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Complexity, catastrophe and physics

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The study of out-of-equilibrium dynamics (e.g. dynamical phase transitions) and of heterogeneous systems (e.g. spin-glasses) has progressively made popular in physics the concept of complex systems and the importance of systemic approaches: systems with a large number of mutually interacting parts, often open to their environment, self-organize their internal structure and their dynamics with novel and sometimes surprising macroscopic ("emergent") properties. The complex system approach, which involves "seeing" inter-connections and relationships i.e. the whole picture as well as the component parts, is nowadays pervasive in modern control of engineering devices and business management. It is also plays an increasing role in most of the scientific disciplines, including biology (biological networks, ecology, evolution, origin of life, immunology, neurobiology, molecular biology, etc), geology (plate-tectonics, earthquakes and volcanoes, erosion and landscapes, climate and weather, environment, etc.), economy and social sciences (including cognition, distributed learning, interacting agents, etc.). There is a growing recognition that progress in most of these disciplines, in many of the pressing issues for our future welfare as well as for the management of our everyday life will need such a systemic complex system and multidisciplinary approach.

A central property of a complex system is the possible occurrence of coherent large-scale collective behaviors with a very rich structure, resulting from the repeated non-linear interactions among its constituents: the whole turns out to be much more than the sum of its parts. It is widely believed that most of these systems are not amenable to mathematical, analytic descriptions and can only be explored by means of "numerical experiments". In the context of the mathematics of algorithmic complexity [1], most complex systems are said to be computationally irreducible, i.e. the only way to decide about their evolution is to actually let them evolve in time. Accordingly, the "dynamical" future time evolution of complex systems would be inherently unpredictable. This unpredictability does not prevent however the application of the scientific method for the prediction of novel phenomena as examplified by many famous cases (prediction by Einstein of the deviation of light by the sun's gravitation field, prediction of the spin by Pauli, prediction of the existence of neutrinos by Fermi, and of the intermediate bosons within the electroweak theory by Weinberg and Salam, etc.). In contrast, it refers to the frustration to satisfy the curiosity, strengthened by the anguish and hope that humans have always casted on their futur. Is modern science really putting out of reach the graal of predicting (some of) the future evolution of complex systems?

This view has recently been defended persuasively in concrete prediction applications, such as the socially important issue of earthquake prediction (see the contributions in [2]). In addition to the persistent failures at reaching a reliable earthquake predictive scheme, this view is rooted theoretically in the analogy between earthquakes and self-organized criticality [3]. In this "fractal" framework, there is no characteristic scale and the power law distribution of sizes reflects the fact that the large earthquakes are nothing but small earthquakes that did not stop. They are thus unpredictable because their nucleation is not different from that of the multitude of small earthquakes which obviously cannot be all predicted.

Does this really hold for all features of complex systems? Take our personal life. We are not really interested in knowing in advance at what time we will go to a given store or drive in a highway. We are much more interested in forecasting the major bifurcations ahead of us, involving the few important things, like health, love and work that count for our happiness. Similarly, predicting the detailed evolution of complex systems has no real value and the fact that we are taught that it is out of reach from a fundamental point of view does not exclude the more interesting possibility to predict phases of evolutions of complex systems that really count.

It turns out that most complex systems around us do exhibit rare and sudden transitions, that occur over time intervals that are short compared to the characteristic time scales of their posterior evolution. Such extreme events express more than anything else the underlying "forces" usually hidden by almost perfect balance and thus provide the potential for a better scientific understanding of complex systems.

These crises have fundamental societal impacts and range from large natural catastrophes such as earthquakes, volcanic eruptions, hurricanes and tornadoes, landslides,avalanches, lightning strikes, meteorite/asteroid impacts, catastrophic events of environmental degradation, to the failure of engineering structures, crashes in the stock market, social unrest leading to large-scale strikes and upheaval, economic drawdowns on national and global scales, regional power blackouts, traffic gridlock, diseases and epidemics, etc. It is essential to realize that the long-term behavior of these complex systems is often controlled in large part by these rare catastrophic events: the universe was probably born during an extreme explosion (the "big-bang"); the nucleosynthesis of all important atomic elements constituting our matter results from the colossal explosion of supernovae; the largest earthquake in California repeating about once every two centuries accounts for a significant fraction of the total tectonic deformation; landscapes are more shaped by the "millenium" flood that moves large boulders rather than the action of all other eroding agents; the largest volcanic eruptions lead to major topographic changes as well as severe climatic disruptions; evolution is characterized by phases of quasi-statis interrupted by episodic bursts of activity and destruction; financial crashes can destroy in an instant trillions of dollars; political crises and revolutions shape the long-term geopolitical landscape; even our personal life is shaped on the long run by a few key "decisions/happenances".

The outstanding scientific question is thus how such large-scale patterns of catastrophic nature might evolve from a series of interactions on the smallest and increasingly larger scales. In complex systems, it has been found that the organization of spatial and temporal correlations do not stem, in general, from a nucleation phase diffusing across the system. It results rather from a progressive and more global cooperative process occurring over the whole system by repetitive interactions. An instance would be the many occurrences of simultaneous scientific and technical discoveries signaling the global nature of the maturing process.

Standard models and simulations of scenarii of extreme events are subject to numerous sources of error, each of which may have a negative impact on the validity of the predictions [4]. Some of the uncertainties are under control in the modelling process; they usually involve trade-offs between a more faithful description and manageable calculations. Other sources of errors are beyond control as they are inherent in the modeling methodology of the specific disciplines. The two known strategies for modelling are both limited in this respect : analytical theoretical predictions are out of reach for most complex problems. Brute force numerical resolution of the equations (when they are known) or of scenarii is reliable in the "center of the distribution", i.e. in the regime far from the extremes where good statistics can be accumulated. Crises are extreme events that occur rarely, albeit with extraordinary impact, and are thus completely under-sampled and thus poorly constrained. Even the introduction of teraflop (or even pentaflops in the futur) supercomputers does not change qualitatively this fundamental limitation.

Recent developments suggest that non-traditional approaches, based on the concepts and methods of statistical and nonlinear physics could provide a middle way to direct the numerical resolution of more realistic models and the identification of relevant signatures of impending catastrophes. Enriching the concept of self-organizing criticality, the predictability of crises would then rely on the fact that they are fundamentally outliers, e.g. large earthquakes are not scaled-up versions of small earthquakes but the result of specific collective amplifying mechanisms. To address this challenge, the available theoretical tools comprise in particular bifurcation and catastrophe theories, dynamical critical phenomena and the renormalization group, nonlinear dynamical systems, and the theory of partially (spontaneously or not) broken symmetries. Some encouraging results have been gathered on concrete problems, such as the prediction of the failure of complex engineering structures, the detection of precursors to stock market crashes and of human parturition, with exciting potential for earthquakes. At the dawn of the next millenium, it is tempting to extrapolate and forecast that a larger multidisciplinary integration of the physical sciences together with artifical intelligence and soft-computational techniques, fed by analogies and fertilization accross the natural sciences, will provide a better understanding of the limits of predictability of catastrophes and adequate measures of risks for a more harmonious and sustainable futur of our complex world.

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