The CSS 2008 Roadmap (http://cssociety.org/tiki-index.php?page=Living+Roadmap&bl=y)

The French roadmap for complex systems: March 2008

In general terms, a complex system is any system comprised of many, heterogeneous entities, in which strong interactions among those entities create multiple levels of collective structure and organization. Examples include natural systems, ranging from bio-molecules and living cells up through the ecosphere and human social systems, as well as sophisticated artificial systems such as the Internet, the electrical grid or any large-scale software system. What sets complex systems specificity either not addressed or largely under investigated by traditional science is the emergence of non-trivial superstructures that often dominate the system's behavior and cannot in any easy way be traced to the properties of the constituent entities themselves. Not only higher emergent features of complex systems arise out of the lower level interactions but also the patterns they create act back on those lower levels. In many cases, complex systems possess an impressive robustness to even large scale or multi-dimensional perturbations and other disruptions; and they have an inherent ability to adapt or persist in a stable way. Because of their inherent complexity, which requires analysis at many scales of space and time, science faces novel challenges in learning to observe complex systems, to describe them effectively, to construct them to meet a specification and to develop theories for their behavior and control or management. For artificial complex systems, there is an extra challenge to build them to adapt and persist stably, and this is likely to involve modelling at different levels of detail, from their specification down to their realisation.

Complex systems therefore need intrinsically an interdisciplinary approach: first, because all the questions they address appear in almost the same formulation on objects belonging to extremely different disciplines – from biology to computer networks to human societies; second, because the models and methods to tackle these questions also belong to different disciplines – mainly computer science, mathematics and physics; last, because standard specialized approaches rarely focus on multiple level approaches needed in the context of complex systems, and reachable through more integrated and interdisciplinary approaches.

Two types of interdisciplinary approaches are mainly possible. The first consists in working on an object of research that is intrinsically multidisciplinary, like for instance cognition: it results in raising various questions about the same object starting from viewpoints which can be very different, in contrast to more integrated and interdisciplinary approaches. The second consists in studying the same question in connection with different objects of research. It is this second approach that concerns a science of complex systems. However, the success of these two approaches, complementary one of the other, is intrinsically dependent on the design of new protocols, new models and formalisms for reconstructing emergent phenomena and dynamics at all scale. It is in this joint goal of massive data acquisition on the basis of a set of prior assumptions and their reconstruction by modeling that a science of complex systems can develop. There remains much to do in the theoretical domain to build concepts and models capable of providing elegant and meaningful explanations to the so-called "emergent" phenomena characterizing complex systems, and for in the case of artificial systems even to predict emergent phenomena.

The goal of this roadmap is to identify a set of wide thematic domains for complex systems research over the next five years. Each domain is organized either around a specific question or phenomenon and proposes relevant "grand challenges" – clearly identifiable problems, the solution of which would stimulate significant progress in both theoretical methods and experimental strategies.

Theoretical questions are varied. An important aspect is to take into account the different levels of organization. In complex systems, individual behaviors lead to the emergence of collective organization and behavior at higher levels. These emergent structures influence individual behavior in return. This raises important questions: what are the various levels of organization and what are their characteristic scales of space and time? How do reciprocal influences operate between the individual and collective behavior? How can we simultaneously study multiple levels of organization, as is often required in problems in biology or social sciences? How can we efficiently characterize emergent structures? How can we understand the changing structures of emergent forms, their robustness or sensitivity to perturbations? Is it more important to study attractors of the dynamics or families of transients? How can we understand slow and fast dynamics in an integrated way? Which special emergent properties characterize complex systems that are particularly capable of adaptation in changing environments? During such adaptation, individual entities often appear and disappear, creating and destroying links in the graph of interactions. How can we understand the dynamics of these changing interactions and their relationship to the system's functions?

Questions related to the reconstruction of dynamics from data play also a central role. These include questions related to the epistemic loop – the problem of moving from data to models and back to data, including model driven data production – that is the source of very hard inverse problems. Other fundamental questions arise around the constitution of databases, or the selection and extraction of stylized facts from distributed and heterogeneous databases, or the deep problem of reconstructing appropriate dynamical models from incomplete, incorrect or redundant data.

Finally, some questions are related to governance and design of complex systems. Complex systems engineering concerns a second class of inverse problems. On the basis of an incomplete reconstruction of dynamics starting from data, how can we steer system dynamics toward desirable consequences or at least keep the system away inside their viability constraints? How control can be distributed on many distinct hierarchical levels in either centralized or de-centralized ways – a so-called complex control. And finally, how is it possible to design complex artificial systems, integrating new way of studying their multilevel control?

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All these general questions are detailed in the roadmap. The first questions concern different aspects of emergent phenomena in the context of multi-scale systems. The question of reconstructing multi-scale dynamics addresses the problem of dealing with incomplete, badly organized and under qualified data sets. Another important aspect to consider is the importance played in complex systems by the reaction to perturbation: it can be at once weak in certain components or scales of the system and strong in others. These effects, central to the prediction and control of complex systems and models, must be specifically studied. In addition, it is also important to develop both strategies for representing and extracting pertinent parameters and formalisms for modeling morphodynamics. Learning to successfully predict multi-scale dynamics raises other important challenges, as the question of being able to go from controlled systems to governed systems in which the control is less centralized and more distributed among hierarchical levels. The last general question addressed in this roadmap concerns the conception of artificial complex systems.

Grand challenges for complex systems research draw their inspiration from different kinds of complex phenomena arising from different scientific fields. Their presentation follows the hierarchy of organizational levels of complex systems, either natural, social or artificial. Understanding this hierarchy is itself a primary aim of complex systems science.

In modern *physics*, the understanding of collective behavior and out-of-equilibrium fluctuations is increasingly important. *Biology* (in a wide meaning of the word – going from biological macromolecules to ecosystems) is one of the major fields of application in which complex behaviors must be tackled. Indeed, the question of gaining an integrated understanding of the different scales of biological systems is probably one of the most difficult and exciting tasks for researchers in the next decade. Before hoping to be able to integrate a total hierarchy of living systems, going from the bio-macromolecules to ecosystems, the integration between each level and the next one has to be studied. The first one concerns the cellular and subcellular spatio-temporal organization. At a higher level, *the study of multicellular systems* (integrating intracellular dynamics, such as regulation networks, with cell-cell interactions) is of great importance, as is the question of the impact of local perturbations in the stability and dynamics of multicellular organizations. Continuing on the way to larger scales raises the *question of physiologic functions* emerging from sets of cells and tissues in their interaction with a given environment. At the largest level, *the understanding and control of ecosystems* requires integrating interacting living organisms in a given biotope. In *the context of human and social sciences* also the complex systems approach is central – even if for the moment less developed than in biology. One important domain to be investigated is learning how the individual cognition of interacting agents leads to social cognition. An important situation requiring particular attention due to its potential societal consequences is related to *innovation, its dynamical appearance and diffusion*, frequency and coevolution with cognition. The complex systems approach can also help us to gain an integrated understanding of all components, hierarchical levels and time scales in a way that would help to move society toward sustainable development. In the context of globalisation and the growing importance of long distance interactions through a variety of networks, complex systems analysis (including direct observations and simulation experiments) can help us explore a variety of issues related to the environment, economic development or social cohesion at different geographical scales.

Finally, the growing influence of *information technology* in our societies and the decentralized networks based on it also demands a specific focus by complex systems research. In particular the movement going from processors to networks leads to the emergence of the so called *ubiquitous intelligence* that plays an increasing role in the way to design and manage the networks that will be fundamentally important for the future. In general, the development of vast complex software systems that manage themselves requires great advances in the mathematical and logical science that must underlie them.

Contents of the Roadmap

Reconstruction of multi-scale dynamics, emergence & immergence processes

The data related to complex systems are most often incomplete and difficult to exploit because they are limited to a single level, i.e. refer to observations made on particular scales of space and time. Gathering data effectively first requires the definition of common concepts and pertinent variables for models at each level. Another important problem is obtaining unified and coherent representations for integrating different levels of organization as to predict the dynamics of the complete system. This goal can be achieved by defining pertinent variables at each level of organization, i.e. at different time (slow/fast) and spatial (macro/micro) scales, their relationships, and how they are coupled together in models that describe the dynamics at each level. The challenge is to make explicit integration functions from micro to macro levels (emergence functions) and from micro to macro levels (immergence functions).

Keywords: Micro-macro reconstruction, multi-level experimental protocol, emergence, immergence, dynamical systems, multi-scale systems

Grand challenges:

1. Building common and pertinent references in the life sciences.
2. Achieving coherence in the modeling of complex systems.
3. Development of mathematical and computer formalisms for modeling multi-level and multi-scales systems.

1. Building common and pertinent references in the life sciences

The data relating to complex systems are often incomplete and therefore difficult to exploit. A main challenge is to find common methods to collect data at different levels of observation, which are coherent and compatible in the sense that they can be used in order to integrate a multi-level (multi-scale) system. Thus, it is necessary to find multi-scale models that allow researches to define pertinent experimental variables at each level and to achieve a common reference frame with data reproducibility in the different levels of organization of the complete system.

2. Achieving coherence in the modeling of complex systems

The goal is to find coherence in the definition of variables and models used at each level of the hierarchical system and to make compatible the models that are used to describe the dynamics at each hierarchical level of organization at given time and space scales.

As a first step, one must ensure that natural constraints are taken into account and that fundamental laws are verified at each level of description (definition of pertinent species, symmetry laws, physical laws, conservation laws and so on). The next step is to connect the description and models used at each level to those at other levels:

(i) Modeling the dynamics at microscopic levels can be useful for defining boundaries for global variables and even to obtain correct interpretations for global variables.

(ii) Modeling the dynamics at macroscopic levels can be helpful for defining local functions and variables governing microscopic dynamics.

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

The complexity of natural and social systems stems from the existence of several levels of organization corresponding to different time and space scales. A major challenge of complex systems science is to develop formalisms and modeling methods in order to rebuild the complete system by integration of its hierarchical multi-scale levels. *This goal can be achieved by defining emergence and immergence functions and integrating intra-level (horizontal) and inter-level (vertical) couplings.*

Mathematical models used to describe the dynamics of natural and social systems involve a large number of coupled variables at different space and time scales. These models are in general nonlinear and difficult to handle analytically. Therefore, it is crucial to develop mathematical methods that allow one to build a reduced system governing a few global variables at a macroscopic level, i.e. at a slow time scales and long spatial scales.

Among open questions, we mention the definition of pertinent variables at each level of organization and their relationships. It is also necessary to obtain emergence (resp. immergence) functions that allow analysis to jump from a microscopic (resp. macroscopic) level to a macroscopic (resp. microscopic) level, to study the coupling between the different levels and therefore the effects of a change at one level of a hierarchy on the dynamics at others.
Methods based on the separation of time scales already allow the aggregation of variables and are used in mathematical modeling for integrating different hierarchical levels. However, such multi-level modeling methods need to be extended to computer modeling and particularly to IBM (Individual Based Models) and constitute a very promising research theme. Also, the comparison of multi-level models to experimental data obtained at different levels remains also a major challenge which has to be investigated in parallel to the development of mathematical and computer modeling methodologies for multi-level systems.

Perturbations and robustness of complex systems

An important characteristic of complex systems is their sensitivity and robustness to different kinds of perturbations. This property is today weakly understood, but must be understood if we are to learn how to predict and control such systems. Complex systems are often the result of the coupling of different components and hierarchical levels, all having different characteristic times. As a result, complex systems at certain scales can always be observed in transient evolution, and understanding such evolution is a very important task, crucial for understanding the possibilities for system control. A second challenge relates to the importance of being able to identify the sensitivity to perturbations (appearing at any hierarchical level or on any component) both for systems and associated models. The last challenge tackles the question of the appearance of collective forms or patterns as complex systems evolve; this appearance is often made possible by the existence at many scales in the system of variations of different nature: it is the impact of these variations which it is necessary to study not only as such but also in an objective of prediction and control of emergence and stability of the forms and patterns.

Keywords: transient dynamics, sensitivity to perturbations, local variability, prediction and control, multi-scale dynamics.

Grand challenges:

1. Analysis and characterization of transients in multi-scale dynamical systems.
2. Identification and validation of sensitivities to perturbations in systems and their models.
3. Description and role of variation in the emergence and stability of patterns.

1. Analysis and characterization of transients in multi-scale dynamical systems

Complex systems typically involve the dynamical coupling of subsystems at multiple, hierarchical levels, each running on its own time-scale. Some of these dynamics will not reach their equilibrium during the characteristic time of the whole system; others may reach equilibrium, but then leave it as the result of perturbations from other system components or interaction with the external world. Therefore, the global system contains permanently subsystems in transience.

Most existing results about dynamical systems are related to equilibrium (attractors). When transient regimes are studied (that is when the system is out of equilibrium), it is often for isolated systems and with the goal of understanding the way it reaches equilibrium (for example in the case of the use of Lyapunov exponents). A very important challenge for complex systems research is therefore to comprehend the transients of dynamical systems, deterministic as well as stochastic, either isolated or appearing as subsystems of multi-scales systems.

2. Identification and validation of sensitivities to perturbations in systems and their models

Complex systems are subject to many perturbations. The analysis of their sensitivity to these perturbations is necessary to their comprehension, their prediction and their control. It is important, for a broad spectrum of disturbances, to be able to characterize the sensitivity and the robustness of the systems and their models. This approach provides essential information to the process of modeling. It can also bring very useful knowledge when the perturbations are not experimentally feasible.

Existing approaches to the analysis of sensitivity are not well suited to complex systems, given their multiple scales and often stochastic character. A challenge here is to develop experimental means for rationally exploring the space of possible perturbations, as well as ways to describe their influence on the dynamics of the system (or an associated model).

3. Description and role of variation in the emergence and stability of patterns

In nature one observes a great richness of forms or patterns over many scales. Understanding the emergence and stability of collective forms – living, cultural, climatic, etc. – requires integrating processes at work at many scales other than that at which these forms are observed. In most complex systems, variability is present at all observational scales. Understanding the impact of such variability on the emergence and the stability of collective patterns is a key challenge.

Meeting this challenge requires means for measuring variability and understanding the existing link between variations at the various scales and the appearance or the evolution of patterns. Is variability a condition for the emergence of these patterns? How does it influence the stability of the emergent patterns? Also, in what sense is the heterogeneity of elements within a system linked to its emergent properties?

Spatio temporal morphodynamics

Reconstructing shapes and morphodynamics brings terribly difficult challenges. How might we identify shapes in a flow of noisy images, with missing parts and taken at discrete time steps regularly spaced or not? What are the languages for shapes description that should be developed or even invented?

Keywords:

Grand challenges:

1. Designing strategies for representing and extracting relevant parameters according to the objectives of the reconstruction.
2. Designing morphodynamics formalisms

1. Designing strategies for representing and extracting relevant parameters according to the objectives of the reconstruction.

Examples:

2. Designing morphodynamics formalisms.

Expected results:

Examples:

From optimal control to multi-scale governance

When acting on a complex system, the institution in charge of its governance firstly faces the problem of defining desired objectives. Often, these objectives require integrating the conflicting interests and points of view of diverse stakeholders. Then, in order to compute policy actions to match the objectives, it is often necessary to build a good model of the phenomenon, and which includes the effect of the potential actions. (Here, we touch again on the general problem of modeling and reconstructing dynamics from data, addressed in another part of the roadmap). Unfortunately, current methods computing action policies (reinforcement learning, viability, etc.) are practically usable for models in state spaces of low dimensionality only. Complexity requires extending these methods to multi-scale and higher dimensionality dynamics, and multi-level actions (e.g. central and decentralized). Projecting multi-scale dynamics in smaller spaces, in particular using stylized dynamics, when possible, is another research direction that could open new possibilities for managing good policy actions on complex dynamics. Finally, dynamics are often uncertain and partially unknown, which implies a difficult compromise between exploitation of better known parts of the dynamics and exploration of worse known parts. This problem can be extended to the reformulation of the problem (including the objectives). This framework addresses similarly problems of control and of design.

Keywords: governance, control, multi-criteria, optimal control, viability, negotiation, multi-level, exploration/exploitation compromise, uncertainty, social acceptability, participation.

Grand challenges:

1. Formulating and reformulating the objectives.
2. Extending the scope of optimal control.
3. Projecting complex dynamics into spaces of smaller dimension.
4. Extending exploration / exploitation compromise to problem reformulation.

1. Formulating and reformulating the objectives

First, in a multi-level context, identifying the stakeholders and concerned territory is a problem in itself. Then, the main problem is to take into account a variety of objectives at different levels, which can be more or less negotiated. To solve this problem, one must often articulate the objectives emerging at the different levels.

Multi-criteria analysis is a starting point for solving these problems, but it must be enlarged in order to incorporate several objectives in parallel, and include the reformulation process. Moreover, the choice of indicators linked to the objectives or their achievement must include stakeholder participation and must be easy to use. On the other hand, one must carefully investigate the theoretical consequences of their choice, in particular the potential biases they may introduce.

2. Extending the scope of optimal control

Current methods of optimal control can deal with uncertain non-linear dynamics, and with flexible definitions of the objectives (in viability theory, for instance), but they are limited by the curse of dimensionality: these methods must sample the state space with a given precision, and this requires an exponential computational power when the dimensionality of the state space. Therefore extending these methods to spaces of larger dimensions is crucial to enable their use in the context of complex systems. Moreover, this enlargement should take into account possible distributed actions at different levels, particularly when they are decentralized.

3. Projecting complex dynamics into spaces of smaller dimension

Another possibility to tackle the limits of current control methods is to reduce the dimensionality of complex dynamics (for instance, through the identification of slower parts of the dynamics, the aggregation of the state space, the definition of stylized dynamics and so on). This type of work is also very important in negotiation and formulation processes, in order to give stakeholders intelligible materials from which they can easily express their views.

4. Extending exploration / exploitation compromise to problem reformulation

The compromise between exploration and exploitation is generally necessary in complex systems, when one must make experiments, and therefore spend resources to make experiments or take risks, in order to know better the system dynamics. These expenses must be compared with the potential benefit of such exploration, compared with the mere exploitation of known routines. Of course, they must also take into account the capacity to build good quality models from the exploration, and this connects with the modeling and reconstruction challenges of the roadmap.

This aspect of the problem touches on the question of governance, and must be appropriately communicated in a participative context. Moreover, the results of the exploration can lead to new views on the problem, and possibly new objectives of governance (taking into account, for instance, social acceptability), leading to a complete reformulation of the problem.

The conception of Artificial Complex Systems

Modeling and simulation are complementary tools for exploring complex systems. Complex systems research, recent and rapid in many scientific fields, induces strong interactions between scientific disciplines. It has been spurred by the growth of networks and high performance calculation. Today, information technologies are the favorite research tool within complex systems science. They replace analytic and phenomenological approaches in the study of emerging behaviors. In return, information technologies also benefit from complex system research. Such artificial complex systems are created to analyze, model and regulate natural complex systems. Meanwhile, the emergence and creation of new technologies must find a growing inspiration from natural complex systems, whether they are physical, biological or social.

Keywords: artificial assistants, virtual simulations, functional modeling, regulation, bio-inspiration, autonomous systems, multiplayers evolutive models.

Grand Challenges:

1. Using artificial complex systems for the understanding and regulation of natural complex systems,
2. Using inspiration from natural complex systems for the conception of artificial complex systems,
3. Conception of hybrid complex systems.

1. Using Artificial Complex Systems for the understanding and the regulation of Natural Complex Systems.

Natural complex systems (NCS) include those resulting from nature (biological organisms, ecospheres, etc.), as well as from human activity (towns, economy, transportation, etc.) One key application of artificial complex systems (ACS) is to assist in the study (descriptive, generative or consensus support) of NCS. The major objective is to develop systems that assist the methodical exploration and/or the regulation of NCS. In particular, the conception of such ACS can help human collective intelligence by integrating different levels of expertise in order to harmonize or manage their contradictions in collaborative works. The nature of such a system is different from the nature of the observed system, as they are based on different structures and functioning principles. An ACS could serve to regulate, schedule, repair or modify the NCS. The execution of ACS can be asynchronous and apart from the NCS, or it can be integrated with it.

Examples:

- Rebuild the topology of neural connections in the brain by the means of using neuro-imagery and artificial vision based on a distributed architecture.
- Observe theme-based interaction networks on the Internet (forums, blogs, instant messengings) through software agents.
- Airflight dynamics and network.

2.Using inspiration from NCS for the conception of ACS

In order to create technological systems that would be autonomous, robust and evolving, a new form of engineering will get inspiration from NCS. For example, in order to find security solutions against the perpetual assaults on computer networks, new systems will be able to mimic biological defenses. These ACS are thought to be distributed entities. They are auto-organizing and adaptive. They reproduce the initial behaviors and organizational principles that exist within NCS, but that have no equivalent in traditional technical conceptions. In certain fields, biology will replace physics as the basis of new engineering principles.

NCS also offer yet-unexploited inspiration as models for the realization of decentralized systems that could be robust, modular, and autonomous in dynamic environments (i.e.: “ubiquitous computing” or “ambient intelligence”). Thus, ACS can reproduce the principles of competition and coordination that are observed within NCS.

Bio-inspired artificial conceptions are not constrained by any need to respect the principles of the original NCS. Computer and technological innovation can free designers from experimental data or real examples of functioning mechanisms. Examples include neural networks inspired by bio-neurology and genetic algorithms by Darwinian evolution. ACS created this way can also acquire an *a posteriori* heuristic exploratory role for NCS. Exploring inventions allows us to better understand, and perhaps even to predict, the natural phenomena which inspired them.

Examples:

- Artificial intelligence and neuro-mimetic robotics.
- Collective optimization as a swarm inspired from social insects.
- Evolutionary robotics.
- Intelligent materials, auto-assembling materials, and morphogenetic nanotechnologies.
- Ambient intelligence.
- Immunity or social-inspired computer security.
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3.Conception of Hybrid Complex Systems

The growing spread of computing machines and systems in our society (cellphones, PDAs, etc.), and the complexity of their interconnections illustrate the construction of such hybrid systems. It is natural to model such systems as complex communities of natural and artificial agents that are autonomous and capable of learning.

Emergence in physics: collective behavior and fluctuations out-of-equilibrium

At or near thermodynamical equilibrium, spatial uniformity and temporal stationarity are the rule. Fluctuations around equilibrium states are well understood, and, to some extent, trivial. Transport properties are governed by linear response principles. Away from equilibrium, in contrast, when external constraints are applied or during extremely slow relaxation toward equilibrium (glassy dynamics), one observes the emergence of collective behavior at all scales, giving rise to complex patterns and dynamics as well as "anomalous" transport properties. The fluctuations around such global behavior are often singular, with single extreme events carrying enough weight to influence even long-term averages, and strong finite-size effects. Understanding the underlying mechanisms to these phenomena and identifying the universal features of these non-equilibrium situations is one of the major goals of physics in the 21st century.

Keywords: Morphodynamics, collective behavior, out-of-equilibrium fluctuations, extremal statistics.

Grand challenges:

1. Self-organization and spatiotemporal dynamics of complex matter.
2. Fluctuations out-of-equilibrium.
3. Metastable materials, slow relaxation and glassy dynamics.

Expected results: determine the basic mechanisms and universal behavior out-of-equilibrium, synthesis and self-assembly of complex materials, modeling of disordered systems, relevance beyond physics.

1.Self-organisation and spatiotemporal dynamics of complex matter

In the recent past, the physics of nonlinear phenomena has dealt with the patterns emerging out of instabilities taking place in simple media (such as pure fluids). Concepts such as self-organized criticality and dynamical roughening of interfaces have opened paths to the understanding of the many scaling laws and fractal structures observed in nature. The study of the synchronization and collective behavior of model chaotic systems generated new perspectives on multi-scale spatiotemporal dynamics.

Today, a central issue is to understand the phenomena emerging out of assemblies of more complex objects in interaction (self-propelled agents, nano-particles, biomolecules...). Examples include the emergence of collective motion (from the cooperative motion of molecular motors up to large-animal groups), the self-organization of bio-films and cellular tissues, morphogenesis and morphodynamics, and so on.

With these problems and their relevance to biology, ecology, and even sociology in mind, physicists favor model experiments performed on well-controlled systems kept out of equilibrium: complex fluids such as foams, gels or granular media when submitted to external fluxes (vibration, shear, etc.). The relative simplicity of these systems allows for a finer exploration and deeper understanding, and, often, the observation of the complete spatiotemporal dynamics, which is crucially needed for a meaningful confrontation to theoretical ideas and models.

2. Fluctuations out-of-equilibrium

The 20th century has seen the development of powerful theoretical tools to account for the behavior of systems near thermodynamical equilibrium. Such systems show well-defined average properties, and the fluctuations around these averages can be related to the response to small external perturbations ("fluctuation-dissipation theorem").

Out-of-equilibrium temporal and spatial fluctuations can be so large that it is then quite difficult to define the "typical" state of the system as an average over the fluctuations. For instance, how can one define the resistance to rupture of a material when this quantity is entirely governed by the most important defect? Can one make meteorological predictions given the sensitivity of the weather to small local perturbations? Can one design a risk-managing strategy in highly volatile markets? Physicists are now striving to develop formalisms able to tackle the statistics of the strong fluctuations observed in out-of-equilibrium systems. This implies in particular (i) a clear definition of "typical" behaviour and trajectories, (ii) to account for the scaling laws of fluctuations, and (iii) to extend fluctuation-dissipation theorems beyond equilibrium.

3. Metastable materials, slow relaxation and glassy dynamics

Disordered systems and in particular heterogeneous materials (glasses, colloids, emulsions, granular media, polymer blends...) often exhibit ultra-slow relaxation to equilibrium. Submitted to structural or kinetic constraints giving rise to frustration, the large number of their accessible configurations, make their return to equilibrium impossible to observe on physical timescales.

In such intrinsically non-stationary situations, dynamics is dominated by memory and aging effects so that the response to an external perturbation depends on the history of the material.

Understanding the interplay between structure and dynamics at all scales is a key issue for physicists and a necessary condition for the control of industrial processes and to the development of novel complex materials (adaptive glasses, self-repairing cements, "intelligent nano-materials"). Beyond physics, a number of fundamental problems in theoretical computer science (such as satisfiability questions) and in biology (protein folding, secondary structure of RNA, etc.) are intimately related to this challenge.

In vivo spatio-temporal dynamics at the cellular level

Understanding cell physiology requires integrating the dynamics at different scales of a large number of interacting heterogeneous components. Getting access to the spatio temporal dynamics of molecular processes at the cellular level is a challenge of the post genomic era. Such a goal requires the *in vivo* recording of molecular trafficking. Achieving this goal and designing methods and tools for the appropriate treatment, reconstruction and interpretation of the corresponding data requires interactions at the frontiers of disciplines. A synergy between experimentation to get *in vivo* measurements and the design of relevant theoretical models should lead to the characterization of emergent properties at different scales of molecular assemblies. A main objective should be integrating cell morphodynamics and metabolic, molecular and genetic networks dynamics. Ultimately, we might expect the modeling of a minimal virtual cell that should resume the fundamental constraints for cell survival that might differ whether this cell is prokaryotic or eukaryotic, isolated or in a multi-cellular environment.

Keywords: sub-cellular spatio-temporal dynamics *in vivo*, single molecule tracking and collective behaviors, multi-scale modeling.

Grand challenges:

1. Reconstructing the multi-scale spatio-temporal dynamics of cellular components.
2. Integrating cell morphodynamics and metabolic, molecular or genetic networks dynamics.
3. Towards the modeling of a minimal virtual cell.

1. Reconstructing the spatio temporal dynamics of cellular components

This should be achieved from the *in vivo* observation and recording of cellular components behaviour. In parallel, sub cellular compartments or macromolecular modules or structures with a relative autonomy might be isolated or reconstituted and observed *in vitro*. In any case, we might expect to achieve systematic molecules tracking with the design of appropriate probes and microscopic set up. Indeed, observation at the scale of individual molecules trajectories and processes will provide information about single events. Frequency histograms of the actual experimental values distribution rather than just mean values will provide the relevant measurements and parameters values for further modeling and understanding sub-cellular processes. Appropriate methods and tools should be developed for treatment of the corresponding data and design of relevant models. Some such methods may be based on theories of discrete/continuous processes coming from research in informatics. We expect from a multi scale analysis the characterization of the emergent properties of macromolecular assemblies within the cell.

Examples:

- Investigating the dynamics of membrane organization in live cell membranes,
- Investigating gene expression dynamics at a single molecule resolution (transcription, RNA maturation and protein synthesis).

2. Integrating cell morphodynamics and metabolic, molecular or genetic networks dynamics

A multi scale integration of sub-cellular processes should lead to understanding how metabolic, molecular or genetic networks dynamics underlie cell phenotypes. We expect here the link between networks structure and cell behavior through the characterization of networks spatio temporal dynamics. The challenge is here to go beyond the sole reconstruction of networks topology to get into their physiological meaning through their spatio-temporal dynamics and emergent properties at various scales including macroscopic cell phenotypic traits. Again, such dynamic models may come from informatics.

Examples:

- Reconstruction and multi-scale modeling of the cellular response to environmental changes.
- Coupling cell cytoskeleton dynamics and cell deformation, motility and proliferation rate.

3. Towards the modeling of a minimal virtual cell

Addressing the above challenges should contribute to the elaboration of a minimal virtual cell concept that should resume the properties and constraints of cell physiology observed at all scales thus defining the cell viability domain. The minimal virtual cell should be heuristic in at least two ways. First, by being the most integrated version of a multi-scale model for cell physiology it should help investigating the requirements for biological processes robustness. Second, it should help predicting and possibly controlling cell response and behavior in pathologic or therapeutic conditions.

The minimal virtual cell construction challenge, by defining the cell viability domain, might serve other challenges with experimental and theoretical duality such as the construction of a minimal cellular genome or the *de novo* assembly of a “living-like” cellular system.

Reconstructing the multi scale dynamics of multi cellular systems

Investigation of multi cellular systems and organisms should open new ways for an integrated understanding of their intrinsic complexity. This should be achieved through the reconstruction of multi scale dynamics from the *in vivo* observation and spatio temporal measurement of relevant parameters at all levels of organization. We expect a virtuous cycle between the living systems and their relevant models through experimentation and prediction. This should provide the basis for a renewed approach of living systems physiology opening the way for new therapeutic strategies.

Such a goal requires developing new investigation methods to observe and record the *in vivo* spatio temporal dynamics at different scales in order to achieve the tracking of single molecules as well as single cells in their physiological environment. Deciphering of emergent properties at different scales including stability and robustness, should lead to the understanding of the transition to pathological states.

Keywords: in vivo measurements, data integration, multi scale modeling, robustness and dynamical transition, emergence and immergence.

Grand challenges:

1. Designing new protocols for measuring the coupling of cell behaviors and intra-cellular genetic and molecular processes in multi cellular systems.
2. Exploring the dynamical robustness of multi cellular organisms.

1. Designing new protocols for measuring the coupling of cell behaviors and intra-cellular genetic and molecular processes in multi cellular systems

The genomic era provided powerful tools for investigating the genetic and biochemical content of cells and allowed constructing large databases greatly facilitating molecular biological approaches. However, we do not yet have the relevant observations and theoretical tools for understanding the multi scale dynamics of multi cellular organisms. Such a goal requires the *in vivo* observation and measurement of relevant parameters for sub-cellular molecular trafficking and cell morphodynamics as well as the *in vivo* recording of gene expression spatio temporal dynamics with a resolution at the cellular level. Getting access to this kind of data in multi cellular organisms and reconstructing this data with appropriate theoretical and computational tools to achieve a multi scale integration is the challenge of the post genomic era.

One might consider here any multi cellular organism or autonomous population of interacting cells whatever their fate and potency, proliferation rate or physiological state and functional properties. In any case, the aim is to understand how, in a multi cellular environment, the cell integrates genetic and molecular networks activity. This is a first step to approach multi cellular systems intrinsic complexity that requires close interdisciplinary collaboration for designing experimental procedures and choosing relevant measurements, reconstructing data and finding relevant models. We expect here an exemplar interaction between the biological system and its models through prediction and *in vivo* experimentation.

2. Exploring the dynamical robustness of multi cellular organisms

Multi cellular organisms through their life cycle and evolution through successive generations require remarkable properties of robustness and potential for variation. These properties are observed during embryonic development with the formation of morphogenetic fields as well as in adult organisms with the physiological maintenance and renewal of tissues. The aim is to decipher the relationship between fluctuation, variability and robustness in well-chosen multi cellular living systems. Robustness should emerge as a dynamical property when integrating both bottom-up processes from the genetic and molecular networks and top-down processes from local and global interactions including long distance coupling between cells through physical links such as electric potential or biomechanical forces. We might in addition expect here the exploration of how access to resources i.e. energy and matter acts as a major constraint in shaping organisms.

This challenge also aims at understanding the transition of biological systems towards pathological states.

Physiological functions

Physiological functions result from the integration of cells, tissues and organ properties in the context of the whole organism interacting with its environment. A complex system approach of physiological functions should lead to an iterated cycle combining relevant measurements and experimentation, modeling and simulation. Such a goal requires building multimodal investigation devices for simultaneous in vivo recording at different spatial and temporal scales of relevant parameters as well as designing theoretical methods and tools for appropriate modeling and computer simulation.

Keywords: *in vivo* observation and measurement devices, spatial and temporal multiscale observations, subcellular and supra-cellular functions, organism-environment interaction, ontogenesis, physiological disorders.

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.

Expected results include the design of new investigation devices and theoretical methods and tools for observing, modeling, understanding and then possibly controlling physiological functions.

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

An integrated observation of sub cellular and supra cellular processes requires to either:

(i) Translate in the same spatial and temporal referential heterogenous data recorded in the same organism but at different moments, or

(ii) Design new devices capable of simultaneously recording multimodal data.

The first goal can be achieved through available methods going from spatio-temporal matching to data fusion. These methods are limited by recalibration problems and errors (whatever the rigid or elastic transformations applied).

The second option would be a real breakthrough providing a generation of totally new instrumentation offering instantaneously access to essential structural and dynamic variables (chemical, electrical, mechanical, etc.) at all relevant spatio-temporal scales. This trend can be exemplified by macroscopic data acquisition in medical imaging with optical-PET and PET-CT devices and, for vital physiological variables, by ambulatory integrated sensors providing real-time patient state tracking in a normal environment. In the domain of vegetal biology, phenotypic plant platforms lead to the observation of flow from roots to leaves at different time scales.

Integrating such synchronous, multimodal, multiscale observations in relevant models should provide a good basis for the reconstruction of physiological functions.

2. Characterizing the contextual features determining the onset of operation, maintenance and modulation of a physiological function.

The objective is here to view the function as an integration of subfunctions that should be investigated from different perspectives or using perturbative and comparative approaches.

Different factors or conditions such as resting versus moving, diet-nutrition, training, can influence and move the system towards new functioning modes.

Comparative physiology provides a way to study the conservation or divergence of physiological functions. This approach is relevant for respiration and locomotion in the animal kingdom as well as for fruit maturation in the field of vegetal biology.

Physiological functions should be characterized through the extraction of high-level variables, i.e "thermodynamics variables" along the lines of allometry i.e. preservation of characteristics over the size variations). More generally, we should be able to define invariants (or invariant relationships) attached to physiological functions and the conditions for their conservation.

3. Investigating the relationship between the ontogenesis of a physiological function and its potential disorders.

Physiological functions should be explored through their set up during ontogenesis, maturation and maintenance during growth, adulthood and ageing. The dynamical behavior of physiological functions should be explored as well during pathological events.

Examples:

- Heart embryology: progressive formation of anatomical structures and functional patterns with ill-posed problems related to the partial observations at our disposal (i.e interpolation of highly structurally variable objects from the architectonic viewpoint, installation of nodal tissue functions or sinusal electric waves, etc.)
- Schizophrenia: effects on the highest cognitive levels of the modifications induced by the disease at the level of more elementary neurological functions

Ecosystemic complexity

Defined as the close association of an abiotic environment and a collection of living organisms, an ecosystem, essentially, is characterized by a great number of physicochemical factors and biological entities which interact with each other. The multiplicity and diversity of these interactions as well as the fact that they involve a vast range of levels of organization of Life and a broad spectrum of space and temporal scales justify the expression of "ecosystemic complexity".

Moreover, the ecosystems, be they natural, managed or artificial, are subjected to "perturbations" (e.g. natural hazards or biotic and abiotic stresses) and deliver many and diversified commercial and non-commercial products and "services". To identify, qualify, formalize and quantify these modes of disturbance and these products and services define research topics that refer, according to cases, to the sciences of the universe and/or the social sciences.

To account for this ecosystemic complexity, to understand the resilience of the ecological processes and to open the possibility of ecosystem management and control, require to articulate various strategies: for reconstructing the spatial and temporal dynamics, starting from observations and from increasingly instrumented experiments; for theoretically and experimentally identifying the retroactive mechanisms and the emergence phenomena; for modeling and validating these models.

Keywords: ecological dynamics, adaptation and evolution, ecological services, multi-functionality of the ecosystems, integration of data, coupling of models, networking, space-time dynamics, multi-scale models, disturbance and resilience, stability and dynamic transition, emerging behavior, feedback and retroaction, functional organization.

Grand challenges:

1. To develop observation and experimental systems for the reconstruction of the long-term dynamics of ecosystems.
2. To model the relationships between biodiversity, functioning and dynamics of the ecosystems.
3. To associate integrative biology and ecology to decipher evolutionary mechanisms.
4. To simulate virtual landscapes (integration and coupling of biogeochemical and ecological models into dynamic landscape mock-ups).

1.To develop observation and experimental systems for the reconstruction of the long-term dynamics of ecosystems.

Improvement of in situ systems of measurement (metrology and sensors); integration of data resulting from networks of observation (spatial and temporal sampling strategies, environmental research observatories) and/or of experiments (microcosms, mesocosms) in models of ecosystems; development of information systems based on a conceptual modeling of the studied ecosystems; multidimensional analysis of data coming from multiple sources ("meta-analysis"); search of invariants or adimensional parameters which enable upscaling.

2.To model the relationships between biodiversity, functioning and dynamics of the ecosystems

These relations, which play a central part in the very vast field of the studies relating to the biodiversity, are declined for various functions (production, transfers of matter and energy, resistance and resilience to perturbations, *etc.*), at different scales of space (station, landscape, area, continent) and of time, with the difficulty in articulating the short time of "functioning" and the long time of the "dynamics of the structures". Historically, the study of these relations was approached according to two reciprocal points of view: initially, wondering about the way the environment and the functioning of the living organisms and their interactions determine the assemblies of species; more recently, and in a reciprocal way, by studying the role of the richness and specific diversity in the way ecosystems function.

3.To associate integrative biology and ecology to decipher evolutionary mechanisms

To understand and model the response of the communities (structure, functioning and dynamics) to the changes of their environment (climatic changes, pollution, biological invasions, *etc.*) rest mainly on a better comprehension of the adaptive mechanisms. This task can now be supported by conceptual, methodological and technological progress made in integrative biology (genomic functional calculus, biology molecular, genetic, physiology and ecophysiology) and by the convergence of approaches from population, molecular and quantitative genetics.

4.To simulate virtual landscapes (integration and coupling of biogeochemical and ecological models into dynamic landscape mock-ups)

Conception of virtual mock-ups, based on a categorical representation of the landscape mosaic, would make it possible to build a typology of representative landscapes (hedged farmland, open field, mixed landscapes, forests, peri-urban areas, etc…). The following phases would consist in modeling: on the one hand, the functioning of the landscape (i.e. biogeochemical cycles, transfers and exchanges: air particulate transport, determinism of the microclimate, transport of water and of associated pollutants in the soil and the watersheds) with as a deliverable the production of functional relations between landscape topology and structure of the exchanges; on the other hand, the very dynamics of the landscape (*i.e.* evolution of its space organization) under the effect of the human activities and of certain ecological processes (for example, colonization of spaces by the vegetation). Such a tool would have a great utility in ecology or epidemiology, in the agronomic disciplines and for the local management of the territory.

5.To design decision-support systems for multifunctional ecosystems

Qualification and quantification of the products and services provided by the ecosystems; integration of these services and products in systems of indicators (dashboards, tools of decision-making assistance, life cycle analysis and eco-balance analysis, *etc.*); formalization and quantification of the perturbation regimes, the human practices and techniques, or the management systems relating to the ecosystems; coupling of models of different nature; taking into account of the stochastic components (whether those are intrinsic or that they are related to the incomplete character of knowledge on the elements of these systems, their interactions and the extrinsic factors likely to disturb them); multifactorial optimization.

From individual cognition to social cognition

Cognition, understood in a wide sense, is a form of information processing. At the individual level, cognition is an emergent process of the neural network within the human brain. How these higher level cognitive processes emerge from lower level dynamics remains largely unknown. In human society, the cognitive activity of individuals is deeply embedded or immerged in the social context, and becomes a form of social cognition. Again, social cognition is an emergent process, and involves the interactions within a social network. In social networks, agents process information content through series of interactions, producing other pieces of information and new social links. This process of social cognition thus leads to the transformation of the social network.

The modern and fast migration of social interactions towards digital media enables the massive collection of data in social cognition, at the level of both its processes (spatial structure of interactions, temporal distributions, etc.) and its products (online documents, user-focused data, etc.). The coexistence of these two phenomena opens today new perspectives for the study of individual and social cognition on the basis of benchmarking models with empirical data. This ought to be a major ambition for a better understanding of the evolution of our societies.

*Keywords***:** Social dynamics, decision criteria modeling, quantitative social measurement, social cognition, inter-individual heterogeneity

Grand challenges:

1. Understanding individual cognition, cognitive constraints and decision processes
2. Modeling the dynamics of epistemic communities
3. Reconstructing collective intelligence processes based on Internet

1. Understanding individual cognition, cognitive constraints and decision processes

The relationship between high-level and low-level cognitive processes remains an unsettled issue :the link between dynamic processes in the neural network and symbolic processes as they are being studied by psychology and linguistics is still open to question. A promising approach consists in exploring in a much more precise manner meso-scale spatio-temporal dynamics, as, for example, in cortical columns, synchronized neural assemblies (or, more broadly, polysynchronic assemblies) and so on. These collective spatio-temporal dynamics may be linked to important symbolic processes. In order to understand better the relationship between dynamic and symbolic processes, we require both theoretical and methodological research as well as the sharing data from very large databases.

Significant progress towards this challenge would not only lead to the unification of an essential aspect of cognitive science, but would also support the new discipline of neuroeconomics, which draws links between neural activity and the psychological and behavioral perspectives on human strategic and social interactions. From the perspective of economics, this brings hopes that decision theory could be revisited, as well as standard game theory, while developing more meaningful notions of « preference » and « utility » which are essential to economic theory.

2. Modeling the dynamics of epistemic communities

Epistemic communities constitute a privileged area for the study of social cognition because both the structure of the underlying networks (team organization, collaboration networks, co-authorship networks, citation networks) and the production of these communities (conferences, journals, papers) is known in a dynamic fashion. In order to exchange concepts, epistemic communities create their own language whose evolution reflects their own activity.

This makes it possible to address very precise topics pertaining to how these scientific communities are collectively processing information – to cite a few: how new concepts or new issues are being adopted? What are remarkable structures for innovation diffusion (effect of authorities, local traditions, etc.)? What is the effect of the breakdown of individuals in communities or the creation of links between communities on the development of knowledge? Which are the relationships between individual trajectories and community evolutions? What tools should we create to visualize these evolutions more clearly?

Examples:

- Emergence and diffusion of new concepts in bibliographical databases
- Detection of emerging fields
- Dynamics of collaboration networks
- Paradigmatic comparison of distinct epistemic communities

3. Reconstructing collective intelligence processes based on Internet.

The quantity of information stored on the Internet will soon have strongly overwhelmed that stored on paper. The Internet concentrates today various types of knowledge storage systems (papers, encyclopedias, etc.). It is also a place where discussions (weblogs, forums) and commercial transactions (auction and trade websites, web services) occur, and naturally produces massive systems of referencing (of individuals through personal web pages as well as for institutions and organizations). It also serves as an external memory for relationship networks (friendship networks, workgroups, etc.) and offers a kind of « world agenda » with hundreds of thousands of events which are being announced every day. How is this new tool modifying social cognition processes (new kinds of encounters, new kinds of exchange, new kinds of debates, new kinds of collective building of knowledge)? For the first time, we may empirically work on such questions while having data of considerable precision. How can we use these new sources of information to better understand social dynamics and to create and provide tools for visualizing the complexity of social activity within the Internet? A major challenge is to transform raw information available from the Internet in structured flows of information and to make it possible to visualize, model and rebuild social cognition processes at work on the web, in a multi-scale fashion.

Examples:

- Impact of weblogs in political and civil debates,
- New dynamics for the collective elaboration of knowledge (Wikipedia, open-source software, etc.),
- Measuring the propagation of social emotion following important social events,
- Comparative study of cultural differences through geo-localized information,
- Formation of epistemic communities, friendship networks, etc…

Innovation, learning and co-evolution

Novelty in complex systems appears under a variety of processes, through the emergence of new entities and new categories, through the modification of interaction processes, through changes of their temporal or spatial scales, through their dynamical transformation. Within a complex system science perspective, the main question is to know whether the modes of change are comparable when going from natural and artificial towards social systems. A first challenge is to identify which dynamic conditions are favorable to innovation. Is innovation always associated to jumps, ruptures or bifurcations, or can it proceed from more regular trends? Which processes are explaining the frequent observation of innovation cycles? A second challenge is to determine whether there is an acceleration of innovation in human society through time, by identifying relevant measures of societal changes. A third challenge is to understand how intention and reflection are framing the innovation in social systems and how the feedback effect of learning affects individual and collective cognition over historical time.

Keywords: innovation, emergence, bifurcation, co-evolution, learning, acceptance, society of information

Grand challenges:

Understanding dynamic conditions of innovation
Modeling innovations and their rhythms
Understanding the relation between cognition and innovation

1. Understanding the dynamic conditions of innovation

Can innovation only be analyzed ex-post, or can it be predicted, from which indicators and explanatory variables? Are the signs that announce the change in a specific regime of the system's dynamics, through the amplification of fluctuations around a trajectory, through intensification of pre-existing processes, or through the transition between quantitative toward qualitative variations? How innovation becomes accepted, through introducing itself in existing structures or by replacing them, or by inducing modifications of these structures, which make them compatible? Which relationships are established between new artefacts, new functionalities and the new practices that use them? What kind of factors the learning processes have to combine in order to link these different aspects together? How can be explained the formation of subsets of many innovations which lead to the observation of large cycles in the evolution?

2. Modeling innovations and their rhythms

Certain analysts suggest that there is an acceleration of the production frequency of innovations, especially through the technical revolutions and the evolution towards a society of information. Is this observation a reality or an illusion? Answering that question requires a rigorous definition of innovation and of information and careful determination of the time intervals that measure its frequency. How to build reference times that are relevant for characterizing the rhythms of emergence, succession and co-presence of innovations? In other words, is the regular hour time meaningful or should one imagine other measures of societal time?

3. Understanding the relation between cognition and innovation

Societies build and assimilate innovations that concern as well the artefacts that they produce as their own practices and the institutions they create. Is it possible to understand the social dynamics of innovation without introducing the individual and collective intentionality and reflexivity? Is social innovation in continuity or in rupture with biological evolution? Does the fact that innovation is targeted, that the selection of innovation is guided, that the processes of learning and acceptance are conveyed through legal, economic or cultural regulations introduce different characteristics and effects for innovation in human societies? Within these processes, is it possible to identify at meso-levels social milieux or networks or geographical spaces that would be more favorable to innovation, or loaded with a specific innovative capacity? What are the expressions of the interactions between innovation and individual cognition? Can the social control on innovation reach as far as the biological transformations?

Territorial intelligence and sustainable development

A physical territory is a system that naturally integrates a variety of processes usually analyzed by a diversity of disciplines (economics, sociology, and so on). These processes activate natural and social resources and include individual and collective strategies, whose dynamics are coupled in building the territory. Planned and unplanned actions as well as reiterated practices and strategic anticipations are taken by households, firms or government bodies. Physical infrastructures as well as immaterial long lasting socio-spatial configurations constrain these actions and also shape the territory at several scales in space and time. For mastering that complexity, simulation models are needed: for understanding the relationship between processes and structures; for evaluating and preparing individual and collective action; for measuring their impact on the viability of spatial structures. Such models are important issues for helping decision-making and may then contribute to change the evolution of territories.

Keywords: geographical space, territorial configuration, rural and urban regions, networks, systems of cities, multi-level and multi-actor governance, resources, regulation, sustainable development, negotiation, geographical information systems, cellular automata, spatial simulation, multi-agents systems

Grand challenges:

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

1 Understanding territorial differentiation

Territories are reorganized at different scales, from local to global, through the expansion of material and immaterial networks and the diversification of levels where decision take place. “Network territories” are forming by articulating places according to connectivity and not only in continuity, at the level of individuals as well as at the level of global firms. In parallel contiguous territories are partially intersecting, for instance when their future is governed by several decision centers. Are the classical territorial models still valid for representing geographical differences? How can they be replaced?

The evolution of territories is usually described in terms of geohistory, territorial viability, or adaptation and innovation capacity. It must be related to processes as institutions, technological innovations, transformations of social practices and representations. Within that dynamics, modes of circulation and concentration of information are essential. Very often, the networks that convey information are not observable; they have to be reconstructed through simulation models. The challenge is to couple dynamic models representing spatial interactions at a variety of scales and geographical information systems that can integrate and visualize the located information and the evolution of networks and territories.

2 Towards a reflexive territorial governance

Territorial governance is no longer a simple hierarchical top down control but a multi-level and multi-actor process. Intermediate control structures are emerging between territorial scales. New models of legitimating are invented between representative and participative democracy and inclusive governance. Moreover, the growing interest for sustainability invites to take into account the natural dynamics that operate at different scales of time and space as well.

The building of a well-informed, “reflexive” governance, relies on the invention of new decision models which consider processes and institutions, configuration of competition and cooperation, symbolic and practical interactions. Natural and social dynamics have to be coupled in identifying organization levels, scales of time and relevant territorial subdivisions for a reflexive control. A further difficulty is to include the diversity of the strategies of the actors in such models. Generally speaking, the question is to identify which structures are emerging at meso level and to understand what are the linkages between micro, macro and meso levels.

3 Viability and observation of territories

The retrospective and prospective analysis of territories is essential for improving knowledge about the long- term sustainability of geographical entities in their social, economic, ecologic and ethic dimensions. Questions of measurement are fundamental. Choosing indicators, their weighting, defining norms, identifying objectives and stakes are specific problems for territories that are both complementary and competitive. More reliable spatio-temporal databases are needed for measuring the evolutions and comparing territorial dynamics.

The challenge is to organize the comparability of territorial dynamics. A major issue is to adapt or create sources of information that where established for administrative or political units at a given period in time, for evaluating territorial entities (cities, regions, networks) that have their own dynamics. The problem is crucial for long-term studies of the resilience and vulnerability of urban systems, or for a comparative evaluation of agenda 21 programmes (which combine societal, economic and ecological objectives).

Ubiquitous Computing

Today's technology makes it possible and even necessary to radically change the way we gather and process information, even necessary to discover new structural principles that permit the design and analysis of vast software systems that will pervade our lives, adapt appropriately, and make decisions that have hitherto been made by us. We need to move from the current monolithic approach to the networked collaboration of a huge number of possibly heterogeneous computing units. This new approach should be based upon models of mobile populations of agents, with a regime of interaction between them that involves concepts such as security, authorisation, trust, resource allocation, negotiation, and so on. It will allow us to add intelligence to the different artefacts that are increasingly present around us, and compensate for the foreseeable limits of classical computer science (end of the Moore era). This long term objective requires solving four main problems: innovating in physical layout and communications (distributed routing and control), deploying self-regulating and self-managing processes, designing new computing models, and specifying adaptive programming environments (with machine learning, retro-action and common sense). We have reached today the technological limits of Von Neumann's sequential computational model. New paradigms are already being developed to meet the ever growing demand of our modern society for computational power, but much work remains to be done. The heart of those new paradigms is the distribution of computing tasks on decentralized architectures (e.g., multi-core processors and computer grids). The complexity of such systems is the price to pay to address the scaling and robustness issues of decentralized computing. Furthermore, it is now technologically possible to flood the environment with sensors and computing units wherever they are needed. However, an efficient use of widely distributed units can only be achieved through networking, while physical constraints limit the communication range of each unit to a few of its neighbors (ad hoc networks). At another scale, the concept of peer-to-peer (P2P) networks also implies limited visibility of the whole network. In both types of networks, the issue is to make an optimal use of the complete data that is available on the whole network. The challenges of this framework are targeted toward new computational systems, but also address some issues raised in social or environmental networks, which are treated in other pages of the present road map.

Keywords: peer-to-peer networks, ad hoc networks, observation of multi-scale spatio-temporal phenomena (trophic networks, agriculture, meteorology), epidemic algorithms, logical and mathematical models of communication processes, information theory, spatial computing, self-aware systems, common sense, privacy.

Grand challenges:

1. Local design for global properties: routing, control, confidentiality.
2. Autonomic computing: robustness, redundancy, fault tolerance.
3. New computing paradigms: distributed processing and storage, fusion of spatial, temporal and/or multi-modal data, abstraction emergence.
4. Specification of adaptive programming environments: machine learning, retro-action, common sense

1. Local design for global properties

Routing, control, confidentiality— In order to better design and maintain large networks we need to understand how global behaviors can emerge, even though each element has a very limited vision of the whole system and makes decisions based on local information only. Generic models are given by calculi of processes and by epidemic algorithms, in which each element exchanges information with its immediate neighbours. Important issues are the computational role of each element, the different types of information that are exchanged (which should also take into account privacy constraints) and the appropriate selection of the corresponding neighbors. Both choices influence the global behavior of the system. The disciplines and methods relevant to this challenge are: information theory, dynamical systems, statistical physics, epidemic algorithms, bio-inspired algorithms, calculi of mobile processes.

2. Autonomic Computing

Robustness, redundancy, fault tolerance— Large scale deployment of computational systems will not be possible without making those systems autonomous, in a way that resemble properties of living systems: robustness, reliability, resilience, homeostasis. However, the size and heterogeneity of such systems makes it difficult to design analytical models. Moreover, the global behavior of the system also depends on the dynamical and adaptive behavior of the whole set of users. The disciplines and methods relevant to this challenge are: bio-inspired systems and self-aware systems.

3. New computing paradigms

Distributed processing and storage, fusion of spatial, temporal and/or multi-modal data, abstraction emergence— The networking of a large number of possibly heterogeneous computational units (grids, P2P, n-core processors) gathers a huge computational power. However, in order to efficiently use such power, new computing paradigms must be designed, that take into account the distribution of information processing on weak or slow units, and the low reliability of these units and communication channels. Similarly, data distribution (sensor networks, RFID, P2P) raises specific challenges: integration, fusion, spatio-temporal reconstruction and validation. The disciplines and methods relevant to this challenge are: modes of interaction among agents, neuro-mimetic algorithms, belief propagation.

4. Specification of adaptive programming environments

Machine learning, retro-action, common sense— Programming ambient intelligence systems (domotic, aging, fitness) must include the user in the loop. The specification of the expected user behavior requires a transparent link between the low-level data that are available and the user's natural concepts (e.g., symbol grounding). On the other hand, the research agenda must start by studying actual habits. Such a co-evolution process between the user and the system leads to hybrid complex systems. The disciplines and methods relevant to this challenge are: brain computer interface, programming by demonstration, statistical learning.

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