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1 Why did you begin working with complex systems?

My acquaintance with systems composed of interacting subunits - of which complex systems constitute a particularly significant class - dates from my research in nonequilibrium statistical mechanics during my PhD and post doctoral years at the Université Libre de Bruxelles under the direction of Ilya Prigogine and the University of Chicago under the direction of Stuart Rice. The principal questions of interest at that time were linear transport theory and the derivation of kinetic equations describing the approach to equilibrium, using perturbative expansions. Things began to shift in 1966 and onwards. The extension of thermodynamics to open systems far away from equilibrium and the discovery of nonequilibrium induced self-organization phenomena, the dissipative structures, by the Brussels group to which I had the privilege to participate, showed that systems of interacting particles are capable of exhibiting unexpected behaviors not reducible to those of their individual elements that would be next to impossible under equilibrium conditions.

There was a lot of excitement accompanying these discoveries and a real sense of urgency to elucidate the onset and the principal characteristics of the associated phenomena. During the 1970's to mid 1980's this program was tackled successfully both at the macroscopic and the microscopic levels of description using the methods of nonlinear dynamics and chaos theory on the one side, and those of the theory of stochastic processes (master and Langevin equations) on the other. Theoretical work in fields ranging from fluid mechanics, optics, material science and chemistry to biology in conjunction with laboratory scale experimental developments showed that similar behaviors were recurring in very different contexts. Meanwhile starting in the 1980's new issues were being raised in connection with life sciences, large scale natural systems such as the atmosphere, and human systems such as competing agents in the stock market where the elementary subunits are no longer particles but entities capable of reasoning, of reacting and of adapting. The key question of interest here was prediction, to which I became exposed through my long standing collaboration with my wife Catherine Nicolis.

Eventually, it was the search for a unified description of such problems that gave rise to the idea of complex systems as a field of science in its own right embodying, in fact, the most exciting and the most innovative facet of systems composed of interacting particles. Throughout my work in the field I have been stressing the view of complexity as part of fundamental mathematical and natural science, and the need to keep investing on mathematically and physically motivated issues and on the sharpening and further development of the associated techniques. There can be no "soft" approach to complexity: observing, analyzing, modeling, predicting and controlling complex systems can only be achieved through the time-honored approach provided by "hard' science. The novelty brought by complex systems is that in this endeavor the goals as we set them in traditional approaches are reformulated and the ways to achieve them are reinvented in a most unexpected way. This view has been at variance with the one that had prevailed for some time, namely, that the perception of a system as complex reflects essentially the practical difficulty to gather detailed information, following the presence of often prohibitively large numbers of parameters and variables masking the underlying regularities. Fortunately this latter view which, if true, would identify "complexity" to "complication" and would reduce it to nice metaphor and an appealing way of putting things, is now recognized to be obsolete.

2 How would you define complexity?

Complexity is the conjunction of several properties (some of which are reviewed in the sequel) and, because of this, no single formal definition doing justice to its multiple facets and manifestations can be given. It is useful to compare this with the concept of nonlinearity (itself a necessary condition for complexity) which in contrast can be defined straightforwardly, as it corresponds to a structural feature built in the evolution laws, namely, deviation from strict proportionality between the effects and the underlying causes.

One popular idea surrounding complexity is that an object can be regarded as complex when there is no short description of it. The concept of algorithmic complexity pioneered by Andrei Kolmogorov and Gregory Chaitin has the great merit to propose a quantitative measure capturing this idea: the complexity of an object in its digitalized expression of binary sequence of length K is the size of the shortest computer program (measured in number of bits) generating it. Although algorithmic complexity accounts for certain features of natural complex systems in its basic philosophy it is fundamentally different from the complexity one is concerned with in nature, where one seeks to identify emergent properties, concerted behavior and evolution. In particular, algorithmic complexity is insensitive to the time needed to accomplish a program (assuming that the latter will eventually halt). But in nature it is important to produce certain forms of complexity as the system of interest evolves in real time. The probability to produce a prescribed pattern/sequence out of the enormous number of a priori possible ones is usually exceedingly small. In contrast, under appropriate conditions dynamical systems are capable of exploring their state space continuously thereby creating information and complexity; at the same time they act like efficient selectors that reject the vast majority of possible patterns/sequences and keep only those compatible with the underlying dynamics. Furthermore, dissipation allows for the existence of attractors that have asymptotic stability and thus reproducibility. It therefore seems legitimate to state that algorithmic complexity is a static, equilibrium like concept whereas physical complexity takes its full significance in a dynamic, nonequilibrium context. To tackle physical complexity, one needs a nonequilibrium generalization of classical information theory.

Attempts at a compact definition - or at least measure - of physical complexity beyond its algorithmic aspects as formalized by the Kolmogorov-Chaitin complexity have been reported in the literature. A interesting measure, on the grounds of its relation to prediction, is the amount of information necessary to estimate optimally conditional probabilities. In a quite different vein one associates complexity to "value" of some sort, for instance, the time required to actually retrieve a message from its minimal algorithmic prescription. In this view a message is complex, or deep, if it is implausible and can only be brought to light as a result of a long calculation. This introduces the time element that is so conspicuously absent in the Kolmogorov-Chaitin complexity. While capturing certain aspects of physical complexity, none of these definitions/measures manages to fully encompass its multiple facets. The question, how to define complexity is thus likely to remain open for some time to come. It may even turn out to be an ill-posed one: after all as stressed already above, complexity does not reflect any build-in, immediately recognizable, structure as is e.g. the case of nonlinearity; it is, rather, a set of attributes that spring into life from the laws of nature when the appropriate conditions are met.

3 What is your favorite aspect/concept of complexity?

A most appealing aspect of complexity research is to provide a forum for the exchange of information and ideas of an unprecedented diversity cutting across scientific disciplines, from pure mathematics to biology to finance. On the one side one witnesses the encounter and cross-fertilization of nonlinear dynamics, chaos theory, statistical physics, information and probability theories, data analysis and numerical simulation, in close synergy with experiment. And on the other side, insights from the practitioner confronted with large scale systems as encountered in nature, technology or society, many of them outside the strict realm of traditional mathematical and natural science, where issues eliciting the idea of complexity show up in a most urgent manner, are increasingly integrated into the general framework. This multilevel approach, with its conjunction of complementary views and its reassessment of principles and practices confers to complex systems research a marked added value beyond the traditional disciplinary approach to the understanding of nature.

It is often stated that fundamental science is tantamount to the exploration of the very small and the very large. This assertion becomes, simply, obsolete in the light of complex systems research. There exist huge classes of phenomena of the utmost importance, fundamental as well as practical, between these two extremes waiting to be explored in which the system and the observer - the external world and ourselves - co-evolve on comparable time and space scales. This adds further credence to the relevance and unique status of complexity in contemporary science.

Coming now to more concrete issues, one aspect that I view as especially innovative is that complex systems lie at the cross roads of the deterministic and probabilistic views of nature. Let me make this point more precise. The conjunction of multiplicity of possible outcomes, of the sensitivity associated with occurrence of criticalities or of deterministic chaos and of the lack of a universal and exhaustive classification of all possible evolution scenarios characteristic of complex systems confers to them an intrinsic randomness that cannot be fully accounted for by the traditional deterministic description, in which one focusses on the detailed pointwise evolution of individual trajectories. The probabilistic description offers the natural alternative. The evolution of the relevant variables takes here a form where the values featured in a macroscopic, coarse grained description are modulated by the random fluctuations generated by the dynamics prevailing at a finer level. This highlights further the variety of the behaviors available and entails that the probability distribution functions, rather than the variables themselves, become now the principle quantities of interest. They obey to evolution equations like the master equation or the Fokker-Planck equation which are linear and guarantee (under mild conditions on the associated evolution operators) uniqueness and stability, contrary to the deterministic description which is nonlinear and generates multiplicity and instability.

Thanks to its inherent linearity and stability the probabilistic description of complex systems is the starting point of a new approach to the problem of prediction, in which emphasis is placed on the future occurrence of events conditioned by the states prevailing at a certain time as provided by experimental data. This approach finds nowadays intensive use in, among others, operational weather forecasting, where it is known as ensemble forecasting.

A second appealing aspect at the very basis, in fact, of complexity is the emergence of levels of description obeying to their own laws. There is an apparent paradox accompanying the transition to complexity. On the one side complexity seems to follow its own rules reflecting the emergence, at some level of description, of new qualitative properties not amenable to those of the individual subunits. But on the other side, since the laws of nature are deterministic these properties are bound to be deducible from the interactions between lower order hierarchical levels. Because of this, the concept of emergence is still viewed by many as an expression of ignorance.

A first instance where this apparent conflict can be resolved thereby allowing one to quantify the concept of emergence and to establish a connection between different hierarchical levels pertains to the macroscopic description, in which individual variability and more generally deviations from a globally averaged behavior are discarded. Suppose that the system of interest is described by a set of n macroscopic observables, where n can be as large as desired and that it operates in the vicinity of a criticality. An important result of nonlinear dynamics is that for certain (generic!) types of criticalities there exists a limited number of collective variables, to which one refers as order parameters, obeying to universal evolution laws characteristic of the criticality at hand, to which one refers as normal forms. All other variables follow passively the evolution of the order parameters. The specific nature of the original evolution laws is immaterial as long as it gives rise to the relevant bifurcation and enters only to specify the values of the parameters present in the normal form. We here have a first instance of how a new level of description following its own rules is being generated. Notice that the essential property sought here is closure, namely the existence of an autonomous set of laws for the relevant variable pertaining to the level of description considered.

A most exciting point is that under certain (generic!) conditions the probabilistic description itself acquires the status of an emergent property, free of heuristic approximations, starting from a deterministic microscopic level description. This passage from the Liouville equation to the master or Fokker-Planck equations depends crucially on the unstable, chaotic character of the microscopic dynamics. A second important ingredient is a judicious choice of "states", through an adequate partition of the full phase space spanned by the variables descriptive of the elementary subunits into cells. As the microscopic trajectory unfolds in phase space transitions between cells - states - are induced, which are isomorphic to a probabilistic process. Such considerations are also instrumental for building a microscopic theory of irreversibility, also viewed in this context as an emergent property.

It should be realized that there are limits to the hierarchical view, reflecting the failure of the decoupling between levels of description. This is what happens, in particular, in nanoscale systems, in systems subjected to strong geometric or nonequilibrium constraints, or in phenomena such as earthquakes, floods, and financial crises associated with the occurrence of extreme values of the relevant variables. A full scale description becomes then necessary, in which the fine details of the structure of the probability distributions begin to matter. Universal laws governing some key observables can still be extracted, examples of which are given by fluctuation type or more generally large deviation type theorems.

4 In your opinion, what is the most problematic aspect/concept of complexity?

To remain relevant, complexity research needs to strike the right balance between the search for generic features and qualitative insights (which should anyway remain one of its main goals) and the specificities and hard empirical facts that are as a rule present in any concrete system of interest.

Complexity has to consolidate further its roots as part of fundamental science and, at the same time, demonstrate its identity and its specificity as compared to related disciplines like nonlinear dynamics and statistical physics. And it has to produce results that could not be otherwise obtained, useful to the practitioner, in major fields outside the traditional realm of mathematical and natural science like brain research, the economy, or the evolutionary and adaptive behaviors in which current attempts, though promising, still remain in their infancy.

Challenges of this kind are usually not part of the goal of traditional scientific disciplines, from cosmology and the nanosciences to molecular biology and sociology. They reflect the special status claimed by complexity research as well as its ambition to constitute a new, "post-Newtonian" scientific paradigm and to play an integrating role in today's highly fragmented scientific landscape.

5 How do you see the future of complexity? (including obstacles, dangers, promises, and relations with other areas)

Complexity is a fundamental discipline in its own right. It contributes to our understanding of nature and has the potential of a significant impact on science and technology. It opens new perspectives, proposes novel strategies and addresses long-standing problems and real world issues of relevance in everyday life. On these grounds, it should be expected to play an increasingly important role in the future.

Complexity research attracts audiences of an unprecedented diversity. There is an inherent danger that this might eventually prove to be a "mixed blessing" in view of the highly heterogeneous, if not loose, character of the community. It is not rare to even see the concept of complexity grossly misused. Care should thus be taken to improve the often poor communication currently existing between different subgroups. In particular, natural and social sciences should come closer together and share expertise.

To achieve the goal of shaping a coherent, clearly recognizable supercritical size complexity community appropriate training and collaborative programs will have to be initiated. There is at present a lack of complexity related education in most academic Institutions even though the subject appeals to young people, and a lack of public awareness of the benefits of complex systems approach. This gap should be filled, and this will probably require imagining and implementing practices of a new kind. In doing so one should not succumb to the temptation of dilution, encouraging prospective complexity researchers to learn a "little bit" of "everything". On the contrary, a hard core of researchers of high level technical expertise in fundamental aspects and in the elaboration of advanced methodologies should be secured. This knowledge should become available in appropriate forms to less technically oriented parts of the community through joint ventures of various kinds. And conversely, insights from these sectors should be integrated to stimulate new developments at the fundamental and technical levels.

There is at present a strong academic community of high level researchers worldwide working in complexity related topics (even though some of them would rather stress their disciplinary identity), as well as a number of case studies where complexity research has been successful. They should constitute the nucleus from which the above envisioned activities could be successfully materialized.

Suggestions for further reading

1. G. Chaitin, *Meta Maths*, Atlantic Books (2006).
2. P. Gaspard, *Chaos, Scattering and Statistical Mechanics*, Cambridge University Press, Cambridge (1998).
3. P. Glansdorff and I. Prigogine, *Thermodynamic theory of sturcture, stability and fluctuations*, Wiley, London (1971).
4. H. Haken, *Synergetics*, Springer, Berlin (1977).
5. S. Kauffman, *The origins of order*, Oxford University Press, New York (1993).
6. G. Nicolis and I. Prigogine, *Self-organization in nonequilibrium systems*, Wiley, New York (1977).
7. G. Nicolis and C. Nicolis, *Foundations of complex systems*, World Scientific, Singapore (2007).