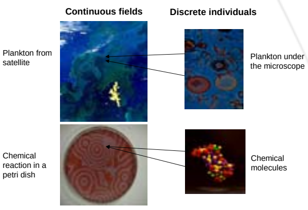
IFISC

COMPLEX SYSTEMS: NONLINEAR AND STATISTICAL PHYSICS

Complex systems, a central paradigm at IFISC, are characterized by emergent and collective phenomena of many interacting units. Fundamental understanding of these systems comes from Statistical Physics together with the Theory of Dynamical Systems, which includes the study of chaos and the effect of fluctuations and random events on systems evolution. Generic phenomena under consideration include synchronization, phase transitions, nonequilibrium instabilities, spatiotemporal pattern formation, or dynamics and evolution of complex networks.

MICRO-MACRO CONNECTION

The discrete nature of organisms or chemical molecules is generally missed when a description in terms of continuous fields (density of particles or concentration of substances) is used to model processes in Nature. And this is specially relevant in certain situations, mainly those in which the number of individuals is small, like in populations close to extinction.



We approach this problem by considering Individual Based Models of the system dynamics, derive the corresponding evolution equation for the continuous fields and study both levels of description, and the relations between the two approaches.

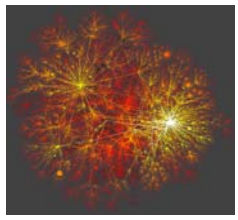
EMERGENT PHENOMENA

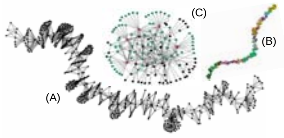
Order at large scales emerges from small scale interactions in complex systems, so that knowledge about the individual units composing the system is not the guide to understand collective behavior: The whole is more than the sum of its parts.

Emergent phenomena are widespread: Traffic is an emergent phenomena which is not understood studying the engines of the cars, society is more than the sum of individuals and the mind is more than the sum of many neurons. The photograph shows emergent patterns in a flock of birds.

COMPLEX NETWORKS

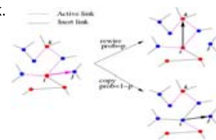
Networks are the skeleton of a complex system, as they describe the interactions between its elements. Complex networks are ubiquitous percolating all domains of knowledge from the social sciences to technology and biology. Complex network science has become a cross-disciplinary area which studies self-organized non-equilibrium complex systems. How do networks form, how do they influence the dynamical processes running on them, and how the dynamical processes actively interact with the network, shaping their architecture, are open question being addressed at IFISC. The Figure shows a skitter data depicting a macroscopic snapshot of Internet connectivity, with selected backbone ISPs (Internet Service Provider) colored separately. (By K. C. Claffy)





Complex network models isolate essential features of real networks The Figure displays three scale-free networks : (A) network with large clustering mimicking a heterogeneous, one-dimensional network; (B) pattern formation in the previous network; (C) a random scale free network.

Network plasticity leads to generic absorbing transitions from an active to a frozen phase in the coevolution of networks, i.e., interaction between dynamical process and the network. The figure illustrates network coevolution dynamics for a two-state node network.

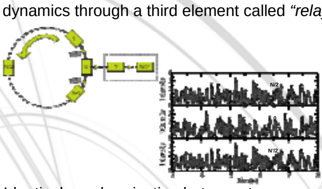


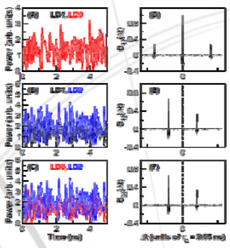
SYNCHRONIZATION PHENOMENA

Systems of coupled multiple units, from simple oscillators to chaotic devices, achieve synchrony despite their natural differences. This pervasive phenomenon is observed in lasers, Josephson junctions, networks of neurons, cardiac pacemaker cells, chorusing crickets, fireflies that flash in unison, applauding audiences, etc. Transition to a synchronized collective rhythm is selforganized and feedback induced.

• *Zero-lag long range synchronization*

Synchronization between distant elements can be obtained by relaying their dynamics through a third element called *"relay"*



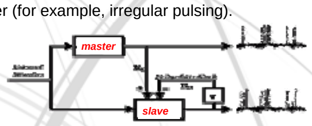


Identical synchronization between two elements can be obtained through an uncorrelated mediating signal.

• *Anticipated synchronization*

A slave system is an identical copy of a master system which, by means of a positive unidirectional coupling can synchronize its dynamics to that of the master. With a delay feedback line in the dynamics of the slave, it is possible to reach a regime in which the slave anticipates the dynamics of the master by a time equal to the delay time. This remarkable synchronization regime has been shown to be structurally stable and can be used to design a control scheme that eliminates some unwanted behavior in the master (for example, irregular pulsing).

Pulses fired by the slave anticipate (i.e., predict) the pulses fired by a master excitable system.



STOCHASTIC PHENOMENA: COHERENT BEHAVIOR INDUCED BY RANDOMNESS

Counter intuitively, noise can have in many circumstances a constructive effect leading to phenomena such as noise induced transitions, stochastic or coherence resonance, etc. Heterogeneity or diversity among the set of units composing a complex system is a source of randomness in a complex system. When many different units interact strongly coherent collective behavior might be induced by such diversity.

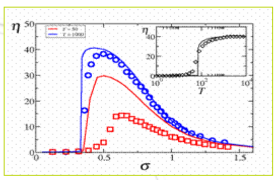
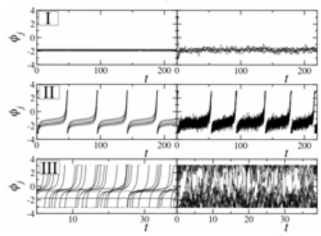


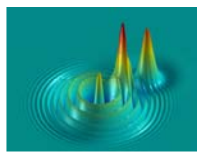
Illustration of a diversity-induced resonance in an ensemble of coupled bistable systems



Transition to a coherent regime of collective firing in an ensemble of coupled excitable systems induced by diversity

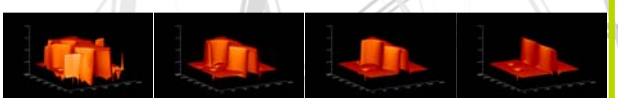
LOCALIZED STRUCTURES

Localized structures, also known as dissipative solitons, are commonplace in nature and appear in such a different fields as fluid mechanics, nonlinear optics, chemistry, granular media, gas discharges, population dynamics, etc. We study their existence, stability properties and interactions. The figure shows three oscillatory localized states interacting through their tails.



POLY-RHYTMIC MEDIA

Development of a stable wall structure in two-dimensional poly-rhythmic media: The 3D plot represent the amplitude of the oscillations of the corresponding point in the space. The media can oscillate in two different stable regimes of amplitudes and frequency. Inside the wall width, both the amplitude and frequency are different from these in the rest of the media. The wall is formed due to a nonlinear locking phenomena that prevent the colliding fronts from mutual annihilation.



CLUSTERING AND EXCLUSION UNDER COMPETITIVE NONLOCAL INTERACTIONS

Interactions between different entities competing for the same resources arise in a large variety of physical, chemical, biological and economical systems. The principle of competitive exclusion states that two entities competing for the same resource will not coexist: one will become extinct. But coexistence is empirically observed despite competition: The reason is in the shape of the nonlocal competition interaction leading to pattern forming instabilities. The figures show the time evolution (vertical axis) of evolving species showing extinction and emergence of new ones (left) and clustering (right) groups of similar species forming.