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.