

# Preface

Complexity became a major scientific field in its own right as recently as 15 years ago, and since then it has modified considerably the scientific landscape through thousands of high-impact publications as well as through the creation of specialized journals, Institutes, learned societies and University chairs devoted specifically to it. It constitutes today a paradigm for approaching a large body of phenomena of concern at the crossroads of physical, engineering, environmental, life and human sciences from a unifying point of view.

Nonlinear science and statistical physics had been addressing for some time phenomena of this kind: self-organization in nonequilibrium systems, glassy materials, pattern formation, deterministic chaos are landmarks, witnessing the success they have achieved in explaining how unexpected structures and events can be generated from the laws of nature in systems involving interacting subunits when appropriate conditions are satisfied - an issue closely related to the problematics of complexity. And yet, on the one side, for quite some time these attempts were progressing in rather disconnected ways following their own momentum and success; and on the other side, they were remaining confined to a large extent within a community of strong background in physical and mathematical science, and did not incorporate to a sufficient degree insights from the practitioner confronted with naturally occurring systems where issues eliciting the idea of complexity show up in a most pressing way. Last but not least, there was a lack of insight and of illustrative power of just what are the minimal ingredients for observing the sort of behaviors that would qualify as “complex”.

A first breakthrough that contributed significantly to the birth of complexity research occurred in the late 1980's - early 1990's. It arose from the cross-fertilization of ideas and tools from nonlinear science, statistical physics and numerical simulation, the latter being a direct offspring of the increasing availability of computers. By bringing chaos and irreversibility together it showed that deterministic and probabilistic views, causality and chance, stability and evolution were different facets of a same reality when addressing

certain classes of systems. It also provided insights on the relative roles of the number of elements involved in the process and the nature of the underlying dynamics. Paul Anderson's well-known aphorism, "more is different", that contributed to the awareness of the scientific community on the relevance of complexity, is here complemented in a most interesting way.

The second breakthrough presiding in the birth of complexity coincides with the increasing input of fields outside the strict realm of physical science. The intrusion of concepts that were till then not part of the vocabulary of fundamental science forced a reassessment of ideas and practices. Predictability, in connection with the increasing concern about the evolution of the atmosphere, climate and financial activities; algorithms, information, symbols, networks, optimization in connection with life sciences, theoretical informatics, computer science, engineering and management; adaptive behavior and cognitive processes in connection with brain research, ethology and social sciences are some characteristic examples.

Finally, time going on, it became clear that generic aspects of the complex behaviors observed across a wide spectrum of fields could be captured by minimal models governed by simple local rules. Some of them gave rise in their computer implementation to attractive visualizations and deep insights, from Monte Carlo simulations to cellular automata and multi-agent systems.

These developments provided the tools and paved the way to an understanding, both qualitative and quantitative, of the complex systems encountered in nature, technology and everyday experience. In parallel, natural complexity acted as a source of inspiration generating progress at the fundamental level. Spontaneously, in a very short time interval complexity became in this way a natural reference point for all sorts of communities and problems. Inevitably, in parallel with the substantial progress achieved ambiguous statements and claims were also formulated related in one way or the other to the diversity of backgrounds of the actors involved and their perceptions as to the relative roles of hard facts, mechanisms, analogies and metaphors. As a result complexity research is today both one of the most active and fastest growing fields of science and a forum for the exchange of sometimes conflicting ideas and views cutting across scientific disciplines.

In this book the foundations of complex systems are outlined. The vision conveyed is that of complexity as a part of fundamental science, in which the insights provided by its cross-fertilization with other disciplines are incorporated. What is more, we argue that by virtue of this unique blending complexity ranks among the most relevant parts of fundamental science as it addresses phenomena that unfold on our own scale, phenomena in the course of which the object and the observer are co-evolving. A unifying presentation of the concepts and tools needed to analyze, to model and to predict com-

plex systems is laid down and links between key concepts such as emergence, irreversibility, evolution, randomness and information are established in the light of the complexity paradigm. Furthermore, the interdisciplinary dimension of complexity research is brought out through representative examples. Throughout the presentation emphasis is placed on the need for a multi-level approach to complex systems integrating deterministic and probabilistic views, structure and dynamics, microscopic, mesoscopic and macroscopic level descriptions.

The book is addressed primarily to graduate level students and to researchers in physics, mathematics and computer science, engineering, environmental and life sciences, economics and sociology. It can constitute the material of a graduate-level course and we also hope that, outside the academic community, professionals interested in interdisciplinary issues will find some interest in its reading. The choice of material, the style and the coverage of the items reflect our concern to do justice to the multiple facets of complexity. There can be no “soft” approach to complexity: observing, monitoring, 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 are reassessed and the ways to achieve them are reinvented in a most unexpected way as compared to classical approaches.

Chapter 1 provides an overview of the principal manifestations of complexity. Unifying concepts such as instability, sensitivity, bifurcation, emergence, self-organization, chaos, predictability, evolution and selection are sorted out in view of later developments and the need for a bottom-up approach to complexity is emphasized. In Chapter 2 the basis of a deterministic approach to the principal behaviors characteristic of the phenomenology of complex systems at different levels of description is provided, using the formalism of nonlinear dynamical systems. The fundamental mechanism underlying emergence is identified. At the same time the limitations of a universal description of complex systems within the framework of a deterministic approach are revealed and the “open future” character of their evolution is highlighted. Some prototypical ways to model complexity in physical science and beyond are also discussed, with emphasis on the role of the coupling between constituting elements. In Chapter 3 an analysis incorporating the probabilistic dimension of complex systems is carried out. It leads to some novel ways to characterize complex systems, allows one to recover universal trends in their evolution and brings out the limitations of the deterministic description. These developments provide the background for different ways to simulate complex systems and for understanding the relative roles of dynamics and structure in their behavior. The probabilistic approach to

complexity is further amplified in Chapter 4 by the incorporation of the concepts of symbolic dynamics and information. A set of entropy-like quantities is introduced and their connection with their thermodynamic counterparts is discussed. The selection rules presiding the formation of complex structures are also studied in terms of these quantities and the nature of the underlying dynamics. The stage is thus set for the analysis of the algorithmic aspects of complex systems and for the comparison between algorithmic complexity as defined in theoretical computer science and natural complexity.

Building on the background provided by Chapters 1 to 4, Chapter 5 addresses “operational” aspects of complexity, such as monitoring and data analysis approaches targeted specifically to complex systems. Special emphasis is placed on the mechanisms underlying the propagation of prediction errors and the existence of a limited predictability horizon. The chapter ends with a discussion of recurrence and extreme events, two prediction-oriented topics of increasing concern. Finally, in Chapter 6 complexity is shown “in action” on a number of selected topics. The choices made in this selection out of the enormous number of possibilities reflect our general vision of complexity as part of fundamental science but also, inevitably, our personal interests and biases. We hope that this coverage illustrates adequately the relevance and range of applicability of the ideas and tools outlined in the book. The chapter ends with a section devoted to the epistemological aspects of complex systems. Having no particular background in epistemology we realize that this is a risky enterprise, but we feel that it cannot be dispensed with in a book devoted to complexity. The presentation of the topics of this final section is that of the practitioner of physical science, and contains only few elements of specialized jargon in a topic that could by itself give rise to an entire monograph.

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