The physics of complex systems: Methods and concepts from nonlinear dynamics and statistical physics

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Assumptions and methods in complex systems research (P. Gaspard)

General Introduction. We survey different aspects of methodology in complex systems research: the importance of the phenomenological context, logical incompleteness and emergence, the micro/macro levels of description and the hierarchy of scales in a given system, the issue of the time scales with regards to monitoring and observatories.

Probabilistic approach. The issue of the number of degrees of freedom: deterministic or stochastic systems

Deterministic systems: Trajectory equations versus generalized Liouville equation, initial conditions on real numbers and probability distribution, sensitivity to initial conditions and chaotic dynamics, the issue of prediction;

Stochastic systems: Langevin equations versus master equations;

Mean-field equations: the (re)emergence of determinism on larger/longer scales.

Dynamical aspects of information. Chaitin-Kolmogorov algorithmic complexity, dynamical randomness and the probability of histories, Kolmogorov-Sinai entropy per unit time, epsilon-entropy par unit time.

Deterministic aspects of non-equilibrium phenomena (T. Gilbert)

The fractality of non-equilibrium states. We introduce model systems which serve to illustrate the main concepts: the phase-space dynamics of systems away from equilibrium is characterized by fractal states, whose properties encode the transport processes they underlie.

Examples include diffusive systems with absorbing boundaries, in contact with reservoirs, or acted upon by external forces, whether subject to dissipation or not.

Dynamical entropies and entropy production rate How the characterization of hydrodynamic processes emerges from subtle differences between dynamical randomness and instability; Fast vs. slow timescales; fractality and information loss.

Physics of information and emergence of molecular order in non-equilibrium systems (D. Andrieux)

Physics of information Information is carried, stored, retrieved and processed by machines, whether they be electronic computers or living organisms. All information has to be carried by a physical substrate, be it paper, silicon chips or holograms, and the handling of this information is physical. Therefore, information is ultimately constrained by the fundamental laws of physics. It is therefore not surprising that physics and information share a rich interface. For instance, Landauer's principle provides a minimal dissipation to erase a sequence of random bits.

Information generation in complex systems Nanoscale systems are able to present directed motions or coherent behaviors despite the presence of molecular noise. Recent developments have revealed the crucial role played by nonequilibrium conditions in explaining these properties. Indeed, nonequilibrium conditions allow the emergence of a temporal order, which in turn can be used to generate information.

Copolymerizations processes Processes such as the replication of DNA by which genetic information is copied at the molecular level serve to illustrate the above concepts. We show that molecular information can only be stored and retrieved reliably away from equilibrium. In this way, dissipation allows the emergence of temporal ordering and the spontaneous generation of information, explaining a key feature of complex systems.

Suggested reading

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