – for instance for rescue operations – presents a special challenge for research. Robots could be decisive in such operations and the potentially most rewarding strategy is to use populations of interacting and communicating robots. A population of robots can share information, exploit economies of scale, and combine their functions to achieve more sophisticated tasks. The robots must ultimately have developed features for identification, communication, and analysis—always taking advantage of cooperation when possible (see also 'Engineering Emergence in societies of information agents' in 3.1).

3.2.2. Software as a Complex System: Facing the Software Crisis

From manufacturing and communications, to transportation, health and energy, the day-to-day functioning of our society depends crucially on software systems. Today's software is among the most complex of human inventions, and tomorrow's systems will be more complex still, aiming to manage computing systems that will be everywhere, embedded in every object in the physical environment, always connected, and always active. Yet software engineers already find it exceedingly difficult to make reliable predictions of development and maintenance costs and an alarming fraction of large projects end as failures. We need to alter profoundly the way we conceive of software systems and components.

Hitherto, computer scientists have elaborated formal theories of computation, and tried to design software systems as reliable multi-component machines that will work in an efficient and predictable way. Increasingly, this will face difficulties. In the context of today's interconnected computing systems, emerging software components systems cannot be considered as self-contained or isolated, but instead interact continuously with an independent environment. These systems are effectively decentralized and dynamically fluctuating, having ill-defined boundaries as new elements enter the system or existing elements leave. Moreover, software components increasingly involve autonomous elements, and computer scientists now accept that only small portions of large software systems can be dealt with by the traditional logic-grounded engineering approach. The behaviour of large-scale software systems often appears to be less like that of a machine, and more like that of a human organization or living organism.

Because the Science of Complex Systems focuses explicitly on decentralized systems and adaptive behaviour, it provides a different mindset for a novel approach to software engineering. The complex systems hypothesis is that software should be written to provide flexible, robust, adaptable and possibly evolvable architectures, methodologies and management tools. Software components cannot be designed to exhibit specific, predictable, and deterministic behaviour on their own, in the presence of autonomous components, situated in an open and dynamic environment, the challenge is to build software so that systems as a whole behave in robust ways.

Methods in complexity science to study topological structures might lead to interesting insights and might help to improve the design process. Studies of software systems seem to indicate structural regularities - a fractal structure - relating to a highly heterogeneous distribution of connections between software modules. Interestingly, this heterogeneous structure seems largely independent of software functionality suggesting that these regularities are due to constraints operating on top of design processes. Software systems unlike other engineered systems- are designed to for high functionality and high evolvability much more like living systems. Exploring such constraints will help to illuminate the kinds of structural configurations that can be reached in the apparently huge space of possible software designs.

3.2.3. Robots as Complex Dynamical Systems: emergence of symbols

Many complex systems can in themselves be seen as implementing computational processes; in fact all physical processes implement in some way a computational process. A good example stems from recent novel ideas in robotics. Viewing robots as complex dynamical systems entirely changes the perspective, the frame of reference. Behaviour is no longer seen as something that can be programmed and controlled by a central microprocessor, but as emergent from a dynamical system constituted by the robot's morphology, the materials, and the environment. For example, while in the development of walking robots the goal previously was, in essence, to control the trajectories of the joints, it has now changed to setting the parameters of the dynamical system and then providing only minimal control input.

While the dynamical systems perspective entirely changes the design philosophy, there is an additional, surprising impact of deep theoretical significance. Symbol grounding, a notorious problem in artificial intelligence and the cognitive sciences, can now be formulated as follows: How is it possible that within a continuous dynamical system, the agent, something as discrete as symbol processing can emerge? The foundation may actually be provided by the notion of attractor states and transitions between them: attractor states are, within a completely continuous system, discretely identifiable states, and they are, so to speak, natural to the agent and non-arbitrary because they result from the system-environment interaction dynamics. We can imagine that by adding sensors to the agent, e.g. pressure sensors on the feet or angle sensors to the joints, and using copies of the motor control signals, something like a very basic body image can be extracted, that may be seen as a symbolic representation. Because we include the motor control signals, this body image captures something like the causal structure of the agent's behaviour, and can thus be used by the agent to control its behaviour.

While these considerations are preliminary and speculative, their impact not only for robotics, but for artificial intelligence and cognitive science can, in our view, hardly be overestimated. For instance, in the field of (ontogenetic) development there is the issue of self-learning. The complex systems perspective provides a take on it: Morphology and materials provide the constraints so that exploratory movements will be natural to the agent and thus generate useful sensory stimulation for learning, a principle that has been called "information self-structuring". By providing a link between physical dynamics and information processing (or neural processing), there is the potential of making inroads into understanding the origins of cognition. This interaction of physical and information processes is what an embodied perspective of intelligence is investigating. The project EC-AGENTS is studying such issues in groups of embodied agents (e.g. robots) with the idea that emergence of ontologies – in particular language – in such systems could give hints how to construct the next generation of embodied artefacts.

3.3. Complexity as a computing paradigm

The current roadmaps of the semiconductor industry closely orient themselves on the slopes of the power laws describing microelectronic advancement over the last 30 years. To keep going at the current pace for some more years will require massive investments in research and in reliable production technologies in the very-deep-submicron region.

Efforts in the 1980's into the design, construction, and programming of massively parallel computers launched or furthered a number of important research areas associated with parallel processing, including cellular automata, molecular computing, etc. But as single processor machines became rapidly more powerful in the 1990s, the movement away from serial processing lost energy. Now, however, as single processors reach a performance plateau, we are seeing a renewed interest in the clustering of processors into parallel networks. As we move towards parallel machines made up from basic building blocks (the SONY cell CPU would be an example within developed computing machines) the problem of how distributed computation can be implemented, particularly at the level of programming parallel architectures, becomes again relevant. More generally, efforts to construct machines with a huge number of components are gaining ground (see e.*g.* amorphous computing). Complex systems science can offer ways to analyse massively parallel computation, as well as new paradigms for instructing a huge number of system components to perform a given task.

3.3.1. Reliable computing in presence of noise

Most efforts in computing accept implicitly the well-established concept of user-programmable memory-processor computing architectures. Nature, in the meantime, has evolved an entirely different approach. Multi-cellular organisms grow from a single cell into complex organizations with on the order of 10^{13} cells; they develop reliably while responding and adapting to changing context and environmental conditions, and achieve computational capabilities unmatched by any artificial system. In particular, most theoretical approaches to computation deal with deterministic worlds often far from the noisy reality of our environment. But brains, ant colonies and humans deal with a changing context in which reliable decisions have to be made. How complex systems evolve to cope with such uncertainties and yet adapt and innovate is one of the greatest challenges that if resolved could pave the way for a new programming paradigm.

One promising idea starts from von Neumann's general approach to achieving reliable computation in the presence of noise and with possibly faulty units, which is always the case in nature. Von Neumann found that high levels of redundancy were required to solve the problem, given a predefined architecture, yet after 50 years, we now know that nature performs well under noisy conditions not only through redundancy (which it does, though less than we thought) but by exploiting so-called "distributed robustness" – the natural availability of alternative pathways along which computations may proceed. A principle aim, then, is to recast the problem of reliable computation into a new approach based on bio-inspired solutions, incorporating distributed robustness intrinsically in the design and also allowing the computing network itself to evolve through tinkering. Mounting evidence indicates that network architecture has a profound impact on reliable computation. Understanding how to build fault-tolerant, noise-resistant computational systems will provide enormous insight into how complex systems evolve and adapt, insight which can then be exploited in the creation of new and robust technological designs.

This chapter will address research efforts that - inspired by such natural systems - are now moving towards the next generation of computing systems that are based on novel design principles allowing us to guide a large number of entities to self-organise in order to ‘execute’ a collective task. Such computing systems will be quite different from other proposed forms of organic computing, however, such as DNA computing and membrane computing, which essentially follow the traditional digital computing paradigm, manipulating bits in the manner of Turing machine type programmable hardware devices. Systems as described above cannot be user programmed to execute reproducible sequences of instructions but will rather adapt autonomously in interaction with the environment and configure themselves by mechanisms of self-organisation or via evolution. This also raises the questions how can we move from current hardware-software co-development towards hardware-software co-operative co-evolution.

3.3.2. Evolvable Hardware: Towards plastic hardware

Biology exploits distributed architectures with inherent evolvability, based on the potential to change the relationships between the component parts of a system or even the physical structure of the system. Hardware along these lines has been realized to some extent, with the advent of programmable hardware in the form of Field Programmable Gate Arrays (FPGAs). The possibility of modifying the functionality of the systems without replacing physical devices has provided the basic substrate for enabling adaptive hardware solutions. Additionally, the capability of changing the system function without stopping its normal operation (something that is usually termed as dynamic reconfiguration) has allowed for implementing solutions whose operation can be monitored or changed remotely.

There is still a lack of hardware platforms able to implement self-adaptive autonomous systems. Even if current programmable devices can be reconfigured in real time, they still strongly depend on external design tools that perform the low-level compilation steps needed to obtain the correct configuration for a given functionality. Current solutions have the main drawback that the user himself has to adapt the behaviour of the systems. The need for an actual self-adaptive - plastic - hardware platform is of paramount importance with an ever-increasing amount of distributed computing elements. This means that the basic elements constituting the programmable hardware should be able to perform autonomously and in real time the compilation steps that currently are completed using external software tools.

This design philosophy would imply fault tolerance and self-repair of the device and would allow developing autonomous devices able to adapt autonomously their behaviour to changing environment conditions. Since evolvable hardware principles permit a system to adapt to the current operating conditions, they will allow for a smooth system recovery in case of malfunction or for a transparent system match in case of environmental fluctuations.

There are two major challenges to be tackled by complex system research that may be addressed by evolvable hardware principles. The first one refers to architectural exploration and discovery. Traditional engineering approaches to system design and integration are based on well–known rules for creating functionality from a set of predefined primitives. While this approach is valid for mid- to large-scale system integration, the ever-increasing complexity of the systems to be integrated is seriously limiting the capability of traditional design teams of determining the optimal architecture to be used for an integrated system. This is due to the fact that as the number of specifications for a system increases, the problem to be handled is easily becoming a complex multivariate optimisation task, being thus quite difficult to find the global optimal solution. The use of open-ended evolutionary principles may in this respect facilitate the search for the most efficient system architecture.

Case study: Space mission:

A very important aspect is the possibility of developing actual autonomous artefacts whose functionality does not depend of an external agent in charge of monitoring the status of the system and generating new functionality as demanded by the current environment conditions. This is of special relevance in the case of systems working in distant or poorly characterised environments, as is the case of space exploration missions. For instance, the NASA has embraced the BEES (Bio-inspired Engineering and Exploration Systems) approach for its Mars mission.

3.3.3. Artificial Cells and Systems Chemistry

A very promising avenue for achieving robust and adaptable computing is by building artificial cells (see the FET funded project PACE). An artificial cell would, like any natural cell, be a self-maintaining structure able to self-replicate and evolve. However, it would be constructed from non-living material, and should form on its own given the right conditions. Our ability to control the material and the conditions encouraging the formation of artificial cells opens the door to their programmability. Artificial cells will accumulate, process, and control information through their interactions with each other and their environment; hence, they represent novel devices for information technology. In contrast to other types of computing elements, artificial cells will be noisy, self-regulating, evolving entities, with wet, real-world embodiment that gives their computation a potentially different character – taking advantage of the valuable plasticity of complex systems based on autonomous adaptive elements.

Computing with artificial cells should be seen not as a successor of digital computing but as a type of process controlling machine for ‘chemical factories’. Artificial cells would communicate via messages expressed on their surfaces, and the possibilities for such collective message passing will enable a wide range of complex behaviours. For example, such cells will self-organize the repair of their own defects, or of those other structures in which they are embedded, thereby opening up a range of applications in medicine, manufacturing, computer systems and the environmental science. Artificial cells will be able to process information from the environment and initiate chemical responses that could be used for example to establish communications networks.

Programmable artificial cells will have many applications – for example, in manufacturing customized molecules, supra–molecular assemblies or even larger scale “tissues”. In nature, the programmed response of cells at the microscopic level enables biological tissues to change their character in response to external demands. An important goal of research into artificial cells is the development of novel materials that can autonomously and dynamically modify their micro-structure in order to react to changes in the environment as well as to specific external or internal stimuli. These materials would be very desirable for macroscopic robotics, e.g. for intelligent artificial muscles, adaptive optics, etc.

A key advantage of chemical automata is their size, as illustrated by the vast information-processing capabilities of biochemical systems (including cells). In systems composed of small molecules (akin to the networks of intermediate metabolism in cells) there is extra potential in the form of error tolerance, since the number of interacting agents can become gigantic. Design principles of such automata will invariably lead to a deeper understanding of emergent and designed complexity, going well beyond contemporary understanding of collective properties.

3.3.4. Self-organising neuronal hardware

An attempt towards understanding brain function but also towards the possible construction of novel computing hardware is the emulation of neural circuits using the physics of conventional CMOS (complementary-metal-oxide-semiconductor) devices. Inspired by the architecture of the human brain, researchers aim to build artificial “neural” systems in analogue hardware. Artificial neural systems based on the direct implementation of cell models into analogue hardware are as massively parallel as their biological archetype and do in consequence exhibit the same attribute of fault tolerance. This fact offers the fascinating perspective to use large contiguous silicon areas as a computational substrate even if individual devices (transistors) are faulty with a certain probability.

Research along these lines aims to develop radically new information processing architectures naturally suited to systems involving hundreds or millions of component devices. A research programme to develop highly complex network architectures based on faulty nano-scale devices has to be complemented by strong research efforts to study the processes of internal and interaction based self-organisation. Complex systems in neurobiology always show emergence of internal structure via self-organisation (including perceptual input from and motor response to the external world). If designed and programmed to perform along traditional lines – to carry out specific sequences of instructions – such devices will almost certainly suffer from substantial performance problems and have reduced reproducibility from device-to-device. To achieve high performance, we must instead aim to develop devices that adapt and configure themselves – for example, through the local strengthening and weakening of "synaptic" links between elements, as happens in natural neural circuits. The goal will be to develop highly complex network architectures based on faulty nano-scale devices.

3.4. Living Systems as Complex Systems

Information technologies allow us to acquire and to store extraordinary amounts of data. We are currently creating a wealth of empirical data on living systems that was simply not available only 10 years ago. For example, revolutionary new methods of data acquisition in molecular biology – micro-array technologies to study collective patterns of gene expression – have catapulted many laboratories from studying the expression of one or two genes in a month to studying tens of thousands in a single afternoon. Similar progress was possible in the neurosciences where a wealth of data on neuronal activity is now available.

The resulting radical increase in data and information causes novel challenges and has led to a 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 life sciences. More powerful means of exploiting this wealth of information could advance our understanding of living systems, as well as our ability to design effective therapeutics, to entirely new levels.

To cope with these challenges we will need to develop novel IT tools and rely on concepts from Complex Systems Science. This will also drive novel ideas for IT system design based on insight on how living systems handle and execute information ('the living as information processing') .

3.4.1. Computational Biology and Systems Biology

Even if we knew the exact nature of each biochemical component in each cell of an organism, we would still know very little about how the organism works as a system, both at the cellular and super-cellular level. Biological systems have obvious structure and organizational principles, but they have evolved to employ all available mechanisms, including the ones that span different scales and different modes of operation. Their behaviour cannot be understood either by "reading the DNA" (even though in principle all the information is there) or by studying the biological components one by one or one level at a time.

Such systems complexity problems are actually well known in computing: they are typical of information processing systems, where even small programs can be extremely subtle (and where in general predicting the behaviour of a program may be impossible). Biology is increasingly dealing with information processing mechanisms at the sub–cellular and intra–cellular level, in genomes and signalling pathways, and the same problems are becoming evident there too. The typical reaction to systems complexity in computing has been to make sure the systems are "well engineered" in the first place, so the problems do not arise as often. Unfortunately, this approach is not directly applicable to biology, where reverse engineering is more the issue.

In Biology we have non-engineered complex systems that are (in many critical ways) information processing systems. We must start from a complex systems perspective, in the broadest sense, to even appreciate the challenge; neither a mechanistic approach (build all possible models) nor a phenomenological approach (conduct all possible experiments) will work on its own. A combination of "mechanistic" modelling and "phenomenological" observations will likely lead us somewhere. However, it is now evident that even when we are able to fully characterize a model from a mechanistic point of view, the model itself can express "emergent" phenomenological behaviour that is not evident from the parts list.

In the words of Sydney Brenner "The problem of biology is not to stand aghast at the complexity but to conquer it". The benefits of understanding how biological systems work will obviously be immense, from a medical and social point of view but IT itself stands to gain from better insight into the functioning of complex biological systems.

Direct causality versus network causality

One central problem in post-genomic biomedical research is to forge new tools and improve our ability to anticipate the phenotype of a cell or organism, starting from the data generated by high-throughput biology: sequence of genomic DNA (genome), RNA (transcriptome) and protein (proteome) concentration, activity, localization, interaction. Researchers have typically tried to establish statistical correlations between a given molecular polymorphism and an individual feature. However, such correlations have no validity outside the feature under scrutiny, and do not entail any causal link. In contrast, it would be desirable that causal links of general validity be established that would allow to derive general understanding of how higher-level functioning is rooted in molecular level networks of interaction. The goal could become to re-establish a causal tree strongly rooted in the molecular level where the abundant data are found. In networks of interactions, straightforward causality is replaced by a "diluted" causality that obviously constitutes a major difficulty on the way to achieve this goal. Indeed, methods coming from statistical mechanics are for example crucial to tackle diluted causality in networks and to relate microscopic interactions to macroscopic behaviour in the network.

Impact in medicine: 'computational medicine'

A goal for the future will be to apply our understanding of the dynamics of a network of interaction to control disease. Most cures today rely on hitting a single therapeutic target, although it is reasonable to assume that often, simultaneously hitting two targets or more is required to re-adjust the whole network towards a non-pathological steady state. Disease control is thus likely to increasingly rely on simulations as means to investigate unperturbed and perturbed behaviour. The powerful techniques of molecular biology have demonstrated innumerable cancer-related aberrations in the structure and functions of the macromolecules that control the death in mammalian cells. At least 200 genes that may promote or prevent cancer have been identified in the human genome. Remarkably, despite this wealth of information, clinical oncologists and tumour biologists possess virtually no comprehensive theoretical model to serve as a framework for understanding, organizing and applying the data. This requires cumulative efforts of dissimilar sciences such as biology, medicine, physics, mathematics, computing and others. Appropriate models and simulation tools will allow to correlate genetic and epigenetic events with corresponding changes in tissue morphology as it proceeds serially from normal tissue to a small tumour, for example, and then to a larger tumour and eventually invasive cancer. A complex systems approach will lead to insights into new systems-oriented therapies.

3.4.2. Modelling the Brain

Increasingly we know how single neurons work, including details about the varieties of their dynamics and cell geometries, and functions of myriad ionic currents and neuro-modulators. Yet we still know relatively little about the coherent behaviour of collections of hundreds of billions of such neurons, or how brain function is associated with the activation of correlated activity among distinct populations of connected neurons. In dealing with the profound complexity of the brain, careful experimental analysis and theory building are essential. However, analytic approaches conducted separately at each level generally fail to provide a full picture of neural patterns in a behaving organism. There are obvious limits on the number of levels simultaneously observable during any given experiment, and despite the power of mathematical and computational approaches, they have not yet provided a multilevel picture of the non-linear relationships between brain and behavioural events.

A promising development, however, is the ability to perform large-scale neural simulations in a relatively fast time due to development of neural computations on a cluster computer such as at Livermore, which has 150,000 nodes. A new initiative in Switzerland, between EPFL and IBM, is now tackling the problem of building a simulation of a mini-column of 10,000 nerve cells on a cluster of 10,000 nodes. In this, and a variety of other, ways the theories being proposed can be increasingly realistically simulated to test principles involved in one or the other theoretical approach. Such simulations must be an integral part of any approach, so as to properly test any proposed complex system framework by comparing to activity and behavioural response results in the real brain.

The challenge presented to the complex systems approach by the global brain is thus enormous, presenting problems of creating a mathematical framework strong enough to help decipher the various networks of activity in the brain, as well as providing an understanding of learning. At an even higher level is the problem of building a framework to help comprehend how cognitive processes are supported by brain activity. Such a framework will open novel perspectives on how to address cognitive capacities in artificial systems, in particular when developed in close synergy with a complex systems perspective on perception and action. It would help in allowing development of autonomous control systems for robots, as well as for software agents able to perform a range of tasks in which some form of reasoning and value-judgment is required; industry and the service sector could use such systems in many areas.

3.5. Complexity in Business, the Environment and Society

Systems – businesses, societies - involving people, technologies – in particular IT - and processes often function well despite imperfections. Just as often, however, they turn up surprises – business organizations fail to respond to clear opportunities, communities lack the coordinating abilities required to manage resources effectively, or technologies, in practice, create more problems than they solve. From stock market crashes to ecological disasters, our long-standing inability to understand the dynamics of the societal processes has immense costs. In the social sciences, most pressing problems involve the nontrivial interactions of many individuals, often facilitated by opportunities of novel IT infrastructures. Such systems, as a rule, throw up surprising emergent phenomena that often pose problems – from SPAM to market failures or excessive volatility or corruption leading to systemic dysfunction.

Systems of all kinds – businesses, societies, and the ecosystem - pose challenges to our understanding of system functioning that need novel approaches. Every level of modern life – personal, organisational, economic, political - presents difficulties of management under an increasingly complex, alienated, and threatening set of conditions. The problem is that current structures of governance are not designed to address either the opportunities or threats inherent in ‘global complex emergent systems’, i.e. human institutions.

Current complexity science recognises that business and society are complex adaptive systems but lacks the means to apply it other than by analogy. Yet, it seems now clear that advances in IT – in particular the capacities to simulate in great detail entire classes of such systems - brings to these problems a set of tools specifically suited to achieving an understanding and skills for practical management well beyond anything imagined in the past. This will open new realms for using IT in various areas that were until now considered part of the non-quantitative sciences and will help in our understanding of the relation between individual and collective behaviour in business and society.

The required solutions do not exist yet and requires research combining various expertises ranging from computing over economics and social sciences to mathematics. Bringing a collaboration of sociological and the technological factors to work together could bring enormous opportunities. Simulations could be used to better design, for instance, urban environments, to study evolution and impact of laws and regulations or motivational interventions etc. The long-term potential to tightly couple real complex systems and their models will open a range of applications for ubiquitous and ambient technologies with a direct impact on our everyday socio-economical environment. The same is even more urgent concerning environmental challenges, which involve an even more intricate fabric of technologies, combining nature with human interventions.

At this stage, it seems, however, that the practice of, for instance, business systems is still well ahead of the science of business systems. Therefore we have to invest into research in this area. A vision is a new type computer system - eliciting local information based on models and meta-models and making suggestions for organisational or political measures based on micro simulations posing formidable research challenges.

Case study: Massive Multi player online role playing games (MMORPG)

In MMORPG the line between real economy/society and games becomes to some extent blurred. In the design of MMORPG, the designers establish the basic operations and rules (for characters and game operation rules etc) that cannot predict/control the actions of thousands of players and their interactions with each other. It is similar to an economic system (including individual incentives of the human agents): although the operations at micro scale are clear the macroscopic structure that arises can only be observed.

3.5.1. Computational Social Sciences and Economics

The effectiveness of complex organisations (e.g. corporations, government agencies, health systems, and other administrations) is crucial in advancing the wealth of Europe and so is better coordination of the workings of social systems in general. We are dealing with large-scale, dynamic systems that engage hundreds of millions of people, yet their effective management is an extremely challenging task. Most current social science research on the management and regulation of complex organisations depends on observing existing organisations, yet this approach has serious limitations: one can only observe those organisations that happen to exist; and it is very hard to draw valid conclusions that can be extended to other organisations.

We are now at a stage, however, where it is feasible to study the emergence of a complex organisation ‘in silico’, via large–scale simulations, and to experiment with factors that might affect its growth and stability. The challenge is to provide grounded and validated models that would allow societies to better understand consequences of *e.g*. deployment of technology, global climate change or business organisations to anticipate the effects of restructuring and to provide advice on structures that would optimise the effectiveness of organisations. Such simulations have the potential to bring all pertinent factors together in a setting where researchers and decision-makers can test alternative scenarios and, thereby, devise strategies on the basis of a legitimate understanding of the relationship between cause and effect. A number of practical demonstrations of this approach have already proven that major corporations can save hundreds of millions by avoiding costly mistakes (making “virtual” mistakes instead) or by discovering unexpected solutions to problems through virtual exploration. Other applications could include advanced economic analysis of deregulated electrical power systems and markets, the large-scale economic and technical analysis of hybrid fixed and mobile telecommunication systems, or the detailed modelling of epidemiology of contagious diseases.

As we learn more about the behaviour of large-scale systems, the value of precise predictions, or even the possibility of making such predictions, is increasingly called into question. More plausible and advisable is the aim of managing such systems in a less ambitious way, using analytical tools and representations to identify the kinds of small-scale interventions that can guide the system toward a more desirable state. Making adequate preparations today is a serious and very difficult problem, especially with today’s interconnected populations, infrastructures and world economy. In the future, society will use large-scale social simulations to better understand the link between individual motivation and collective behaviour in helping for instance communities prepare for disasters, either natural or otherwise.

Case study: transport networks in economy

Modern society is underpinned by a complex physical infrastructure that moves people and goods from place to place. Examples include logistics (e.g. Lorries carrying goods to arrive ‘just-in-time’ while respecting environmental constraints and traffic disruptions), utility supplies), and personal travel (with interactions between modes of transport operating on different geographical scales). This infrastructure grows increasingly more “intelligent,” making it ever more difficult to ensure robust and efficient operations along predictable lines. For instance a serious motorway accident may not only result in a blockage of the motorway, but trigger a dramatic rise in mobile phone traffic locally, disrupting emergency services. Engineering workable solutions to these problems demands not only technological insight, but an adequate understanding of how people make decisions when faced with uncertainty and means to simulate models of systems where all these aspects are accurately modelled. For example the TRANSIMS system generates synthetic populations of millions of agents with characteristics modelled following demographic data and simulates the emergent dynamics of their use of the transportation network. Altogether, the combination of new technologies with novel control approaches has the potential to change the operation of today’s traffic and production systems in a revolutionary way.

Case study: Simulation of financial markets:

Theoretical understanding of the link between individual and collective behaviour – along with the possibility of exploring systems with powerful simulations – will lead to profound new insights in various areas of global concern, such as the stability of international financial markets and governments. The world of finance can be regarded as a network composed of a huge number of strongly interacting individual components – banks, corporations, nations, etc. – with massive flows of assets, control, and information between them. Natural fluctuations in this system sporadically cause severe social and political problems. Traditional attitudes toward risk management have not adequately taken into account risks associated with extreme events. Large-scale agent-based simulations are now routinely used to shed light on these characteristics and on how individual decisions can lea to aggregate behaviour of the markets.

3.5.2. Business “Ecosystems”

Over the last decade or two, we have witnessed a gradual transformation in the structure and operation of business enterprises due to innovations in process management, the Internet, and increasing dependency on the business ecosystem for generating value for consumers. Central to the modern business enterprise is the role of IT infrastructure. People, business processes, and IT tools form one ‘IT fabric’ that provides communication, collaboration and coordination facilities. Businesses characterised by such IT fabrics are, in themselves, large-scale, dynamic phenomena, as companies are immersed into markets and exposed to regulatory forces, financial objectives and competitive pressures. Enterprises are therefore increasingly dependent on large ‘business ecosystems’ consisting of a plethora of specialized service providers, partners, suppliers and others. This dependency is driving enterprises to invest more in understanding and managing their interactions in these ecosystems in which they are embedded in order to get better visibility into the complex dynamics of value-chain processes, handle a growing volume of information, reduce costs and streamline operational processes. This is leading towards an erosion of the boundaries between individual enterprises and their environment, such as we currently see in the biotechnology industry, where networked clusters of firms alternately, or even simultaneously, both collaborate and compete with their closest ‘relatives’, rapidly changing position and role in highly dynamic networks of knowledge and capital in a fashion that reminds one of the heydays of silicon valley. This would certainly be a potentially more flexible alternative to the currently dominating landscape of super-large multinationals.

On the engineering side, we observe that designing the architecture of the large-scale systems requires creation of the visionary blueprints which will take into account changes on the longer time-scale and fit new requirements and changing circumstances. Such engineering should provide dependability, usability and reliability features through an evolving technology and cycles of renewal and adaptation. This will allow such systems, much as their natural analogues, to grow, evolve and adapt (often in real-time) to changing environments. To this effect, we are for instance beginning to see investment in advanced monitoring technologies such as industrial sensors, which are steadily being deployed at various physical areas of the “global” value chains in order to provide information in real-time about business operations – inventory levels, production operations, real-time logistics and interactions between multiple levels of decision-making.

Despite the absence of scientific understanding, these large-scale, dynamic systems are here, and we need to deal with them. Facing up to these challenges will require insights and inspiration from complexity science, especially by exploiting analogies with natural systems such as ecosystems. Understanding (and guiding) the entire system, guessing behavioural dynamics under an endless flow of events and pressure of data streams poses several grand challenges. A detailed understanding of the effects of local decisions and material changes on the macro-dynamics of a system will, thanks to ubiquitous communication and robotic technologies, allow biasing its evolution in desired directions.

The emerging information and communication technologies will allow us to utilize advances in the Science of Complex Systems – especially in the context of supply chain management, network theory, distributed adaptive systems and collective intelligence – to realise dramatic improvements in future business systems. Moreover, as the mentioned IT fabric also involves people, the need to get a better grasp of human organization has become pressing. In addition to the above engineering efforts we need therefore a new approach combining various disciplines from the social and human sciences with engineering: anthropology, game theory and behavioural economics will enhance IT to make for instance business processes run smoother and make economy more resilient.

A number of fundamental questions require intensive study. For example, what are the similarities and dissimilarities between businesses and ecosystems? What models are needed to monitor and make decisions on millions of operations being done in business value ecosystems and networks? Which empirical studies are needed based upon real-time sensing to model business processes in the value chains? Or the ongoing dynamics of our relations with the natural environment? And, can models of "self-similarity", a ubiquitous feature of complex systems in the natural world, enable large, medium and small enterprises in business ecosystems to thrive and operate efficiently by sharing critical processes and operations and avoiding duplication of activities within the value chain?

Moreover, complex systems will point to new principles of organisation; for instance self-organization principles will enable to make better use of scarce resources, and will be perfectly suited to utilize the potentials of novel detector and communication technologies in the upcoming age of ubiquitous computing, while the presently applied centralized and hierarchical control approaches will be overwhelmed by the flood of local information available in the future.

3.5.3. Understanding Innovation

Governments pursue economic development primarily through the innovation of new technologies, goods and services. It is imperative that strategies for achieving such innovation be based on a deep understanding of the processes whereby innovations happen and become embedded in economic and social practices. These processes include the cognitive processes whereby people generate new ideas about possible artefacts and the technical and organizational processes that produce such artefacts, as well as the social processes through which these artefacts come to be valued and exchanged in the marketplace. To formulate effective strategies to encourage innovation processes, it would certainly be desirable to model them, in order to improve understanding of their dynamics, to identify likely candidates for control levers, and to evaluate the effects of alternative policies. But successful innovations bring in their wake large-scale transformations in the structure of the relationships between agents and between agents and artefacts, transformations that bring into being new kinds of entities, new kinds of relationships, and new kinds of activities around which agent and agent-artefact relationships are structures.

But on the other side of the coin, these profound changes that are, as it were, unintended (or at least unforeseen) consequences of innovations, can threaten the stability of social systems. In the past, generally, there was enough time to integrate such changes into the fabric of society as they occurred. More recently, however, the predisposition of our societies to innovate more and more rapidly, leaves less and less time for that integration. In a way, we seem to be out-innovating ourselves. What, for example, will be the consequences of the combined NBICS innovation cascade that is about to hit us, and on which our institutions have no grip whatsoever? This would seem potentially dangerous for the stability of global society, because it will engender a very small elite that has the know-how and the information to control ever more aspects of our social and environmental dynamics, and because the remainder of society can no longer even intuitively form itself an image of what is actually going on.

In those circumstances, it would seem of the utmost urgency that we gain sufficient understanding of the innovative process itself to be able to anticipate some of its outcomes, and at least avoid the most dramatic surprises.

Complex systems theory provides a set of concepts and tools that can be mobilized to address these important issues. In fact, ideas of multi-level hierarchies of heterogeneous interacting entities, engaging in processes with very different spatio-temporal scales are necessary merely to describe the organization of agent-artefact space and the transformations in this structure, which generate new attributions of artefact functionality.

3.5.4. The Environment

Planet Earth is arguably one of the larger complex systems that we are struggling to understand and exploit in a sustainable manner. The co-evolution between information-processing (i.e. active) living things and the force-driven (i.e. passive) environment is growing ever tighter with time. Our evolution as a technological species marks the latest in a series of major transitions. With our technology we are profoundly altering the planet, and we have begun to monitor and understand our effects. International agreements such as the Kyoto Protocol mark a first attempt to alter our actions accordingly. As we look ahead, the pressing concern for the human species is to find and follow a safe, sustainable path into the future. This should minimize detrimental changes (to us and fellow species) in the Earth system whilst ensuring an acceptable quality of life for all of our growing population.

Thus posed, we have a complex, adaptive control problem for an evolving cybernetic system. The agents of change (us) are entwined in the system and have to operate with limited knowledge, including an awareness of the multi-scale nature of the system both in space and time, and the delays between cause and effect inherent to the system. In this, they are helped by their own self-reflexivity, i.e. the fact that they can change their own behaviour as a result of their observation of the system's dynamics. But they are handicapped by the fact that for this self-reflexivity to actively contribute to change, they need to know how to manage and control the societal dynamics involved, and transform individual learning and decision-making into collective action. That part of the process in turn requires a fundamental review of our institutions and modes of governance.

A key element of the solution will be the design and implementation of appropriate economic incentives, technologies, policy instruments, institutions, and approaches to governance to effect the transition to sustainability. In a "technophile" vision of the future, information and communication networks and technology may become the 'central nervous system' of a planetary, adaptive response system that steers human activities to be better in tune with the automatic self-organisation of the Earth system.

One fundamental stumbling block in trying to represent and tackle the problem is a lack of models that capture the nested hierarchy of subsystems within the Earth system. To this end, we require multi-scale simulations that encapsulate a stunning range of relevant time and space scales. A theoretical framework must also be built that weaves together relevant generalities from complex systems research with valid threads from existing attempts to provide a theory of the evolution and functioning of the Earth system. For credibility the theory must of course be consistent with our increasingly in-depth, historical, biological, chemical, physical and geological knowledge of the Earth system.

The challenge is thus to make tools that citizens can understand, without extensive training, and use in comparing and evaluating environmental policy options. Some projects of this kind have been completed, in different parts of the world, to make models that integrate geophysical, ecological, and human land-use data available through a GIS (Geographical Information System) for local citizens to use to appraise environmental options (e.g. whether to impose development boundaries preventing further building around urban areas; whether to encourage fishing or arable in river basins). The vision is to develop exemplars of such integrated environmental models and to provide a computational infrastructure (a user interface, a deliberation forum, a voting interface etc.) that would encourage citizens to become involved and permit them to make their views known.

But that encouragement will only lead to productive changes when there is an institutional structure in place that can channel this involvement in constructive ways. That in turn presumes that we are able to resolve some of the questions raised in the following section

3.5.5. Society

The rapid elimination of traditional boundaries between different societies, through the emergence of new modes of transport, increasing flows of trade, and electronic means of communication and information processing, is transforming our societies in ways that cannot yet be fathomed. Add to this the increase in the world's population, further fuelled by the extension of life expectancy in ever larger parts of the world, and the increasing contrasts between educated and non-educated, between rich and poor. And finally throw in the mix the increasing competition for resources that all this will engender, as well as the impact of their exploitation on the Earth's ecosystem, and one has all the ingredients for a fairly volatile societal dynamic in the coming century. Our institutions, including democracy, were invented in a very different kind of world, which had a middle class that was educated and numerous enough to create a link between the richest and the poorest in society. Will these institutions be sufficiently robust or resilient to deal with the changes on the horizon? Maybe they will, and maybe they won't! The current trend towards closure of the western world is not an encouraging sign.

How could Complex Systems Social Science contribute to an easing of the emergent tensions? Primarily by achieving a better understanding of the information flows through society, how they affect decision-making and how the dynamics of the networks that carry these flows spread the information (or the reverse), empowering certain groups while disenfranchising others, and in general creating sub-networks that are to varying extents separate from the overall system. The most stable social systems are the ones that are the most homogeneous from an information distribution perspective. Democracy and other bottom-up governance systems are a good example of that fact, as all members in such systems share imperfect knowledge.

How do the Internet and other modern communication systems change the balance between 'top-down' and 'bottom up' information processing? How could one use these same tools to achieve a more synergistic approach to the problems we are facing? How to structure the communication networks for optimal equality of access to information? And, most importantly, what do we need to do to keep the system stable? Many of the approaches referred to above may contribute to improving our knowledge of this domain, and the social sciences are beginning to deal with the issues concerned. But we need to make sure that the investment required of the European Union to develop Complex Systems Science as an important sector of economic development does not only benefit the economy. We do not only need several thousand Complex Systems scientists in the coming years; sometime later, we will need to educate the European public in the uses and abuses of all the new tools that are emerging, and to develop the structures to do so!

3.6. Grand Challenges and Thematic Area for FP7

The 'Grand Challenges' are one of the most important parts of this Living Roadmap because they establish specific, tangible targets for complex systems research. For example, Figure 2 shows a number of candidate Grand Challenges beginning with "Managing Information and Material Flows in Complex Systems". From specific Grand Challenges like this it is possible to abstract more general Strategic Areas for the direction of funding in FP7.

3.6.1 Processes for Eliciting and Discussing Grand Challenges from the CS Community

The Grand Challenges come from the complex systems community and represent a reasonable consensus within the Roadmap on the *direction* that complex systems research should take, and by implication the direction of policy on funding that research. Like all journeys, future directions become clearer the closer they get. This is why we must have a *living* roadmap that can be updated as Complex Systems Science advances. This dynamic is supported by the ONCE-CS portal (http://www.once-cs.net) which allows all members of the community to participate in an on-going debate on the Grand Challenges and to suggest new Grand Challenges of their own.

The list of abbreviated challenges in Figure 2 below presents the most popular Grand Challenges voted by the complex systems community, using the ONCE-CS portal: Readers are urged to participate in ranking these challenges or contributing to them.

Position	Title	Votes	Avg.
1	Bridging the gap between Evolutionary Computation and Biology	42	3.90
2	Collective Robotics and Collective Behaviours	33	3.79
3	The Brain as a Complex System	21	3.76
4	Collective Evaluation and Quality Driven Production Networks	56	3.75
5	Constraint Satisfaction, Statistical Physics and Message-passing Algorithms in Information Theory and Computational Biology	11	3.73
6	Emergent Semantics	18	3.72
7	Herding behaviour	17	3.71
8	Biological Systems as a Complex System	23	3.70
9	Managing Information and Material Flows in Complex Networks	27	3.70
10	Peer-to-Peer Web Search	13	3.69
11	Towards a personalized medecine	3	3.67
12	Evolutionary Engineering of Complex Software Systems	6	3.67
13	The Physics of Computation and Artificial Intelligence	29	3.66
14	Logistics on the Nano-Scale: Integration of Information-, Bio- and Nanotechnology	8	3.62
15	Noisy computing	5	3.60
16	Toward a Paradigm Change in Computer Science and Software Engineering	7	3.57
17	Information Technology Potential of Programmable Artificial Cells	7	3.57
18	Information access as a Complex Adaptive System	2	3.50
19	Exploiting New Processor Architectures and computational parallelism for complex systems	4	3.50
20	Ontogenetic programming	10	3.50
21	Complex Organisations: structure and dynamics	10	3.40
22	Earth system analysis and management	6	3.33
23	Optimization of Application Integration	3	3.33
24	Towards a science of complex systems	12	3.25
25	Potentials of Upcoming Sensor and IC Technologies for Flexible Traffic Operation and Production in Complex Networked Environments	4	3.25
26	Evolving Cooperative Communities in Peer-to-Peer Systems	4	3.25
27	Self-adaptive Hardware Enabling Physical Complex Systems	4	3.25
28	An Internet that measures and manages itself	5	3.20
29	Information Overload	5	3.20
30	The financial world as a complex system - regulation and global stability	5	3.20

Figure 2. The ONCE-CS Grand Challenges
(30 first Grand Challenges according to the evaluation of the community at March 22 2006)

3.6.2 The Living Thematic Areas

Any member of the community can suggest a Grand Challenge, and this usually reflects their own specialism and interests. Thus, a number of Grand Challenges are very similar, and it is useful to synthesise them into *Thematic Areas* for complex systems research. In fact, this process was already initiated in the Orientation Paper, and the five previous sections represent this synthesis.

The bottom-up process sketched in the previous subsection is therefore a way for the complex systems community to give collective expression of the problems that individuals believe to be important in our new science. The Wiki mechanism of the ONCE-CS portal gives everyone the possibility of joining in a discussion of any of the Grand Challenges, and gives everyone the possibility of expressing their view on the importance of the individual grand challenges. The view that emerges gives a synthesis of the views of the whole community on particular challenges, from which higher-level challenges can be abstracted. These higher-level challenges are a snapshot of the community's view of the important areas for strategic research funding in FP7.

Other mechanisms for identifying strategic research areas include the recent ONCE-CS sponsored meetings in Brussels (Science of Services, 29-30 January 2006) and Rome (Presentation and discussion at the FET IP evaluations, 7 March 2007). Such face-to-face meetings allow the community to synthesise its views, prior to discussion through the ONCE-CS portal.

The following thematic areas have been identified from all the consultations:

- Thematic Area 1 : Information systems as complex systems
- Thematic Area 2 : Design of complex adaptive artificial systems
- Thematic Area 3 : Towards petacomputing for CS data management and modelling
- Thematic Area 4: Education, and Applications in Private and Public Sectors

This first version of the living roadmap includes *all* the grand challenges proposed grand by members of the community. They are listed (somewhat arbitrarily) by thematic area.

THEMATIC AREA 1: Information systems as complex systems

Grand Challenges

Information Infrastructures: Internet as a socio-technological community
Engineering Emergence in societies of information agents
Collaborative Information: Discovery and Exchange
A Science of Services and Business Ecosystem
Understanding Innovation
Information access as a Complex Adaptive System
Information Overload
P2P Data Management
Network Security as a Complex Adaptive System
Impact of CS-based methods on challenges to ICT
Knowledge-level management of complex IT systems
The Metaloger1: a toolset to support complex emergent systems
An Internet that measures and manages itself
Production in Complex Networked Environments
Evolving Cooperative Communities in Peer-to-Peer Systems
Managing Information and Material Flows in Complex Networks
Prospective Practice for the Citizen, based on Complex Systems Science

Collective Evaluation and Quality Driven Production Networks

THEMATIC AREA 2: Design paradigms for complex adaptive artificial systems

Grand Challenges

Artificial Cells and System Chemistry
Adaptive Computation & Evolvable Hardware
Collective Robotics and Collective Behaviours,
Emergent Semantics
Ontogenetic programming
Software as a Complex System: Facing the Software Crisis
Embracing Complexity in Design
Bridging the gap between Evolutionary Computation and Biology
Peer-to-Peer Web Search
Exploiting New Processor Architectures & computational parallelism for complex systems
Potentials of Upcoming Sensor and IC Technologies for Flexible Traffic Operation and
The Physics of Computation and Artificial Intelligence
Noisy computing
Bayesian Computer
Information Technology Potential of Programmable Artificial Cells
Evolutionary Engineering of Complex Software Systems
Logistics on the Nano-Scale: Integration of Information-, Bio- and Nanotechnology
Herding behaviour
Intelligent infrastructures
Using networks of unreliable components for information processing – From CMOS based neural microcircuits to nanoelectronics
Constraint Satisfaction, Statistical Physics & Message-passing Algorithms in Information
Optimization of Application Integration
Self-adaptive Hardware Enabling Physical Complex Systems
Toward a Paradigm Change in Computer Science and Software Engineering
In a Search of Technology Seeds from CS Research

THEMATIC AREA 3: Towards peta-scale computing for CS data management and modelling

Grand Challenges

e-Science: High Throughput Protocols, Reconstruction and Simulation
From Components Biochemistry to Systems Biology
Personalized Health: towards a personalized medicine
The Brain as a Complex System
Computational Social Sciences and Economics
Computational Ecology
Towards a science of complex systems
Earth system analysis and management
Biological Systems as a Complex System
Theory and Computational Biology
Challenges for detection of neuronal currents by MRI
Complex Systems Control and Emergence
Complex Organisations: structure and dynamics
Simulation of innovation processes
The financial world as a complex system - regulation and global stability

THEMATIC AREA 4: Education

Grand Challenges

European Doctoral Education in Complex Systems

As can been the list lacks coherence, with some proposals very similar to each other, and some representing very specific minority interests. Using these thematic areas, this first list of grand challenges can be reorganized, some can be renamed and some can be added. To review the Grand Challenges, suggest your own Grand Challenges, and make comments please go to:

http://complexsystems.lri.fr/Portal/tiki-view_tracker.php?trackerId=2

In formulating and reformulating these lists it should be realised that they will form the basis of calls for FET-ICT funding under FP7. It is highly desirable that the list be coherent and particular grand challenges expressed in an attractive and concise way, so that their importance is clear to both scientists and administrators. Even if the formulation of a call is mainly by thematic areas, their lists of grand challenges gives the examples of what is expected.

The *process* for synthesising these Grand Challenges will involve the following steps:

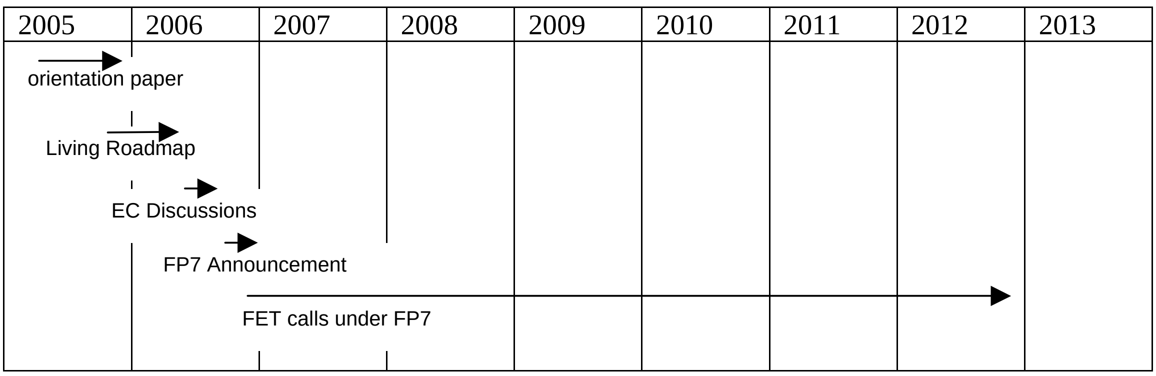
(1) A small group will take responsibility for each Thematic Area

(2) That group will suggest a synthesis of the Thematic Area, and this will be posted on the Portal

(3) After noting the response of the community, the editors of the Living Roadmap will change it to reflect the synthesis and discussion about it.

(4) The editors of the Living Roadmap will present this synthesis as Appendix 9 to the roadmap. This will be *the* major document sued for discussing funding of complex systems inside the European Commission.

3.6.3 The schedule for the transition from roadmap to funding policy



The CS community should note that the time to respond to the Living Roadmap is not very limited because the Commission will begin to formulate policy for FP7 during the summer of 2006.

4. Capacity for research in complex systems in Europe

The previous sections have explained the nature of the new Science of Complex Systems and shown its strategic importance across European research and to a wide spectrum of civil and commercial applications that are central to its economic success. In the context of this opportunity, Europe has to plan to increase significantly its capacity to undertake and exploit Complex Systems Science.

In December 2003 EXYSTENCE registrations were UK (88), Italy (49), France (37), Germany (29), Spain (18), Belgium (12), Netherlands (11), Portugal (11), Sweden (10), Switzerland (10), Finland (11), Greece (7), Hungary (7), Austria (6), Denmark (6), Poland (6), Ireland (5), Luxembourg (1), Czech Rep (1), Slovenia (1), Cyprus (0), Estonia (0), Latvia (0), Lithuania (0), Malta (0), Slovakia (0), Bulgaria (0), Romania (0), and Turkey (0). Since then the number of active scientists and centres has increased considerably, with recognised centres of excellence in many European Countries.

The longest existing centre of excellence in Complex Systems Science in Europe is the Solvay Institute in Brussels, founded at the beginning of the last century for quantum physics, where Ilya Prigogine did much of his work. A 'living list' of centres involved in Complex Systems Science is given in Annex C, to be updated continuously as more centres join the emerging European network.

Some European nations are already aware of the strategic need to increase capacity in complex research. For example, the Engineering and Physical Research Council of the United Kingdom has programme of investment in Complexity Science that includes a € 20 million portfolio of research projects on 'Novel computing: coping with complexity', € 1 million on 'Taught courses in complexity science and complex systems', and € 13 million for the establishment of two centres for 'capacity building in complex systems'[4].

As another example, a major initiative is underway in France to create two complex systems institutes, one in Paris and one in Lyon. This amounts to an investment in complex systems capacity of approximately € 1.5 million per year. Again the research base is seen as lacking in capacity. The Collegium Budapest is another example of an Institute receiving major national funding for Complex Systems science, while the Institute for Scientific Interchange (ISI) in Torino is receiving major support from Regione Piedmonte and the Laplace Foundation[5].

The situation is similar or worse in most other European countries. Europe has many excellent scientists working in areas related to complex systems, but overall the picture is one of fragmentation and inadequate capacity to deliver the science that will be essential to Europe's economic and social wellbeing between 2007 and 2013.

The general picture in Europe of a lack of capacity in research infrastructure, lack of scientific capacity to support SMEs, the need to develop capacity for Regions of Knowledge and to develop the research potential of convergent regions, the need to develop capacity to exploit Complex Systems science in society, and the need to increase capacity for international cooperation.

[4] http://www.epsrc.ac.uk/ResearchFunding/Programmes/Cross-EPSRCActivities/ComplexityScience/EPSRCsPlans.htm
[5] http://www.progettolagrange.it/en/il_progetto/index.html

4.1 Research infrastructures

4.1.1 Creating Open Observatories.

There is a need for open observatories for all kinds of complex systems (at the European level), to collect and share data. Complex systems are all different and seen in multidisciplinary ways. There is a strong need to organise data in homogeneous ways from these different point of views. The data have to be open to large classes of users, and, in general to everybody who is interested in, and capable of, using them (*cf.* the debate about genomes).

4.1.2 Archiving Massive Data Sets

Across a wide spectrum of applications in the natural sciences as well as the earth and life sciences and the social sciences, Complex Systems Science involves the collection and archiving of huge data sets. For example, certain biological projects currently generate terabytes of image data each day they sample, as do applications in metropolitan transportation planning. The indications are that in future such projects will generate terabytes of data per day. Even allowing that storage technology will continue on its current price-performance trajectory, data management and retrieval threatens to overwhelm individual projects. There is need for one or more centralised European data repositories 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.

4.1.3 High-throughput Internet Infrastructure

Complex Systems Research is characterised by massive data sets, and the need to synthesise data from many incomplete and inconsistent multilevel sources into useful information. European scientists will need access the archives discussed above and have massive data sets downloaded or distributed across networked processors in real time. The volumes of data involved mean that European researchers must be supported by high capacity Internet links.

<u>Grid and cluster computing for the reconstruction and simulation of multilevel dynamics</u>

Complex systems research will require massive computing power for data processing, reconstruction, modelling and simulation. This will require new generations of multiprocessor clusters to replace those currently in use, and support for new technologies such as grid computing.

<u>Creating open challenges for reconstructing data.</u>

Open challenges with clear rules can be organised for *reconstructing* the data of all kinds of complex systems through common simulation platforms. The rules of the reconstruction protocol concern the data (or more generally the stylised facts extracted from data), and the definition of the quality of the result. The inductive methods are unconstrained, but the use of tools associated with methods can benefit a lot from common simulation platforms.

4.2 Research for the benefit of SMEs

Complex systems research will create new scientific knowledge that can be applied by SMEs in commercial applications. To do this they will need access to the same infrastructure described in the previous paragraphs, and they can use this infrastructure for applications-oriented research.

The capacity for SMEs and complex systems researchers to interact needs to be increased in Europe. It is much less than, for example, in Japan and the USA.

SMEs will increasingly need people qualified in Complex Systems Science, and capacity here needs strengthening, as discussed in Section 5.

4.3 Regions of knowledge

A number of research-driven clusters associated with universities, research centres, enterprises and regional authorities are beginning to emerge in Europe. These have been supported by FET-funded coordination projects such as EXYSTENCE (complEX sYSTEms Network of exCEllence), and ONCE-CS (Open Network of Centres of Excellence in Complex Systems). Both these projects show that European scientists want to work within collectively chosen, relevant, regions of knowledge and that support from the EC can have a significant impact.

Complex systems science is particularly suited to the formation of scientific research clusters because of its inherently interdisciplinary nature and its method of reconstructing the dynamics of complex systems by making new protocols for data collection and analysis. In practice, this has led to the formation of networked teams of researchers of very high competence, able to conduct research at the highest levels at the scientific frontiers.

The regional centres of knowledge forming at present are mostly in countries such as France, Italy, Germany and the UK, with less progress in other European States. Some of the new member countries such as Hungary and Poland have outstanding institutions able to act as the nucleus of regional centres of knowledge, but lack the resources to develop their potential. It is essential that each European country develops several regional centres of knowledge, in order to develop the potential of these regions consistent with European regional policy.

The regional centres of knowledge within European countries are themselves being networked both autonomously and in response to actions such as EXYSTENCE and ONCE-CS. A new European Complex Systems Society has been founded that has initiated a successful annual European Conference on Complex Systems. Currently there is an effort to create an ERAnet and ERAnet+ to coordinate national level support for Complex Systems Science.

Europe's need to develop regional centres of knowledge in complex systems is limited by the available number of qualified people. To address this, an ambitious and coordinated programme of doctoral training is required across Europe (*c.f.* Section 5).

4.4 Research Potential of Convergence Regions

The EU recognises knowledge as a major engine of economic growth. The Commission estimates that R&D investment is responsible for 25% to 50% of economic growth in Europe, the Structural Funds aim to promote economic convergence between the EU's more and its less prosperous regions.

Both the EXYSTENCE and ONCE-CS coordination projects created new connections with the less prosperous regions of Europe, but much remains to be done in terms of trans-national secondments of research staff in the convergence regions; acquisition and development of research equipment in selected centres; and organisation of workshops and conferences to facilitate knowledge transfer.

There is strong synergy between the research needs of the European complex systems community and the EU's regional policy. In particular there are significant opportunities to identify needs and opportunities for reinforcing the research capacities of emerging and existing centres of excellence in Convergence Regions, and these may be met by European Structural and Cohesion Funds.

4.5 Complex Systems Science in Society

Complex Systems Science will increasingly be at the heart of the future European Knowledge Society, and is essential for the latter to be effective and democratic. Its interdisciplinary nature can provide a stimulus for the harmonious integration of scientific and technological endeavour. It encourages a Europe-wide debate on science and technology and their relation with society and culture.

Complex Systems Research will play a major role in European Society over the next decade. The science will underlie new products and services affecting all aspects of personal and civic and life. Complex systems science will reduce gap between science and engineering, since much complex systems research is concerned with the design, control and management of real systems. Complex Systems Science will have a major impact through the ‘science of services’ and related innovations in ICT, and make a major contribution to this fundamental economic sector.

Complex Systems Science can contribute to the strengthening and improvement of the European science systems, themselves complex, by providing a deeper understanding of self-organisation at the individual and institutional levels to support “self regulation”.

It will be necessary to increase the current limited capacity for scientists to communicate its concerns and activities to the public, and for society to learn about Complex Systems Science. Complex systems scientists must engage with the general public who are stakeholders in the new science and its applications. A ‘black box’ approach to Complex Systems Science is not acceptable, since many elements of complex systems are normative and the public must be drawn into a debate on Complex Systems Science and technology and their place in society. There is need for improved communication between the complex systems scientific world and the wider audience of policy makers, the media and the general public.

Complex systems science is *the* science of the future. It is essential that young people be drawn into science in general and the Science of Complex Systems in particular. One exemplar of this is the international RoboCupJunior movement, which promotes children’s interest and excitement in Science, Technology, Engineering and Mathematics (STEM) through a variety of robotics events involving dance, rescue and soccer. This example encourages participation in the basic sciences leading to the involvement and experimentation with the complex systems of team robotics.

The complex systems community is well placed to engage young people in science, due to its experience in creating advanced introduction courses and schools on the subject. There is the potential to extend this work to focus on high school pupils and undergraduates in highly attractive ways. Many young people are fascinated by the complex systems they live in and want to find ways to understand and improve them. The Science of Complex Systems can offer hands-on experimentation through well-organised programmes that can be web-delivered across Europe.

Many universities in Europe are organised along traditional departmental lines, with students studying entirely within domains such as chemistry, mathematics, economics, biology, sociology, psychology, history, and so on. The concepts and concerns of Complex Systems Science cut across the traditional domains, and are at the research frontiers within the domains. It is becoming accepted that there is a dichotomy in the science of complex systems. On the one hand, the study of any particular system requires the deep domain knowledge developed within traditional subject boundaries. On the other hand, the study of complex systems requires deep knowledge of the transversal principles of complex systems that are best understood when viewed across the domains. This suggests that university education in Europe will be reorganised to preserve the best of deep domain-based knowledge, and to add to it the new perspectives provided by Complex Systems Science.

One approach to this is a 'hub-and-spoke' model in which universities create centres for Complex Systems Science as the hub of a network with spoke links to the existing domain-based departments. In the short term this offers an incremental approach that immediately connects all domains through CS science and allows knowledge transfer between them. In the longer term the hub and spoke structure encourages the development of a network with many connections between departments and domains, and a richer more interdisciplinary education for students.

At postgraduate level the European complex systems community is leading an initiative for a European PhD in complex systems. This will establish a core curriculum in Complex Systems Science to be mastered by all students, alongside undertaking more traditional in-depth domain-based research with a supervised by both domain expert and a complex system expert. This initiative comes bottom-up from the complex systems community, and has been embraced with great enthusiasm. The European Complex Systems Society is coordinating this initiative.

4.6 Capacity for international cooperation

The European complex systems community can contribute considerably to cooperation with third countries. The fundamental importance of Complex Systems Science to the social and economic well-being of nations and regions is increasingly being recognised across the world. Those nations that are already behind scientifically will find it increasingly difficult to catch up unless they are assisted in developing their own capacity in the new science and its applications.

Within Europe, to satisfy its objectives of economic development and harmonisation, it is essential that new member states are integrated into the mainstream of Complex Systems research as a matter of urgency, as discussed above. The same applies to states in Europe in which the new science is less well developed.

It will be to the detriment of Europe if its neighbours in Eastern Europe and Asia do not develop capacity in Complex Systems Science, since falling behind will exacerbate economic and social under-development and create political uncertainties.

The same is true for the countries of the wider world with emerging economies where a poor science base inhibits essential development. If these countries are not supported in developing their own sustainable capacity in complex systems they will fall further and further behind the developed world, chronically unable to develop economically, socially and politically. Complex Systems scientists will be able to make 'long links', connecting those in third countries to the centres of Complex Systems Science in Europe and the rest of the world.

Currently, fact-finding research exchanges are underway with India and China, with the intention of forming stronger links between them and the European complexity community. Existing links with South America, especially the Complex Systems Institute of Valparaiso, have the potential to be strengthened. The outcome of such meetings will be reported in the Living Roadmap as it develops.

4.7 Scope and Challenges

4.7.1 Creating open challenges and platforms for new kinds of control methods.

Assuming that the question of reconstruction from data has been done well, *controlling* complex system is the next step. Complex systems cannot be controlled by centralised strategies, calculated in advance and forever. Because they are systems of systems, there is a generic need to combine centralised control and distributed control of the subsystems. Furthermore, in a changing world, strategies have to be designed in order to be robust and adaptive. A well-know example of such a contest is RoboCup: “to have a team of humanoid robots beat the world champions at soccer by 2005”. Ideally such contests will be easy to state and understand, and their protocols must be well defined.

4.7.2 Creating open challenges and platforms for designing new kinds of artefacts and software.

The design of new artefacts becomes one of the most crucial challenges, like an airbus, a medicine, or a city. This “Science of the Artificial” concerns new kinds of systems that are not studied just for what they are, but also from the perspective of what they *ought* to be. Design implies many interacting partners who have to predict how artefacts will behave and how they will be used. These processes must be observed and studied for themselves - designing new kinds of platform for designing. In future, systematic consultation of users can be organised on the web, eliciting new specifications for future generations of designs and artefacts.

4.7.3 Creating new kinds of websites for sharing scientific and educational material.

The discussion on questions, methods and tools for complex systems has to be organised in a dynamic way, allowing comments on the discussion. The resulting scientific material must be open to everybody in different languages and using different media, including text, tabulated data, pictures and movies (from Nature and from simulation). All these scientific materials will be useful for creating all kinds of educational material for all ages and for all kinds of people.

All the above points are consistent with the legal principles of *Creative Commons* where all materials are attributed to their creators. These principles generalise those of open software and can be applied to a ‘Science Commons’ of well-archived, well indexed, and freely accessible reusable materials.

4.8 Mapping the European Complex Systems Community

One of the tasks on ONCE-CS is to map the European complex systems community. Our objective is to determine the major laboratories and centres of excellence across European, and to maintain databases of their scientists, their interests, their publications, and so on.

Apart from mapping the academic members of the community, we intend to attempt the more difficult task of mapping the industries and public sector institutions applying complex systems research.

Our expectation is that all of these communities will grow very quickly over the next few years, and that a much richer network structure will emerge. This will lead to new challenges in coordinating the community in useful ways.

This mapping process will begin through the ONCE-CS portal where members of the community can register themselves and their interests. As this process continues its results will be summarised here in the Living Roadmap.

5. Education and Training

The previous section has argued that Europe urgently needs to increase its capacity in complex systems research. But this is a bootstrap problem – where can the new capacity come from when the existing capacity is already far below critical mass? The question is not who will teach the students, but who will teach the teachers? Part of the short-term answer must lie in an urgent and radical programme of education at the masters and doctoral levels. In the longer term, education is required at all levels, from children in schools to adults participating in life-long learning.

Apart from policies that address the initial training of researchers, life-long training and career development, there is a need to establish much more effective industry-academia pathways and partnerships, and to improve the international dimensions of complex systems education.

Some of the necessary instruments to undertake this major educational programme already exist through the Comenius, Erasmus, Leonardo da Vinci, and Grundvig programmes. The Marie Curie programme can be expected to play a major role in providing doctoral students and their supervisors with the opportunity to undertake multidisciplinary research in other universities and other countries.

The number of PhDs required in complex systems to begin the huge educational task will be in the order of thousands across Europe over the next seven years. The creation of programmes and courses will be a major effort that will benefit from coordination at the European level. Already, on-line courses are being produced by European initiatives such as the ONCE-CS coordination action. That initiative is based on a community-driven spirit in which members of the Complex Systems community produce open course materials. For some this reflects altruism, for others an effective way to disseminate research, and for many it is a combination of the two. The ONCE-CS coordination action also has a work package to develop a European PhD in Complex Systems, and this is likely to play a major role in complex systems education. In particular it will define a core curriculum for complex systems education. In this context, networking the community into a European Open University for Complex Systems has the potential to deliver this curriculum across the Internet, providing high quality teaching for large numbers of students at low cost.

Other instruments for education include conferences and residential training courses. The European Conference on Complex Systems held in 2005 established the need for a conference in this area, and a number of educational courses are being run by EXYSTENCE, ONCE-CS and GIACS. In order to build capacity such activities will require considerable support.

5.1 Estimating European Education & Training Needs in Complex Systems to 2013

Estimating the number of people that need to be trained in Complex Systems Science is very difficult. We can expect that Complex Systems Science will open up new areas of application and research that we cannot imagine now. Certainly, there will be a need for specialists to teach in the universities as the science develops and matures. Also, complex systems theory can be expected to permeate all domains over the next five to seven years, and many students at all levels will increasingly need to be taught the subject.

Complex systems science will have a big impact on industry by enabling new types of products and services, and this will create a demand for scientists with complex systems doctorates. Perhaps the greatest impact will be on our social systems, with all large organisations being managed according to principles and practices emerging from the new science. The transition to this from current approaches will require managers at all levels to undergo minimal levels of training in Complex Systems Science. A conservative estimate suggests that some ten million people in Europe have management responsibility. This suggests a huge effort will be required to provide them with minimal in-service training.

The number of scientists in Europe that could be considered to be expert in complex systems is currently quite small, possibly a few hundred in each country or a few thousand across Europe – less than 1% of the 800,000 research scientists and engineers reported for 1995 (Pearson *et al*)[6]. Most of these scientists are first-generation and self-taught. Extrapolating from such uncertain numbers is unwise, but this suggests thousands as the order of magnitude.

As case studies we will take the UK and France. As noted previously, in the UK the EPSRC, one of the main research council is treating complex systems as a priority area for investment. Of its annual £500 million budget, £0.7 million has been allocated to the creation and delivery of taught courses on complexity 2006 – 2007, and £ 8 million has been allocated for research capacity building 2006 – 2011 by the creation of two new research centres. Some thirteen British universities are currently competing for this funding. A major element in this initiative is the training of new PhD students in Complex Systems Science, with the likelihood of an extra one to two hundred PhDs produced by this programme alone in the UK over a five year period.

In France the creation of the new Complex System Institutes of Paris and Lyon will also lead to specialist training PhD training, with at least sixty PhDs being trained per year.

The UK and France together have about one quarter of the European population, and if these numbers were repeated across all European countries we could expect at 2,000 – 4,000 specialist complex systems PhDs to be trained over the next five to seven years. But this is not enough for the demand of universities and industry that we foresee, and we propose a target figure of 1,500 PhDs per year to be achieved as soon as possible. We recommend that the EC expect to fund half this number, with the rest being funded at national level.

5.2 Initial Training of Researchers

Training up to 1,500 PhDs every year across Europe will require a big effort, especially since the capacity to educate so many does not exist in our universities. In the short term the investment is needed to train PhDs who will become the professors training future generations.

How can such large numbers of students be funded? It is possible that a part can be supported by ERA-NET+ on a national basis, and we propose that the other part be supported by the Cooperation Programme (IP and STREPS). PhDs and Post docs can also be supported by the IDEAS programme (in small teams).

5.3 International Dimension

The Marie Curie programme can support mobility of students and supervisors. We estimate 500 people moving each year (students and seniors), which implies five Marie Curie networks each focussed on a question or method in Complex Systems Science.

[6] *Assessing the Supply and Demand for Scientists and Technologists in Europe*, Pearson R, Jagger N, Connor H, Perryman S with de Grip A, Marey P, Corvers F. IES Report 377, 2001. ISBN 1 85184 306 X. [http://www.employment-studies.co.uk/summary/summary.php?id=377]

5.4 Lifelong training and Industry – Academia Pathways

Taking the longer term perspective, there will be a requirement for Lifelong Learning to upgrade those in industry, and the need for knowledge transfer from universities to industry. The Marie Curie Host Fellowships for Early Stage Research Training (EST) and the Transfer of Knowledge (TOK) can support this requirement. Over a period of seven years this could involve 300 people, approximately just one Marie Curie Host Fellowship per year per country.

5.5 Training courses (schools), juniors & seniors & Specific Actions - Excellence

As noted above, there will be a considerable need for educational in terms of conferences and residential training courses. The European Conference on Complex Systems is currently supported by Exystence, ONCE-CS and GIACS, but will require further support after 2007. Similarly, these coordination actions will provide residential schools until 2007. After this it is proposed that Marie Curie Conferences and Training Courses programme (SCF/LCF) can support these essential capacity building activities.

5.6 A European PhD in Complex Systems

The FET ONCE-CS coordination action has a work package dedicated to designing a European PhD in Complex Systems Science. This is done in the context of the Bologna Process[7] and the Lisbon Recognition Convention[8] aimed at harmonising higher education in Europe. There are many other initiatives aimed at European collaborations[9] and most people in the complex systems community find the prospect of a European PhD very interesting. It is likely that the new European Complex Systems Society will play a major role in this initiative.

5.7 Coordinating Education: A European Open University for Complex Systems

In order to increase capacity in complex systems in Europe, a large and sustained effort will be required. In the short term there are insufficient teachers trained to undertake this programme of teaching across Europe. One possible solution to this is the ‘open university’ model developed in the UK and adapted to local circumstances in many countries of the world. We propose a European Open University for Complex Systems (EOUCS) as a major practical way of delivering at a low cost the high-quality high-volume education required in Europe over the next seven years.

Considerations of geography and student numbers suggest that the EOUCS be established as virtual university with most of its teaching being done by e-learning, augmented by specialist residential schools. In the first instance the EOUCS should be concerned with doctoral education, providing core education in Complex Systems Science.

The ONCE-CS coordination action has a work package to produce courses in Complex Systems Science, and the first of these will be presented in the Spring of 2006. These courses will be made in a community-based way, with scientists across Europe providing input and materials on a voluntary basis. The ONCE-CS courses will be produced on a copyleft basis, giving the authors

7 http://www.euractiv.com/Article?tcmuri=tcm:29-117448-16&type=LinksDossier
8 http://www.coe.int/t/dg4/highereducation/recognition/lrc_EN.asp
9 e.g. http://research.microsoft.com/ero/icd/phd/ , http://www.vub.ac.be/gst/eurobio/25eb.html
http://www.uvt.nl/kameleon/phd2005/, http://www.egosnet.org/conferences/panel_session_4.shtml

appropriate levels of protection over their materials while enabling a wide community to use and develop them at no cost.

According to the philosophy of Complex Systems Science developed in this document, doctoral students must undertake in-depth research in an empirical discipline. Generally this means that students will be attached to PhD-awarding institutions in Europe with their domain-based laboratory work and theoretical studies being supervised by a domain expert. Alongside this, their studies in the methods and theory of complex systems will be supervised by a complex systems scientist.

Given the heterogeneous nature of doctoral education in Europe, it will be necessary for the EOUCS to present its courses in flexible ways. Whereas the EOUCS will assess and grade students according to its own regulations, other institutions may use this assessment in different ways according to their own regulations. It is expected that the European Complex Systems Society will bring stability by regulating the assessment of the EOUCS.

The EOUCS can be funded through the EC's eLearning Programme, and instruments such as coordination actions. The EOUCS can also contribute to education worldwide in cooperation with the OECD and UNESCO.

6. Conclusion

This Living Roadmap for Complex Systems Science has outlined the state of European complex system science as far as possible. Generally, its conclusions are that the future and emergent technology of Complex Systems Science is crucial for the economic and social well–being of Europe. To achieve this, up to 1,500 PhDs should be trained each year between 2007-2013. A number of areas of strategic importance have been identified, and a set of Grand Challenges and Strategic Research Areas has been defined to enable the community to focus on them. There is an urgent need to increase capacity in complex systems research in Europe, where this involves investment in infrastructure and a large programme of education, and the creation of special ERAnet and ERAnet+ structures to support this. In particular special measures will be needed for education to produce the large number of PhDs required in this new and developing area.

In particular, our main conclusions are that

- Complex systems science will be at the heart of the future Worldwide Knowledge Society. It is providing radical new ways of understanding the physical, biological, ecological, and social universe. The economic regions that lead this science and its applications in engineering and social management will dominate the twenty first century by their wealth and influence.
- In all domains complex systems are studied through increasingly large quantities of data, stimulating revolutionary scientific breakthroughs. The Science of Complex Systems will develop in the same way that physics developed over the three last centuries through a constantly 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.
- New kind of theories and methods have to be invented, respecting the organization of the whole system much more than today. This applies, for example, in an ideal personalised medicine, and for all in vivo intervention for any given complex system. Centralized control of a system and distributed control of its elements have to be combined. This is also necessary for radical new control of artificial systems as they become increasingly complex, reproducing the main properties of natural complex adaptive systems. Thus Complex Systems Science combines with the sciences of the artificial towards the design of radically new solutions to the grand challenges for Information Communication Technologies (ICT).
- To focus research in FP7, this roadmap identifies a number of Grand Challenges that embody the fundamental questions that Complex Systems Science must answer. From this can be abstracted strategic areas for complex systems research. They relate to all the programmes of the European Community, especially in biology, health, environment, services, government, climate change and ICT.
- The complex systems community needs infrastructure support at the European level, especially in the areas of massive distributed database and platforms for reconstructing multilevel dynamics and designing new methods of governance of complex systems.
- Europe has an urgent need to increase its human resources in complex systems research. Part of the short-term answer must lie in an urgent and radical programme of education at doctoral and masters levels. In the longer term education is required at all levels, from children in schools to adults participating in life-long learning. In FP7, the creation of an Open University of Complex Systems is a priority.

- Even though exploitation of Complex Systems Research in commercial and civil applications is essential to Europe, the academic, business and governmental communities are very poorly networked with very little knowledge transfer to the private and public sectors. This is an area of acute and urgent need, and effective policies are required to address it.

This Roadmap is intended to send a very clear message from the Complex Systems community to policy makers at the European Commission. The Science of Complex Systems is of crucial importance to Europe. Although Europe is relatively advanced in the new science, a large effort is required to consolidate the gains that have been made through EC support over recent years. Significant targeted funding is required in FP7.

From its current strong position due to FP6, Europe can become a *long-term world leader* in the new science by coherent use of the main instruments of FP7: the *Ideas* programme for addressing the fundamental questions through complex systems; the *Cooperation* programme for addressing the main societal Grand challenges; the *Human Resources* programme for rapidly bootstrapping and training a new generation of several thousand young researchers; the *Capacity* programme for developing the big instruments and platforms necessary for this new science.

We recommend that 3% of the funding for the *Ideas funding*, 3% of that for *Capacity*, 3% of that for *Human Resources* and 1% of that for *Cooperation* be dedicated to supporting complex systems due to the essential role it will play in Europe's future.

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, and web services. Thus Complex Systems Science will provide long-term harmony between science and societal needs.

Appendix A: Contributors to the Orientation Paper and Living roadmap:

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Appendix B : European and Worldwide Complex systems Centres

This page is under construction
26th March 2006

Appendix D : Complex Systems : Report 2005 and Outlook 2006

RD 07-0-2006

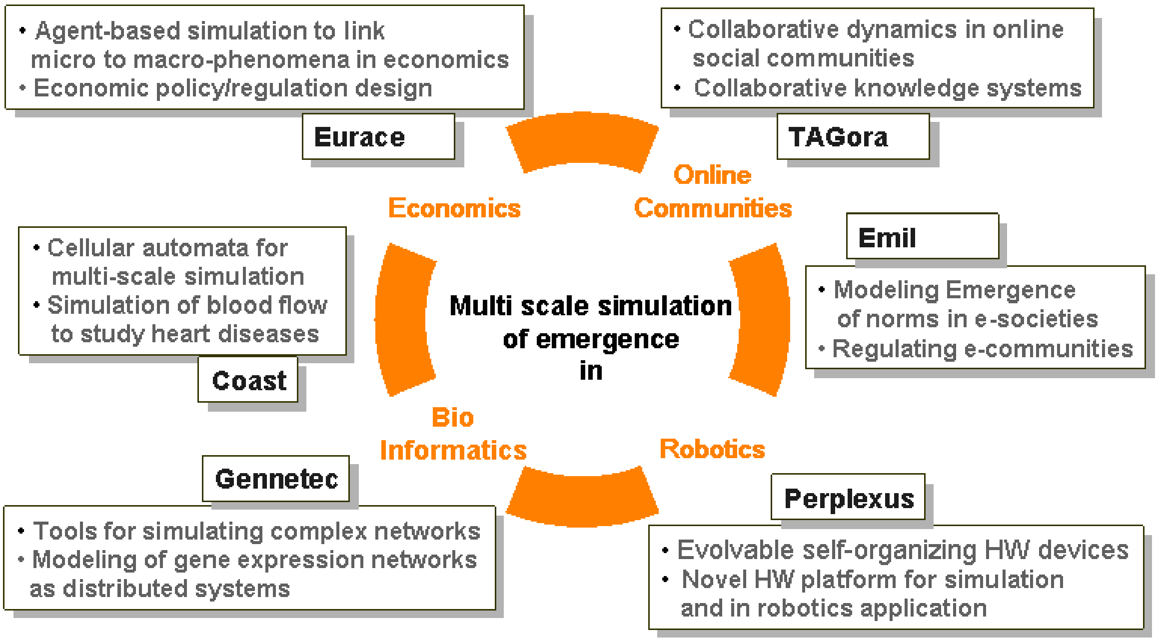
D.1. A new initiative launched: 'Simulation of emergent properties in Complex systems'

The planning of the initiative was initiated in 2003 in reaction to recommendations of experts during the evaluation of proposals received in the IST FET Proactive Initiative "Complex Systems" (call 1 of FP6) and further developed in consultations – via web and via workshops - with the research community. In the present call the aspect of a coherent approach to simulating complex systems as well as establishing formal methods for system description and for linking between component and overall system behaviour has been emphasised.

The received proposals were evaluated and 6 proposals retained for negotiation. The application areas addressed by the ranked proposals are:

- *Large scale information systems* (multi agent systems for large-scale agent-based economics simulation, modelling of e-communities and online web communities, analysis of emergence of conventions and collaboration in SW- agent societies). The area Mission Critical Infrastructures that was called for is not directly addressed by the ranked proposals.
- *System engineering* (self-reconfigurable hardware for applications in robotics and for setup of a multi-scale simulation environment, multi-scale modelling of friction contact phenomena in automotive industry)
- *Bioinformatics* (use of formal methods from computer science in system biology and immunology, multi-scale modelling of blood flow).

The proposals retained will be negotiated beginning 2006 and included in the CS cluster.
Below is a schematic presentation of these projects



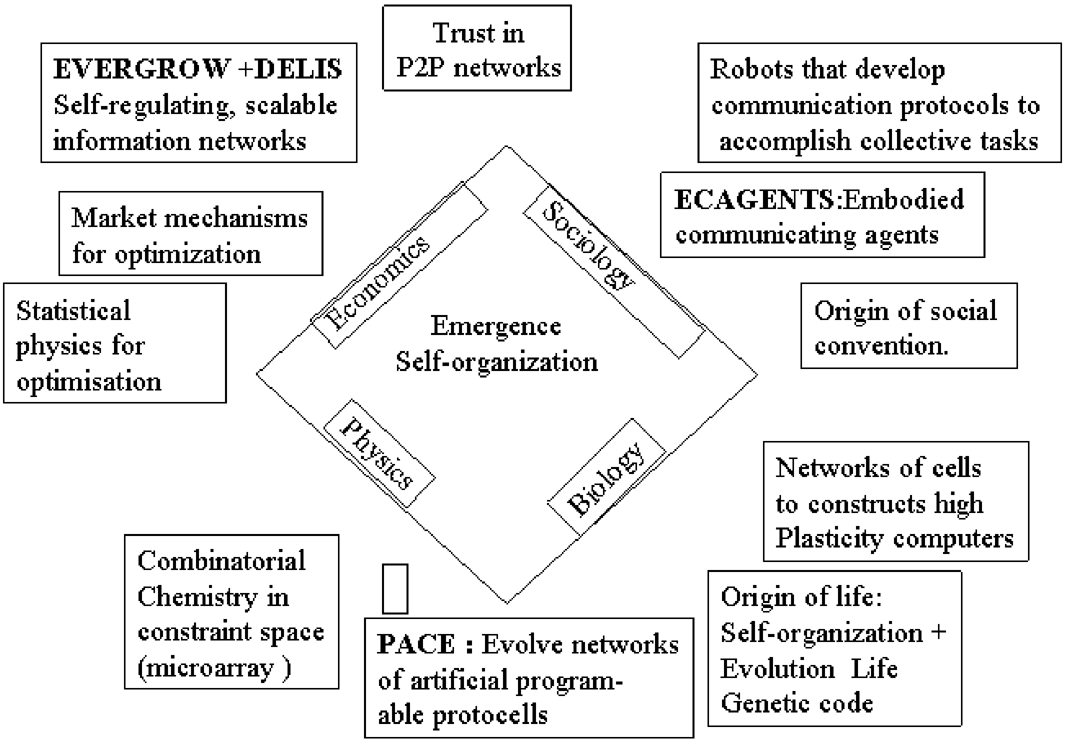
Projects funded in call 5

D.2. Achievements of funded projects in 2005

(*Remark:* a detailed report on achievements in 2005 will be available in the cluster review report of the review meetings in March and May 2006)

Integrated Projects:

PACE explores the utilization of the simplest feasible artificial cells (much simpler than current cells) to build evolvable complex information systems. PACE explores the collective properties of artificial cells, their capacity to process information by self-organization and their suitability as material for building nano-scale robot ecologies. PACE made considerable experimental progress in the first year, in particular major advances in micro-fluidics setup - using a programmable microfluidic interfaces (FPGA-based), the key technology used in combinatorial search of suitable materials. They managed to setup a fully-functional microfluidics environment which in a next step will be used as host for the chemical processes on which two other groups are working on.
EC funding of PACE has stimulated funding in the US by LANL, mainly in the complementary area of experimental chemistry (running for three years and with a budget of about $5M). The company 'ProtoLife SRL', setup to promote PACE results, is regarded as a showcase for the Venice nanotechnology incubator.



Projects funded in call 1

EVERGROW and DELIS study the Internet and P2P networks from a complex systems perspective in an attempt to identify novel mechanisms to harness the power of the Internet and the P2P paradigm. Both projects were considerably restructured as a result of the 2005 review. In both cases the reviewers asked for a stronger focus of research and as a result some strands were dropped and others reinforced.

EVERGROW had already last year one major milestone established: setting up real-time measurement of Internet connections via the DIMES measurement initiative. This year there is a spectacular increase in number of agents and geographic coverage. DIMES works via a SETI style agent that can be downloaded by individual users and then starts locally monitoring Internet connections via TRACEROUTE and PING at a low rate, consuming at peak 1KB/S.. DIMES puts Europe ahead of the US in mapping of the Internet (see CAIDA in US).

DELIS made major progress in first foundations of a next generation search engine based on collaborative mechanisms which puts it at the forefront of research in P2P search engines. It also deployed its first algorithms based on bio inspiration in real-world settings.

EC-AGENTS studies in real software and hardware settings the emergence of communication and language. It focuses on the necessary preconditions for “engineering emergence” that is, of learning how to control and manage complex systems. Hence, this work could provide the conceptual glue to help organise and motivate further work within the initiative. It could also help motivate work in other areas like Beyond Robotics.

STREPS in CS

BISON, COSIN, SWARMBOTS, NEW TIES, ISCOM

Coordination actions in CS

EXYSTENCE (till March 2006), ONCE-CS (from July 2005)

D.3. Links to other initiatives and international collaboration

When it was launched in 2003 the initiative ‘Complex systems’ was a new initiative with no counterparts in the IST programme nor elsewhere in the framework programme.
Now, it has established many links and incited initiatives of similar type.

Within EC:

- The FP7 pillar on simulation will draw on work proposed in the new initiative ‘Simulation of emergent properties in complex systems’.

- The call 6 SO on new search engines draws also on work in EVERGROW and DELIS on the ‘ultimate Google’ (collaborative P2P search engines etc).

- The Software unit included in call 5 a subsection on complexity in SW that draws on work done in projects in FET.

- Within FET there are synergies with the PI in Neuro-IT and ‘Beyond Robotics’ and with recent attempts to extent the reach of ICT by including *e.g.* efforts in system biology

- The FET initiative incited a similar initiative the NEST unit in DG RTD ‘tackling complexity’ focussing on understanding of social networks and networks in biology.

Remark: While it is in general important and stimulating for research in CS to be exposed to real world problems in IST, the uptake of the notion of CS in other units raises the issue of focus of research in CS. The concept of complex systems is often diluted when used in other parts of IST. This issue will have to be carefully addressed in the roadmap on complex systems.

National funding

There are a few national programmes in Europe. In UK EPSRC is having a large programme on ‘complexity’ (£10 M). Smaller funding was granted in Denmark and Sweden. Centres of excellence were launched in for instance Budapest and Paris (region de Ile de France), partially based on direct stimulation from the FET initiative. The Italian Regione Piemonte is sponsoring a centre and PHD grants (2MEuros per year).

International co-operation

The ONCE-CS and EXYSTENCE coordinating actions established links with India and China (several mutual visits in 2005).

- Visit of China (March 2005)
- November 2005: Meeting of RD with president of Santa Fe institute to discuss common workshops (most likely the WS on 'complexity and industry in 2006 will be co-financed by Santa Fe institute and ONCE-CS)
- Visit to India (December 2005)
- Symposium in Torino, 27th-28th March 2006: gathering with scientists decision makers from India, China to discuss collaboration, exchange of students, and common programmes.

D.4. Events in 2005

- *"2nd European Conference on Complex systems" (Nov 14-18th, Paris).* This conference attracted more than 400 researchers (double of the participation in conference of 2004). It was a showcase for FET funded projects but also attracted a much wider audience and establishes this conference as the major European event in this area.
  Introductory addresses were given by Michel Rocard (MEP) and George Haddadd (Director of higher education at UNESCO). Various workshops were organised in parallel to this event on 'complex systems' and governance and one on 'complex systems and industry'.
- *Cluster review in Budapest, March 7th-11th 2005.*
- Invitation for RD to IBM Watson Centre to present European efforts in complex systems.(July 2005)
- *ONCE-CS kick-off meeting in Paris (*September 19th-24th 2005).
- Visits of European Researchers to China and India (March and December)
- Various symposia were organised by EXYSTENCE to bring together complex systems researchers and industrialist. One was organised by HP in Grenoble, others in Warsaw, Helsinki, Vienna, Dresden (see upcoming EXYSTENCE report for details).
- Thematic institutes were organised by EXYSTENCE (3-4 week gatherings of scientists). Themes included 'information networks as CS', ' 'complexity in business logistics' and others (see upcoming EXYSTENCE report for details).

D.5. Events in 2006

- Cluster review in Rome
- School on simulation of complex systems, Torino (this EXYSTENCE school was be organised as an intense workshop with ONCE-CS collaborating to create an online courses and interactive course material for a wider audience of students)
- Workshop on 'CS for system assessment' (this WS will replace the planned joint WS with LANL)
- 3rd European Conference on Complex systems
- Conference on *Mathematics in the Science of Complex Systems*, Warwick University, September 2006.
- Workshop on 'complex systems and industry (this will be a follow-up to a similar event held in 2004 in London and will be co-organised with Santa Fe Institute).
-

D.6. Dissemination and education (2005-2006)

Relation to industry and policy making: EXYSTENCE together with London School of Economics organised various events to bring together stakeholders from business, industry and policy and researchers in CS.

Publications (see also sections in project reports)

-Press articles

- Article in Science on DIMES measurement project of EVERGROW stimulated a surge in interest in this measurement tool
- Various articles on complex systems projects and events (Torino conference December 2004) in **IST results**. Further articles are already planned for early 2006. (see IST results website).
- SWARMBOTS, BISON, NEW TIES all generated a number of articles (available on request)

-Brochure on complex systems

This brochure (edited by Marc Buchanan) is based on contributions from various projects and researchers. Issue date March-April 2006.

*Projected Brochure Contributions (*all contributions are supposed to be non-technical*)*

1) Introduction: “what is complexity” Authors: MB, RD, JJ
2) Interviews
- Interview with Sir Robert May (discuss complex systems in general) M. Buchanan
- Interview with Michel Rocard, MEP, former French prime minister: Paul Bourgine based on speech of Rocard given at introduction to Paris conference + interview on Open software
- Interview with a person from industry (tbd)
3) ‘Infrastructures’: ECLT, Venice, Collegium Budapest, Max Planck Dresden , Oxford. ISI Torino, ENS, Institute of Paris and Lyon, Cranfield & Open Universities.
4) Self-organized P2P cooperation Author: David Hales
5) Distributed Google Author: G. Weikum
6) Emergence of culture in agent societies Author: Gus Eiben + Nigel Gilbert
7) The future of cities: Author: Denise Pumain
8) Game theory for computer science P. Spirakis
9) Artificial cells Norman Packard
10) Complexity and Art: Mario Rasetti.
11) Complex networks in information systems and elsewhere M Buchanan
12) POETIC project: Author: Moreno: art installation based on reconfigurable hardware.
13) Emerging languages Luc Steels
(14) DIMES Internet measurement. Yuval Shavitt , Scott Kirkpatrick
(15) Complexity in management and business Eric Bonabeau , ICOsystems.
(16) Creative Commons: Paula Le Dieu
(17) The brain as CS: Igor Aleksander, Nicolas Brunel
(18) Road traffic (Dirk Helbing)
(19) Integrated Assessment, Climate Change (S. van der Leeuw and R. Dum).

Education 2005 to 2006:

- **Online courses** will be prepare in 2006 as introduction to complex systems and will be put on internet (via the CONNEXIONS software of ONCE-CS)
- January 2005: School on complex systems (Valparaiso, Chile)
- March 2006: School on simulation of complex systems in Torino

D.7. Putting Complex Systems research on the Agenda of FP7: Planned Actions

In broad consultation with the research community an "orientation paper for complex systems research in FP7" was edited (based on 50 contributions from high ranking researchers). For March 2006, this roadmap is scheduled which will extend this orientation paper with a map of research activities across Europe and milestones of research. ONCE-CS has set up an online consultation forum.

Orientation paper for FP7 (issued 09/05)

This orientation paper should serve as a preparatory document for FP7 defining the scope, role and potential impact of research focussed on Complex Systems. It should clarify the use of Complex system research in addressing the main challenges for IST in the coming years. It is a first input to the roadmap.

The questions asked to the scientific community were:

- What impact can CS research have on pertinent technological, scientific and societal challenges in particular for ICT?
- What differentiates CS research from traditional approaches?

The orientation paper was edited by Mark Buchanan and RD based on *from over 50 scientists* answering the above questions. It is an attempt to position complex system research for the seventh framework programme.

The orientation paper will serve as input to the online forum on roadmap and will be a specific contribution to the roadmap. It will be put on the highly interactive website of ONCE-CS.

Roadmap (Edition 1 published end March 2006, with regular updates planned)

The roadmap serves two purposes:

- Preparation of a research agenda with a view on FP7 based on 'grand challenges'.
- Mapping of the research community.

It will be important to position the 'complex system' community along various dimensions:

- With respect to disciplinary boundaries: Measures of how to sustain multi-disciplinarity should be proposed
- With respect international efforts: the focus of attention shifted recently from US to Europe with many US scientists spending considerable amount of time in Europe.

- With respect to industry efforts: what are the needs of industry and what is the impact of CS research.

Input will be invited from a large community and an online forum will be established (online forum will be online beginning of February).

Timeline:

- End January: An online forum established and first draft of roadmap online. *Forum will be organised along 'grand challenges'*. This online forum will ensure input from a large number of researchers and will serve as a continuous mechanism to update the roadmap on regular intervals. It will be accessible from the FET pages which address the ERCIM thematic groups.

-A first draft of the roadmap was be circulated at the beginning of March 2006 (at the cluster review in Rome). The CS review meeting in Rome (week of March 6) was be used to present the roadmap to the IPs (which of course already contributed to it).

-Final touches to the roadmap will be made in March and version 1 of roadmap is available by end March. The idea is to have a new version at regular intervals due to importance for FP7 preparation, with version 2 already a couple of months later and then version 3 after a year).

Sections/tasks of roadmap:

- Orientation paper: what are challenges CS research can help address
- Challenges from society and industry and a research agenda responding to these challenges.
- Map of CS in Europe: attempt to map research teams and research funding in Europe
- Map of common methods/concepts
- Educational measures for multidisciplinary research: 'European PhD in CS as planned by a consortium of European universities)

The roadmap will incorporate these as it develops.

D.8. Timeline of events and actions in 2006

- 30th-31st January: WS on science of services, Brussels
- Mid March: Brochure on CS research
- 6th-9th March: CS cluster review Rome
- 14th March: Negotiation meeting in Brussels for call 5
- March 27th-28th: Meeting Europe-China-India (see above)
- End March: First edition of roadmap of CS
- April 2006: Input to specific programme of FP7.
- May 2006: WS on complex systems and system assessment
- September: 3rd European conference on CS, Oxford
- November (tbc): Symposium on "Complex systems research and industry"

IST-FET Coordination Action
Open Network of Centres of Excellence in Complex Systems
Project FP6-IST 29814

ONCE-CS

Living Roadmap for Complex Systems Science

Version 1.22

31st March 2006

Edited by Paul Bourgine [(1)] and Jeffrey Johnson [(2)]

http://www.once-cs.net

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Executive Summary: Complex systems science - the essential 21st Century science

The new science of complex systems will be at the heart of the future of the Worldwide Knowledge Society. It is providing radical new ways of understanding the physical, biological, ecological, and social universe. *Complex Systems* are ambiguously situated in turbulent, unstable, and changing environments. They evolve and adapt through internal and external dynamic interactions. They are value-laden multi-level multi-component systems of systems and they are not predictable in a conventional scientific sense.

Science is the process of reconstructing theory from data. But complex systems must be observed *in vivo*, requiring new multilevel data collection protocols, and new formalisms to reconstruct intra-level and inter-level dynamics, and their capacity to adapt to changing environments.

Complex systems science bridges the gap between the individual and the collective: from genes to organisms to ecosystems, from atoms to materials to products, from notebooks to the Internet, from citizens to society. It cuts across all the disciplines. It is part of every discipline. It creates new and shorter paths between scientists and accelerates the flow of scientific knowledge. It reduces the gap between pure and applied science, establishing new foundations for the design, control and management of systems with unprecedented levels of complexity exceed the capacity of current approaches. It will benefit industry, the public sector, and all social actors. Complex systems science will be the foundation of Europe's wealth and influence in the 21st century.

The potential impact of this new Complex Systems Science appears in four ways (i) a better understanding of many complex systems and their dynamics to support the pressing needs to engineer and manage complex systems, *e.g.* cancer, multinational companies, drugs, transport, and climate change; (ii) better control of the means of fabrication as dynamic complex socio-technical systems, *e.g.* new processes and materials, multi-site factory production, and supply chain dynamics, (iii) a better understanding of the complex environment in which engineered systems exist, *e.g.* regulation, ethics, markets; and (iv) a better understanding of the design, engineering and management process which is often itself a creative complex multilevel complex human system, capable of great successes but inherently liable to spectacular failures.

This *Living Roadmap for Complex Systems Science* is intended to enable the scientific community's vision on complex systems research and its applications to inform policy for FET ICT funding in FP7. To help focus this vision, a number of strategic areas and Grand Challenges are identified.

Complex systems science is *computer enabled* and ICT will be part of *all* the research programmes of FP7. For example, in Health the new science of complex systems will revolutionise the medical treatment of diseases, and revolutionise the delivery of treatment. Individual problems of individual people will be treated. This requires (i) huge distributed databases of every individual's genotype, phenotype, medical and general history, (ii) new ways of searching, communicating and processing this information, and (iii) new and more efficient ways organising the delivery of treatment to Europe's half billion inhabitants.

Thus, this crucial ICT-based complex systems programme requires a new family of *European platforms*, similar to the big instruments used for physics (*e.g.* CERN) to support the new theories and methods of control and design, many of which have yet to be invented. Europe also has an urgent need to increase its *human resources* in complex systems research, which in turn requires an urgent and radical programme of education at the doctoral and masters levels. In FP7, the creation of an Open University of Complex Systems is a priority. Last but not least, there is also an urgent need to bridge the gap between Complex Systems Science and its applications in industry and the public sector.

The strong momentum recently gained in this domain, due to FP6 funding, may enable Europe to become a long-term world leader in this new science by coherent use of the main instruments of FP7: the "Ideas" program to address the fundamental questions through complex systems; the "Cooperation" program to address the main societal Grand Challenges; the "Human Resources" program to rapidly bootstrap and train a new generation of several thousand young researchers; the "Capacity" program to develop the big instruments and platforms necessary for this new science. If this path is actively followed, Strategic investment in Complex Systems Science will be part of the foundations of Europe's wealth and influence throughout the 21st century.

1. Introduction

1.1 The nature of the Living Roadmap

This *Living Roadmap for Complex Systems* is intended to guide European Research on complex systems from where it is in 2007 to where the various stakeholders think it should be in 2013.

These stakeholders include the complex systems research community in universities, and government and industrial laboratories. Business and commerce will increasingly see itself as a major stakeholder in applying the results of the new science, as will those responsible for social organisations at every level in the private and public sectors.

The Living Roadmap is a result of an extensive consultation exercise in Europe led by the Future and Emerging Technology (FET) unit of the FP6 Information Society Technology priority, in preparation for FP7. It is intended to be an authoritative document on which policy can be formulated by the European Commission. It builds on an *Orientation Paper* that was based on written statements from some seventy five scientists across Europe, and various meetings organised by ONCE-CS with the scientific and business communities. However, these represent only a fraction of the thousands of stakeholders across Europe, and the Living Roadmap, first published on 27th February 2006, is intended to always be subject to criticism and revision.[1]

The roadmap begins in Section 2 by addressing the question what is 'Complex Systems Science'. Until now there has been uncertainty and disagreement in the complex systems community on what 'complex' and 'complexity' mean. Much of this disagreement revolves around specific interpretations of words and nuances of meaning as they are translated from one language to another. We have chosen to define complex system *science* in a way that extends traditional scientific epistemology to a much wider class of systems than can be handled by the traditional sciences, including almost all those that people consider to be complex systems.

Following this, Section 3 identifies what the community thinks are the areas of strategic importance in complex systems research, and provides a tangible approach to this research through a series of Grand Challenges that have been formulated by the community. These Grand Challenges are intended to guide research funding policy in FP7.

Section 4 suggests that FP7 must also address the question of providing infrastructure for complex systems research at a European level. We identify the need for new generations of computation platforms, open observatories, and huge databases that will be essential for European researchers in the next seven years.

Section 5 shows that human resources in complex systems research across Europe exhibit a mixture of strengths and weaknesses. There are some excellent laboratories in most European Countries, and as a result of various coordination actions funded by the EC, the community is much better networked than it was just five years ago. Nonetheless, there is a long way to go in connecting researchers, business and government. Education is identified as an extraordinary challenge in supporting Complex Systems Science in Europe. There will be a major skill shortage at the doctoral and postdoctoral levels that could seriously undermine Europe's ability to become a world leader in this strategic field. The question is not who will teach the students – it is who will teach the teachers. It is essential that a major effort is made to support complex systems education in FP7.

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[1] The Living Roadmap can be viewed at any time on the ONCE-CS portal, http:/www.once-cs.net. Readers can post their comments and suggestions, including adding their own Grand Challenges, and suggesting what they think are the most important Grand Challenges facing the complex systems community.

1.2 The importance of the new science of complex systems

The new Science of Complex Systems is providing radical new ways of understanding the physical, biological, ecological, and social universe. The economic regions that lead this science and its engineering will dominate the twenty first century by their wealth and influence.

In all domains, complex systems are studied through increasingly large quantities of data, stimulating revolutionary scientific breakthroughs. Also, many new and fundamental theoretical questions occur across the domains of physical and human science, making it essential to develop the new Science of Complex Systems in an interdisciplinary way.

This new science 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.

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.

1.3 Grand Challenges on Natural Complex Systems

Complex systems science will be essential for the Grand Challenges associated with the massive information processing involved in the collection of data of many kinds, reconstructing the multi-level dynamics that were responsible for the phenomena they describe, and managing these dynamics. *Personalized Health is one characteristic example of this kind of long term Grand Challenge*. Another, which is just as rapidly appearing on the horizon alongside personalized health, is the integrated monitoring and assessment of the state of our Earth System.

New kinds of data collection and mining, new ways to extract information from the data, new models to describe the dynamics, new remedies, and new approaches to control the implementation of health programs have to be invented. The systemic aspects of this general approach will lead to many grand challenges that will be useful in all the programmes of the European Community, especially in biology, health, environment and climate change, services, government, and the pursuit of peaceful integration of ever larger number of people into stable societies.

Formulating new approaches to integrated management of such systems involves difficulties in *combining centralized control of a system with distributed control of its elements*. Such integrated management has to respect the organization of the whole system much more than is common today. This is true, for example, for personalised health, for the integrated assessment of the environmental state of our planet, but also for all *in vivo* intervention in any given complex system. Such integrated control strategies will be based on solutions to a very difficult class of 'inverse' problems, requiring the best possible estimation of the integral set of multi-level dynamics before intervention.

The potential impact of this new Complex Systems Science appears in four ways (i) a better understanding of many complex systems and their dynamics to support the pressing needs to engineer and manage complex systems, *e.g.* cancer, multinational companies, drugs, transport, and climate change; (ii) better control of the means of fabrication as dynamic complex socio-technical systems, *e.g.* new processes and materials, multi-site factory production, and supply chain dynamics, (iii) a better understanding of the complex environment in which engineered systems exist, *e.g.* regulation, ethics, markets; and (iv) a better understanding of the design, engineering and management process which is often itself a creative complex multilevel complex human system, capable of great successes but inherently liable to spectacular failures.

1.4 Grand Challenges in the understanding and management of the Earth System

The Earth System, as it is conceived for example by the international Earth Systems Science Partnership in which the EU plays a very important role, is neither a natural nor a social system, but is fundamentally neither, and both. It is a system of infinite complexity, linking levels from the individual to the whole of the globe. Its dynamics are party natural, and therefore governed by dynamics outside our control, and partly artificial in so far as we are now living in an era in which human-engineered systems have such an important impact on our terrestrial environment that the natural systems do no longer operate independently. The only epistemology and methodology thus far that have been able to deal with such integrated systems are essentially those of Complex Systems Science.

Not only is the Earth System of infinite complexity, but it also is very unevenly known. In general terms, much more coherent information is available about the natural processes than about the processes governing society. But there are also major differences in density of information at different scalar levels: atmospheric and oceanic sciences operate at the level of the whole earth; social science often operates at the level of the individual community, city, region or country. Down-scaling of the former and up-scaling of the latter is a major challenge in itself.

Thirdly, the fact that societies play such a large part in the current and future dynamics of the Earth System is responsible for the fact that the number of degrees of freedom of the system as a whole is extremely large. This means that mathematical and other solutions need to be found to deal with these kinds of systems. Wherever attempts have been made at understanding such socio-environmental systems, Complex Systems Science models have been among the most powerful tools available.

Altogether, if we are to succeed is maintaining a sustainable relationship between society and the environment, an intense information-gathering network needs to be put in place, covering both global society and all aspects of its natural environment. This will in part be done through nanotechnology. Monitoring information, synthesizing it, deriving models and scenarios and, ultimately controlling the both society and the environment, will be a task of a magnitude never yet undertaken, in which Complex Systems Science will play an essential role.

1.5. Grand Challenges of Society in an Epoch of Globalization

The creation of the European Union was initially conceived as an evolutionary, top-down process driven by the intellectual, business and political communities in each individual country. Recent events have shown that, ultimately, it has affected European Society at all levels, even in the remotest corners. That has led to many questions of governance, social equity, and in general the coherence of European Society. Many of these questions are still unsolved, yet the world population is now caught in a wave of globalization which, willy-nilly, seems to repeat the same kind of process on a much larger scale, involving societies that differ much more than the European nations.

Altogether, the world is facing such rapid social change that the utmost will be demanded of the integrative processes that have thus far allowed different societies to remain intact. Here again, information-gathering on a massive scale will be needed, but understanding the dynamics so thoroughly that projections about the future may be made is an even more imposing challenge. Societies are in essence multi-level multi-network dynamic constructs based on communication, alignment and shared values. The Complex Systems approach will play a prominent role in dealing with these issues in that it provides a language, and a toolkit, that transcends the different social science disciplines, and opens the way to comparative analysis of societal phenomena in different cultural and social situations.

What is needed, however, is the formation of a social science community that embraces the Complex Systems paradigm, decides on the kinds of information it needs, and develops its own approaches and tools, rather than borrowing inappropriately them from other disciplines. Developments in this area are considerably behind Complex Systems approaches in other domains. In view of the high stakes, the formation of such a community is a very high priority.

There is the unresolved in issue that many in human sciences have weak mathematical skills and use exclusively vernacular language to express the deep insights they have into human systems, while those coming from the natural sciences may be insensitive to important concepts expressed in this way. A sustained effort is required to bridge these two cultures, with both extremes learning to use the language of the other. It is unthinkable that ICT-enabled science does not require mathematical formalism and knowledge of computation, but it is equally unthinkable that complex systems scientists should ignore the considerable corpus of knowledge accumulated in the social sciences. This discussion highlights two policy issues: the first is that to proceed in the most productive way possible, complex systems science needs a major programme of education to fill the gaps in our polarised mono-cultural educations systems; and the second is that funding under FP7 should require teams with strength in both mathematical and human sciences.

1.6 Grand Challenges in Design and the Sciences of the Artificial

Artificial systems tend to become more and more complex, often reproducing the main properties of natural complex adaptive systems. Thus one can conjecture a long-term convergence between Complex Systems Science and the sciences of the artificial. In the medium term, Complex Systems Science can combine its efforts with the sciences of the artificial towards the design of radically new solutions to the grand challenges for Information Communication Technologies (ICT). These solutions will require the NBICS convergence (Nano-Bio-Info-Cognition-Socio), which is particularly suited to a transversal approach of Complex Systems Science.

The relations between Complex Systems Science and the sciences of the artificial will become stronger and stronger, for the simple reason that the sciences of the artificial and Complex Systems Science share the same fundamental questions. However, particular sciences of the artificial do not have the transversal viewpoint across the different classes of complex systems.

The science of the artificial is also the science of the design. With natural complex systems, their functional properties are mainly determined by natural evolution. With the artificial, the functional properties can be chosen: designed systems *ought* to behave in specified ways. Complex systems scientists should be aware that there is a considerable body of knowledge about the design process (see, for example, http://www.complexityanddesign.net).

Complex systems research will play a major role in European Society over the next decade. The science will spawn new products and services affecting all aspects of personal and civic life. Complex systems science will reduce the gap between science and engineering, since much complex systems research is concerned with the design, control and management of real systems.

Complex systems science will have a major impact through the ‘science of services’ and related innovations in ICT, and make a major contribution to this fundamental economic sector.

1.7. Grand Challenges in ICT

Nowadays, we 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. These threaten to undermine, for example, the efficiency and value of the Internet and World Wide Web, telecommunication networks, and large software systems. Traditional science and engineering, have always sought to understand and design systems by breaking problems into smaller component parts. Nothing in these disciplines has prepared us to manage such huge, and rapidly expanding, systems. Our intuition offers little or no guidance: we need new ideas, new metaphors and new methods.

The Science of Complex Systems provides a scientifically sound basis for understanding and managing complex ICT systems. It 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. In contrast to traditional approaches, Complex Systems Science accepts and even embraces the frequent irreducibility of system behaviour and seeks to understand coherence of function and organisation in a new way. This novel, decentralised approach is based on the view that function emerges when system components self-organise into highly versatile organisational structures that react to external constraints in the environment. Complex systems research emphasises, in particular, the fact that components and organisational structures are able to adapt their function to novel conditions and tasks.

In the Internet and the WWW, for instance, Complex Systems Science points to a novel decentralized approach – exploiting the activities of independent software agents that acquire local knowledge of web content. It may thus be possible to develop a “distributed Google” with far greater reach and power. Another bottleneck in the current WWW is that computers with distinct content, typically stored in incompatible formats, cannot easily exchange and share that information. The barrier to “semantic interoperability” severely limits the ways that information can be combined and analysed to discover further value and meaning. In studies of emergence of norms in social systems, complex systems research suggests that machines can be designed to learn the skills of communication all on their own; effective languages can thus emerge naturally through inter-machine discourse, thereby vastly improving their interoperability.

Europe is well placed to lead the way into this new era of science and engineering. It can base such a move on a strong base in mathematics, computer science, control theory, and physics as well as on a community of researchers willing to cross disciplinary boundaries in order to set the stage for tomorrow’s approaches in scientific discovery, in engineering and in management and innovation. Information and communication technologies will play a central role in all these efforts as enablers of novel approaches in science and technology.

1.8 Capacity for Complex Systems Research

Complex systems research will require the creation of European platforms with massive computer power for data processing, reconstruction, modelling and simulation of complex systems 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 of big instruments will be even much more demanding than for physics.

There is 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 FP7 timeframe, the organization of data can also be conceptualised in a heterogeneous way, going beyond the simplistic single-purpose directions that have characterized GRID and GEANT efforts in Europe, where CERN's potential flood of data will use almost all of the capacity that has been provided.

In the US's planning, there are vocal advocates 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.

Open challenges with clear rules can be organised for the difficult problems of *reconstructing and controlling* multi-level dynamics based on data of all kinds. The rules of the reconstruction protocol will concern the data (or more generally the stylised facts extracted from data) and the definition of the quality of the result.

1.9 Education and Training

Europe has an urgent need to increase its capacity in complex systems research. But this is a bootstrap problem – where can the new capacity come from when the existing capacity is already far below critical mass? Part of the short-term answer must lie in an urgent and radical programme of education at doctoral and masters levels. In the longer term, education is required at all levels, from children in schools to adults participating in life-long learning.

Apart from policies that address the initial training of researchers, life long training and career development, there is a need to establish much more effective industry-academia pathways and partnerships, and to improve the international dimensions of complex systems education.

Some of the necessary instruments to undertake this major educational programme already exist, through the Comenius, Erasmus, Leonardo da Vinci, and Grundvig programmes. The Marie Curie programme can be expected to play a major role in providing doctoral students and their supervisors with the opportunity to undertake multidisciplinary research in other universities and other countries.

But these existing instruments are insufficient. The number of PhDs required in complex systems to begin the huge educational task will be in the order of thousands across Europe over the next seven years. A European Open University for Complex Systems is necessary to define a curriculum and to deliver a European PhD in complex systems.

1.10 Industrial and Civil Applications of Complex Systems Science

Europe is less successful in exploiting its investment in scientific research than, for example, the USA. Whereas knowledge of complex systems is widespread in Europe through many popular books, there are weak personal links between complex systems scientists and those who might exploit their results. This lack of networks connecting those in business and the public services with European scientists reduces our continent's capacity to exploit Complex Systems Science. Since the complex systems community has expertise in networks and their dynamics, a strong case can be made for support to coordinate complex systems research and its applications in the private and public sectors.

However, such an attempt should be organized in ways that differ profoundly from the traditional discussion between scientists and business or other 'end users' of the scientific research. Rather than being the end-users, the business and civil community should be the providers of the questions, issues and problems that motivate and direct the research of the scientists. The Santa Fe Institute is an interesting case in point, where business not only provides (relatively modest) discretionary ('pump-priming') research funds for the Institute, but meets informally with its scientists at least two times a year. These meetings provide an occasion to network, as well as to exchange the latest information, and new insights, between the two communities.

That model fits into a much more generalized attitude of investment by the civil and business society in institutions of higher education. But the advantage of the (considerable) sums thus raised for Universities dwindles alongside the importance of the fact that this support is of a very diverse nature, because there are so many different individuals, agencies, industries and foundations involved. One of Europe's greatest disadvantages is the relative uniformity of its funding channels.

1.11 Conclusions

If one compares, for a moment, the situation in the US and in Europe, the massive investment by US Universities and large companies in Complex Systems Science in the last few years is striking. Whole new departments are created with anywhere from 30-60 researchers. However, Europe's strength is that it has emphasised the coherent organization of the whole Complex Systems community, across countries and disciplines. In the longer term, this could be an important advantage. Europe can therefore become a long-term world leader of Complex Systems Science by coherent use of the main instruments of FP7 : the "Ideas" program for addressing fundamental questions through complex systems research; the "Cooperation" program for addressing the main societal Grand challenges through the development and application of specific classes of complex systems solutions; the "Human Resources" program for rapidly bootstrapping and training a new generation of several thousand young researchers; and the "Capacity" program for developing the big instruments and platforms needed for the new science.

In this roadmap a number of areas of focus for investment in complex systems are identified, including fundamental research, European platforms for research, education, and coordination of research with its applications in the private and public sectors.

Complex systems science will increasingly be at the heart of the future European Knowledge Society, and is essential for it to be effective and democratic. Its interdisciplinary nature can help to stimulate the harmonious integration of scientific and technological endeavour. It encourages a Europe-wide debate on science and technology and their relation with society and culture.

The fundamental importance of ICT in complex systems science cannot be over-stated. Complex systems science is ICT-enabled and this will require a very large investment at European level.