The CSS Roadmap for Complex Systems Science and its Applications 2012 – 2020

Edited by Paul Bourgine, Jeffrey Johnson, and Davis Chavalarias 7th March 2012

Executive Summary

The new science of complex systems is providing radical new ways of understanding, modeling, predicting, managing the physical, biological, ecological, and social universe. Complex systems are characterised by emergent structures that occur in many domains and questions that apply across the domains in the modern world. Such integrative complex systems science is crucial to the economic and social wellbeing of Europe knowledge society and its citizens. Thus research and education in this area must be central to the European Commission's Horizon 2020 programme.

The new science will progress through their ubiquitous *in vivo* and *in toto* multilevel observation, the ubiquitous multilevel data assimilation by their integrated predictive models, the ubiquitous learning of these integrated models by their associated serious games, the ubiquitous computing of their robust, preventive or resilient individuated strategies in face of their external and internal perturbation and extreme events. Radical new strategies of research and teaching are necessary for *all the previous transversal questions* through *all kind of complex systems*, from atoms to complex matter, from the molecules to organisms, from organisms to the ecosphere, from neurotransmitters to the individual and social cognition, from individuals to human society.

This living roadmap is devoting to each transversal question and each kind of complex systems a chapter presenting their scientific and societal challenges. Its important innovation is its proposition of a Complex Systems Digital Campus (CS-DC) for collective e-science and e-education strategies dealing with all its challenges and for mutualizing them. The CS-DC is a scientific cloud computing ecosystem for e-research and e-education working as a social intelligent ICT system. Having established the research challenges, the research programme of the CS-DC is costing € 260 million per year based on the following recommendations:

1: A programme of living design of CS-DC as a social intelligent ICT system	€ 40 million/year
2: A programme to coordinate open data for research and value-added applications	€ 90 million/year
3: A programme of fundamental research into complex systems science	€ 40 million/year
4: A programme of applications-based research into exemplar complex system	€ 90 million/year

This huge effort is necessary for reconstructing the observed multi-scale dynamics relevant for the "human scales" in between the physics of the two infinites, the nuclear physics in one side and the cosmology in the other side. This huge effort has to be included *in a unique research programme* as for the two infinites physics programme and both programme has to *mutualize their scientific cloud ecosystems*. This huge effort has to be comparable, *given the high scientific value-added and the high societal value-added of complex systems at human scales*. This huge effort is comparable at the European scale to the *French effort of "investissements d'avenir"* with *the same 2020 horizon*.

The programme of CS-DC living design is devoted to mutualize all the software and hardware resources for research and education. Especially, an open forge of software solvers for the inverse problems in CS science will be mutualized. The design is starting with ASSYST roadmap and its Digital Campus as designed by a large work group of scientists from all disciplines and having received the consensus of the whole CS community. Their updating will be designed and submitted in the same way. This programme will have a very high impact on education : by 2020 it will enable the education of many the tens of thousands of Complex Systems Masters and PhDs required by the public and private sectors. Complex systems science combined with new ways of using ICT allows very large numbers of students to be educated in new ways that emphasize creativity, problem solving, and resilience – all at an unprecedented low costs, orders of magnitude less than the cost today.

The two programmes of applications-based research into exemplar complex system and of fundamental research into complex systems science has to be combined as for pure and applied research. It will provide employment for the best of the graduates, and provide the high skill base of highly adaptable problem solvers that European industry will increasingly need. The open forge of inverse problem solvers will be available for industry and its usage is scalable on private cloud computing.

The open data programme will create very diverse and new rich information resources to support the development of new areas or research and new enterprises, in particular through a huge variety of web services, serious games in all sector beginning with personalized health and education. Complex systems science can enable people to create new social and economic order. Complex systems students will be educated to use their creativity and research skills to create new enterprises and jobs, breaking the current cycles of employment boom and bust. The investment we propose in the science of complex systems will pay back many times within its own lifetime and make a major contribution to the social and economic wellbeing of Europe and its citizens for decades to come.

By bridging the gap between science and engineering, Complex System Science can involve more and more layers of the society, contributing in long term to a Citizen Cyberscience in the perspective of the knowledge society. It will contribute to the equality of chances and the more secure freedhom in responsible innovation. It will contribute to change the relations between Science, Engineering, Politics and Ethics.

Contributors to this and earlier road maps on which it is based include:

Fréderic Amblard, Pierre Auger, Jean-Bernard Baillon, Olivier Barreteau , Pierre Baudot, Soufian, Hugues Berry, Cyrille Bertelle, Marc Berthod, Guillaume Beslon, Daniel Bonamy, Danièle Bourcier, Paul Bourgine, Nicolas Brodu, Marc Bui,Yves Burnod , Bertrand Chapron, David Chavalarias, Catherine Christophe, Bruno Clément, Jean-Louis Coatrieux, Jean-Philippe Cointet, Valérie Dagrain, Katia Dauchot, Olivier Dauchot, François Daviaud, Silvia De Monte, Guillaume Deffuant, Pierre Degond, Jean-Paul Delahaye, René Doursat, Francesco D'Ovidio, Marc Dubois, Berengère Dubruelle, Marie Dutreix, Robert Faivre, Emmanuel Farge , Denis Diderot, Patrick Flandrin, Sara Franceschelli, Cédric Gaucherel, Jean-Pierre Gaudin, Michael Ghil, Jean-Louis Giavitto, Francesco Ginelli, Vincent Ginot, François Houllier, Bernard Hubert, Pablo Jensen, Jeffrey Johnson, Ludovic Jullien, Zoi Kapoula, Daniel Krob, Gabriel Lang, Chrsitophe Lavelle, André Le Bivic, Jean-Pierre Leca, Christophe Lecerf, Ales Pierre Legrain, Maud Loireau, Jean-Francois Mangin, Olivier Monga, Michel Morvan, Jean-Pierre Muller , Ioan Negrutiu, Edith Perrier, Nadine Peyreiras, Denise Pumain, Ovidiu Radulescu, Jean Sallantin, Eric Sanchis, Daniel Schertzer, Marc Schoenauer, Michèle Sebag, Adrien Six, Fabien Tarissan, Patrick Vincent.

The Society gratefully acknowledges the great contribution to this roadmap by the European FET project ASSYST funded uner FP7.

[1] The science of complex systems

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. 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, i.e. integrated models, presents a major challenge to modern science but it is becoming more and more accessible through ubiquitous cloud computing. These integrated models will be predictive through data assimilation. *Prediction* in the context of complex adaptive systems in changing, turbulent environment does not mean predict 'what will happen' but *'what can happen', in probability*.

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 reduces the gap between pure and applied science, establishing new foundations for the design, control and management of systems with unprecedented levels of complexity exceeding the capacity of current approaches. For example, in Health the new science of complex systems will revolutionize the medical treatment of diseases, and revolutionize the delivery of personalized targeted treatment of the individual. This requires (i) huge distributed databases of every individual's genotype, phenotype, medical and general history, (ii) new ways of assimilating multilevel data for individuated integrated models, (iii) new ways of participation to the serious game of one's own personalized health and (iv) new and more efficient ways organizing the delivery of personalized treatment to Europe's half billion inhabitants.

In this roadmap we will show that there is a distinctive research domain of complex systems and argue that it is fundamental to the science required for the 21st Century. We begin by giving a widely accepted view of science – that it is the process of reconstructing models and theory from data. We show that there is a large set of characteristics of systems that can make their behaviour 'complex'. Of these, one of the most significant is the ability of some systems to spontaneously reconfigure themselves and behave completely differently. For example, a group of unemployed young people can reconfigure themselves into a successful enterprise. Many systems, such as a clock or a conventional motorcar, cannot do this, even though they may be very complicated. The set of *characteristics* given in Figure 1 can apply to systems in many apparently unconnected domains, from physics to geography and economics. Thus they are not domain specific and their study across the domains is the business of complex systems scientists. The fundamental theory of complex systems science includes *mathematics, statistical mechanics and theoretical computer science* which also cut across the domains, *e.g.* climate change. Many important systems have subsystems from many domains which none of the individual domains can integrate. Integrating science across domains is precisely the challenge accepted by complex systems science. It is a major scientific challenge of the 21st century and significant research funding is needed. Without doubt, the science of complex systems can provide very high added value and CS research is essential to support a thriving European economy in the next decade.

Science is the process of reconstructing formal descriptions of systems from data. It is said that "the grand aim of all sciences is to cover the greatest possible number of empirical facts by logical deductions from the smallest possible number of hypotheses or axioms". Traditionally the validity or worth of a formal description of a system has been its ability to explain previous observations and predict future states. *For determinist prediction, the reconstruction of dynamics has to be exact (Δ=0 between the state dynamics). For stochastic prediction, the reconstruction of dynamics is up the same distribution of probability (Δ=0 between the probability law of the state dynamics, including its mean).*

For many years systems have been categorised into domains such as physics, chemistry, biology, psychology, sociology, economics, geography, philosophy, and so on. In the physical sciences this division enabled great progress and spectacular successes judged by the possibility of making replicable *predications* of their behaviour.

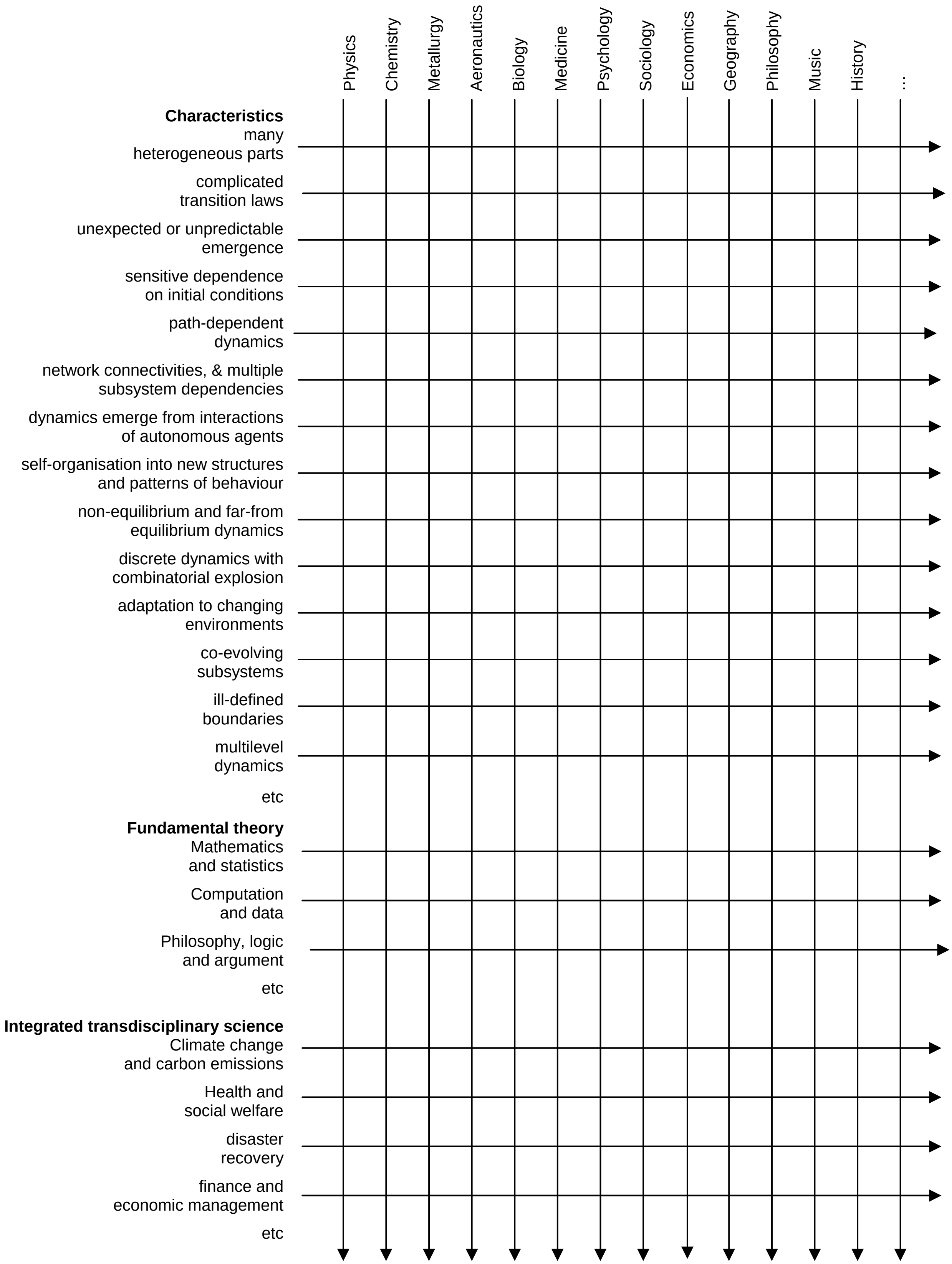

Figure 1. Complex systems science applies across the domains

Systems can exhibit many properties that make them appear complicated or complex. These include having: many heterogeneous parts, *e.g.* a city, a company, the climate; complicated transition laws, *e.g.* economic systems, disease transmission; unexpected or unpredictable emergence, *e.g.* chemical systems, accidents; sensitive dependence on initial conditions, *e.g.* weather systems, investments; path-dependent dynamics, *e.g.* qwerty keyboard evolution, international relations; network connectivities and multiple subsystem dependencies, *e.g.* ecosystems; dynamics that emerge from interactions of autonomous agents, *e.g.* road traffic, parties; self-organisation into new structures and patterns of behaviour, *e.g.* social grouping; non-equilibrium and far-from equilibrium dynamics, *e.g.* fighter aircraft, share prices; discrete dynamics with combinatorial explosion, *e.g.* chess, communication systems; adaptation to changing environments, *e.g.* biological systems, manufacturing design; co-evolving subsystems, *e.g.* land-use and transportation, computer virus software; ill-defined boundaries, *e.g.* genetically modified crops, pollution, terrorism; multilevel dynamics, *e.g.* companies, armies, governments, aircraft, and the Internet.

These properties are *horizontal* in that they cut across discipline domains which are researched *vertically* in great depth on the assumption that they can be isolated to a greater or lesser extent from the other domains. Thus economists and chemists tend to work in isolation from each other, as do metallurgists and psychologists This reflects it taking a decade to become a specialist in any domain and life being limited

The science of complex system is therefore different to any other particular science because it focuses on the *methods* of reconstructing the dynamics of systems of heterogeneous systems across the traditional domains. This methodological perspective and the trans-disciplinary nature of complex systems science make it unique in that it is an ***integrative science*** that strives to combine the methods, knowledge and theory of other domain-based science.

In the modern world it is increasingly realised that global systems are messy combination of many physical, technical and social systems. For example, the so-called ‘anthropocene era’ refers to the interaction between human behaviour and the Earth’s physical and biological ecosystems. Even epidemics have complex dynamics dependent on social structures, transportation patterns, and much else, while the current financial problems of the world arise from interaction between many subsystems and the emergent dynamics of these systems.

The scientific perspective of complex systems methodology is illustrated in Figure 2. As with all science it begins with *data* from which scientists reconstruct phenomenological models. For example, Kepler constructed a phenomenological model in which the planets sweep out equal areas in equal times which Newton formulated as a theory of planetary motion able to reproduce this phenomenology. In the case of the motion of two bodies, Newton’s Laws produce equations that can be solved explicitly making it possible, for example, to predict precisely where a cannon ball will land. In the three-body case the equations cannot be integrated and the system is chaotic. Nonetheless the spatio-temporal behaviour of the system can be *simulated* by iterated computation providing an augmented phenomenology (Figure 2, bottom right). The objective in this modelling is to produce an augmented phenomenology whose *statistical difference* from observation, Δ, is as small as possible (theoretically zero for a perfect model). In most cases simulations can at best sample the space of all system trajectories around given initial conditions and with an error, Δ, which measures the difference between the statistical distributions of the simulated trajectory and the statistical distributions of the data.

As an example for a social system consider the people evacuating a building in an emergency[1]. The motion of people in crowds is observed and a phenomenological model is created of the ways people move with respect to each other. Using this phenomenological model, an agent-based computer simulation can be used to create an augmented phenomenology for this system (Figure 2, bottom-centre). A theoretical

[1] As done, for example, in the scientific success story of Dirk Helbing

model of pedestrian flows can be proposed and permit spatio-temporal simulations to create another augmented phenomenology (Figure 2, bottom-right).

In this case both the agent simulation and the theoretical model gave an augmented phenomenology with small error. In fact this new science can assist the authorities to redesign Mecca for the Hajj pilgrimage which hitherto was subject to fatal accidents with large numbers of people being trampled as the dynamics of the crowd changed. This is one of the major success stories of complex systems science.

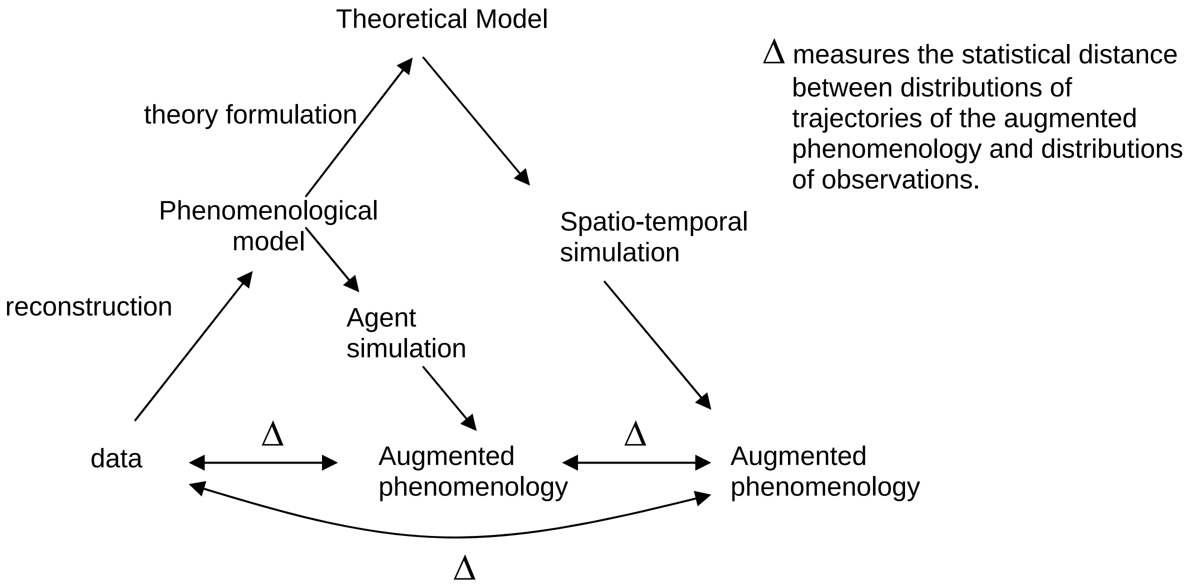

Figure 2. The complex systems methodology for reconstructing models from data

2. The Grand Challenges for Complex Systems Science 2012 - 2020

The 2010 ASSYST roadmap identified a variety of challenges which remain relevant. These are summarised below, augmented by new challenges in ICT and formal aspects of complex systems science. They are organised under three main headings: 1. Questions – the transversal questions of interdisciplinary integrative science; 2. Objects – questions related to specific objects and vertical domains of study; 3. Education and Professional Practice – questions related to the practical problems of educating and re-educating large numbers of people in the new science, taking the science into applications in the private and public sectors, and understanding how the needs of global and local policy will direct and support the development of new science.

1. Questions[2]

1.1. Formal epistemology, experimentation, machine learning

Grand Challenges
1. Computer tools for exploration and formalization
2. Computer assisted human interactions

1.2. Stochastic and multiscale dynamics, instabilities and robustness

Grand Challenges
1. The cascade paradigm
2. Random dynamical systems and stochastic bifurcations
3. Phase transitions, emerging patterns and behavior
4. Space-time scaling in physics and biology

1.3. Collective behavior in homogeneous and heterogeneous systems

Grand Challenges
1 Collective dynamics of homogeneous and/or heterogeneous units
2. Collective dynamics in heterogeneous environments
3. Emergence of heterogeneity and differentiation processes, dynamical heterogeneity, information diffusion

1.4. From optimal control to multiscale governance

Grand challenges
1. Extending the scope of optimal control
2. Projecting complex dynamics into spaces of smaller dimension
3. Projecting optimal control into high and multiscale dimension space
4. Extending exploration / exploitation compromise to problem reformulation
5. Co-adaptation of governance and stakeholders' objectives
    5.1 The static dimension: governance in the context of heterogeneity of stakeholders, points of view and interests
    5.2 The dynamical dimension: evolution of stakeholders' objectives and viewpoints in the governance process

1.5. Reconstruction of multiscale dynamics, emergence and immergence processes

Grand challenges:
1. Building common and pertinent references in the life sciences.
2. Achieving coherence in the modeling of complex systems.

[2] Details of the challenges and background discussion can be found in the 2009 ASSYT Roadmap. http://www.assystcomplexity.eu/db/assyst/ASSYST_roadmap2009_2.pdf

3. Development of mathematical and computer formalisms for modeling multi-level and multiscales systems.

1.6. Designing artificial complex systems

Grand Challenges:
1. Using artificial complex systems for the understanding and regulation of natural complex systems
2. Finding inspiration in natural complex systems for the design of artificial complex systems
3. Building hybrid complex systems.

1.7 Petascale Computing

Grand Challenges:
1. Coordinating huge open-access databases.
2. Data security and privacy – understanding reputation and trust dynamics.
3. The Ultimate Google: new methods of search and data synthesis.
4. New computational architectures for massively parallel and distributed computation
5. Self-configuring self-repairing ICT systems
6. The dynamics of computation – sequential system dynamics

1.8 Formal Aspects of Complex Systems Science

Grand Challenges
1. New statistical theories for predication, experimentation and testing in complex systems
2. New mathematics for representing huge heterogeneous multilevel dynamics
3. From phenomenology to scientific theory: from correlation to entailment
4. Logics and metalogics for integrative science
5. Creating demonstrators of complex systems science and its applications
6. Devising new methods for rapid synthesis of heterogeneous domain-based science
7. Devise new methods for information aggregation and processing, and social learning.
8. New theories of risk and dynamical models of extreme events

2. Objects

2.1. Complex matter

Grand challenges
1. Non-equilibrium statistical physics
2. Damage and fracture of heterogeneous materials
3. Glassy dynamics: glasses, spin glasses and granular media
4. Bifurcations in turbulence: from dynamo action to slow dynamics

2.2. From molecules to organisms

Grand challenges
1. Fluctuations and noise in biological systems
2. Stability in biology
3. Multiscaling
4. Human physiopathology

2.3. Physiological functions

Grand challenges:
1. Integrating multimodal measurements and observations of physiological activities at different spatial and temporal scales.

2. Characterizing the contextual features determining the onset of operation, maintenance and modulation of a physiological function.
3. Investigating the relationship between the ontogenesis of a physiological function and its potential disorders.

2.4. Ecosystemic complexity

Grand challenges:
1. Develop observation and experimental systems for the reconstruction of the long-term dynamics of ecosystems.
2. Model the relationships between biodiversity, functioning and dynamics of the ecosystems.
3. Associate integrative biology and ecology to decipher evolutionary mechanisms.
4. Simulate virtual landscapes (integration and coupling of biogeochemical and ecological models into dynamic landscape mock-ups).
5. Design decision-support systems for multifunctional ecosystems

2.5. From individual cognition to social cognition

Grand Challenges
1st Challenge: Individual cognition, cognitive constraints and decision proceses
2nd Challenge: Modeling the dynamics of scientific communities
3rd Challenge: Society of the Internet, Internet of the society

2.6. Innovation, learning and co-evolution

Grand challenges:
1. Understanding dynamic conditions of innovation
2. Modeling innovations and their rhythms
3. Understanding the relation between cognition and innovation

2.7. Territorial intelligence and sustainable development

Grand challenges:
1. Understanding territorial differentiation.
2. Towards a reflexive territorial governance
3. Viability and observation of territories

2.8. Ubiquitous computing

Grand Challenges
1. Local design for global properties (routing, control, confidentiality)
2. Autonomic Computing (robustness, redundancy, fault tolerance)
3. New computational models: distributing processing and storage, fusion of spatial, temporal and/or multi-modal data, abstraction emergence
4. New programming paradigms: creation and grounding of symbols (including proof and validation)

2.9. Geosciences and the environment

Grand Challenges
1. Understanding and reducing uncertainties.
2. Out-of-equilibrium statistical physics of the Earth system
3. Geoscience, the Environment, Policy and Citizens

3. Education, Training and Professional Practice

3.1 Education and Training

Education is at the heart of policy in Europe and worldwide. The European Commission states that "in the field of education and training the mission of the EC is to reinforce & promote lifelong learning" and "Enable individuals to pursue stimulating learning opportunities" where "lifelong learning is a key to both jobs and growth". The UNESCO educational mission is "to create learning societies with educational opportunities for all populations" and "to offer quality education for all".

Today employers complain that schools and universities do not produce people well trained to participate in the public and private sectors. Old expectations of education no longer hold. In particular the silo-based education that compartmentalises academic knowledge is failing, both in terms of teaching domain knowledge but more importantly our schools and universities are not educating people to be creative and resilient members of society. In countries such as the UK education is driven by the iron regime of subject-based tests that leave little room to develop creativity, teamwork, social and problem solving skills. The science of complex systems can change this. It can provide new insights into epistemology and the social and cognitive nature of learning. ICT is opening up completely new ways of teaching and learning and the science of complex systems is perfectly positioned to lead the way to much more effective education for the citizens of tomorrow.

Education is a complex system. It is a system of systems of systems, embedded in socio-economic systems of systems of systems. Complex systems science can coordinate and inform the huge efforts already underway to create new and more appropriate education systems. It offers new data sources that can inform education. Network science and related methods can give new insights into education as a social system. New methods of display can enable educationists to see new patterns, and give new insights into human social cognition, teaching and learning. If education must be measured, new ways can be devised to gauge what is important, including new measures of 'soft' criteria such as creativity and resilience.

We are entering a new educational epoch that will include personalised learning, lifelong learning, networks of learners worldwide, new kinds of resource, new ways of creating and sharing resource (*e.g.* crowd sourcing), new kinds of social epistemic networks, new kinds of teacher training and new kinds of participatory platforms where people can meet. This is a critical – you only get one childhood.

The 2006 Roadmap for Complex Systems[3] gives a detailed discussion of the needs for education and training in European complex systems science. "The number of PhDs required in complex systems to begin the huge educational task ahead 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". Courses are beginning to appear but progress is slow. Currently there are about thirty European universities proving complex systems education, graduating a few hundred masters and doctoral students each year. As complex systems science increasingly moves into the mainstream of public administration, industry and commerce it is clear that many thousands more are needed for Europe to serve its citizens adequately over the next decade.

Initiatives such as the many residential schools organised by ASSYST and other coordination actions such PERADA are being very successful, but the numbers of students being educated is still far too small. One ray of hope is the new Etoile project funded by FET (Enhanced Technology for Open Intelligent Learning Environments) that aspires to provide no-cost educations to many thousands of students in Europe and worldwide. Etoile is based on new ICT developments in crowd sourcing and social networking. If it is successful it will have a major impact on technical education in Europe and worldwide. However much greater capacity is need at all levels, and to build capacity such activities will require considerable support.

[3] http://css.csregistry.org/tiki-download_wiki_attachment.php?attId=123

The 2006 roadmap discussed initial training of researchers, the international dimension including the Marie Curie programme, lifelong training and industry, including academic pathways, training courses (schools), specific actions for juniors and seniors, a European PhD in Complex Systems, and creating a European Open University for Complex Systems (now called the European Digital Campus), and worldwide collaborations with the OECD and UNESCO. There is progress in all these areas but much remains to be done.

Grand Challenges

1. Create new methods of education to create confident and self reliant people with a sense of self-worth who are creative, able to self-organise, resilient, good at networking and team work, educated across silo domains, and able to operate in complex changing environments
2. Enable orders of magnitude of people to learn better
3. Provide interdisciplinary education
3. Devise new methods for accelerated knowledge acquisition
4. Provide interdisciplinary and specialist lifelong education at low (no) cost.
5. Devise new methods of education to encourage creativity, social networking skills, teamwork, and individual resilience.
6. Work with UNESCO and others to disseminate complex systems education worldwide.

3.2 Professional Practice

Most complex socio-technical systems involve huge amounts of financial and political resource to plan and manage them. Whereas most social policy is experimental with uncertain outcomes, most scientists cannot do experiments on complex socio-technical systems because they do not have the mandate and they do not have the money. Government and local councils spend millions and billions of Euros on services and infrastructure for health, transport, agriculture, utilities, housing, welfare, and so on. The many try-it-and-see policy experiments involved are not instrumented from a scientific perspective, and society does not learn efficiently from its mistakes. There is a huge and urgent task for complex systems science to engage with policy in ways that policymakers find useful. But this involves ways of working that are unfamiliar to many complexity scientists who, despite their professional knowledge, rarely have experience of making practical decisions about large complex systems, or balancing many delicate competing requirements in the context of poor data and poor understanding. Policy makers are often masters of managing complexity. However policy makers will increasingly need complex systems scientists to advise on the possible outcomes of policies and to suggest new ways for dealing with new and unprecedented problems. In the United Kingdom the Royal Society runs a scheme to connect scientists with senior civil servants and members of parliament. Such schemes could be implemented across Europe at local, national and European levels.

Similar arguments apply to connecting complex systems science to business and industry. In particular complex systems science should be able to provide insights into the personal, social and economic dynamics of start-ups and creating the kinds of environment that can enable individuals to generate new economic activity bottom-up in the context of new kinds of financial structures such as microcredits, new kinds of social dynamics such cascading information systems and social networking.

Grand Challenges

1. To connect complex systems scientists better to policy makers
2. To connect complex systems scientists better to business can commerce
3. To focus complex systems science on the spontaneous creation of economic activity and wealth
4. To connect complex systems science and its potential better to the general public

4. Recommended policies to the EC for supporting Complex Systems

The EC proposes €80 billion for Horizon 2020 [4] for the next programme period (2014-2020). The budget for FP7 is at €52 billion (2007-2013). In addition, the fields of education and vocational training are to be strengthened and it is proposed to overcome current fragmentation in the area by creating a new integrated programme for education, training and youth. The budget earmarked for this is €15.2 billion, and the aim is to have a clear focus on developing skills and mobility.

Given the fundamental importance of complex systems science across all areas of R&D we propose that 1.6% of this budget should be devoted as a line-item for complex systems science, *i.e.* €40 million per year. In particular we recommend

Recommendation 1: The Digital Campus for Education and Research

The new integrated programme for education, training and youth should explicitly contain programmes for education in complex systems science. In particular 1.6% of the €15.2 billion budget, € 40 million per year, should be allocated to education and training in multidisciplinary complex systems science. Based on its highly innovative approach to low-cost high quality education complemented by extensive experience in high-quality master-class schools and extensive use of social intelligence and social networking education, the complex systems community can provide excellent value for money. Furthermore the many of educational services provided by the complex systems community are *scalable* and can be provided at almost no cost to very wide communities of learners across Europe.

This recommendation suggests extending the Digital Campus to coordinate all research in complex systems science with the programmes of education suggested. Thus the digital campus will have a Digital Library providing access to all complex systems resources for students and researchers. The digital campus will provide virtual spaces where researchers can meet and exchange ideas. It is suggested that all funded European complex systems projects should be required to deposit all their publications and research outputs with the digital library, including all data and all programmes used to process those data. Apart from delivering education, the European Digital Campus can coordinate a distributed network of high throughput platforms for multiscale multimodal data, a distributed network of IaaS (Infrastructure as a Service) in a scientific cloud computing, a library of inverse problem solvers and autonomic computing (Figure 2), and human resources. The coordination role of the Digital campus, including organising complex systems residential schools throughout Europe will cost €40 million per year.

€40 million/year

Recommendation 2: A programme to coordinate data for research and value-added applications

Data lies at the heart of complex systems science and Europe desperately needs new open-access data repositories. Research is urgently required so that we have ‘an internet you can trust’ and an internet that can trust you to use data ethically and responsibility. Research is also required into the cost and value of data, including how publicly funded data becomes privately controlled, and how data collected by the private sector such as telephone and electronic transaction data can be made available to researchers. Research is also required into new methods of synthesizing data from many heterogeneous sources into forms that can be used for research and problem-solving in the public and private sectors. Consideration should be given to creating a ‘synthetic micropopulation’ for the whole of Europe as the basis of bottom-up modelling at local, national, regional and European levels.

€90 million/year

Recommendation 3: A programme of fundamental research into complex systems science

We have identified the following areas for fundamental research into complex systems science

1.1. Formal epistemology, experimentation, machine learning

[4] https://ktn.innovateuk.org/web/energyktn/articles/-/blogs/5095877

1.2. Stochastic and multiscale dynamics, instabilities and robustness
1.3. Collective behavior in homogeneous and heterogeneous systems
1.4. From optimal control to multiscale governance
1.5. Reconstruction of multiscale dynamics, emergence and immergence processes
1.6. Designing artificial complex systems
1.7 Petascale Computing
1.8 Formal Aspects of Complex Systems Science

Each of these could be delivered by calls under FET Proactive funded at € 30 million each or an average of € 30 million x 8 areas / 6 years = € 40 million per year

€40 million/year

Recommendation 4: A programme of applications-based research into exemplar complex system

We have identified the following areas for applications-based complex systems research:

2.1. Complex matter
2.2. From molecules to organisms
2.3. Physiological functions
2.4. Ecosystemic complexity
2.5. From individual cognition to social cognition
2.6. Innovation, learning and co-evolution
2.7. Territorial intelligence and sustainable development
2.8. Ubiquitous computing
2.9. Geosciences and the environment

Within these headings there is scope for a wide variety of research calls. Again some of these could be calls under FET Proactive and some could be developed under FET Open. Since complex systems science integrates many disciplines, calls should also be made from within the thematic areas developed for Horizon2020. The actual values allocated to any of the areas identified will vary, but it is essential that funding is available at an average of no less than € 10 million per year each.

€90 million/year

5. Outcomes and Impact

Through many projects and the European Digital Campus for Complex Systems the proposed programme of research will have a very high impact on European scientific education and research. By 2020 it will enable the education of many tens of thousands of students to Masters and PhD level as will be required by the public and private sectors. These students will be educated in new ways that emphasize creativity, problem solving, and resilience. By exploiting the methods of complex systems science combined with new ways of using ICT very large numbers of students will be educated at unprecedentedly low costs, orders of magnitude less than the cost today. This very highly qualified and well motivated population will be the backbone of European industrial recovery, inventing and designing all kinds of new social, physical and socio-technical systems. Our proposed programme of pure and applied research will provide employment for these graduates. It will also provide the high skill base of adaptable problem solvers that European industry will increasingly need. Our programme of open data bases will create rich information resources to support the development of new areas or research and new enterprises. Furthermore many of these people will be educated to use their creativity and research skills to create new enterprises, breaking the cycles of employment boom and bust experienced today. Complex systems science can enable people to create new social and economic order including enabling them to create jobs for themselves and others. The proposed Horizon 2020 programme of research and education in complex systems science will impact on every part of the public and private sectors, helping Europe to become economically strong and socially secure. The investment we propose in the science of complex systems will pay back many times over within its own lifetime.