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 of many scales in the system of variations of different nature: it is the impact of these variations which 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?