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L. Peliti A. Vulpiani (Eds.)

Measures of Complexity

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Editors

Luca Peliti
Dipartimento di Scienze Fisiche, Università di Napoli
Mostra d'Oltremare, Pad. 19, I-80125 Napoli, Italy

Angelo Vulpiani
Dipartimento di Fisica, Università dell'Aquila
Piazza dell'Annunziata 1, I-67100 L'Aquila, Italy

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PREFACE

It has become fashionable to say that current research in theoretical physics is more and more focusing on complex systems. One has even sometimes spoken of the emergence of a "science of complexity", which should deal with the universal features of complex systems - abstracting from the peculiar aspects of the different systems under investigation.

It is indeed possible to identify a few facts which justify these opinions. In condensed matter theory, for example, the main interest has rapidly shifted from the study of "simple" systems - gases, or solids of regular structure and fixed composition - to that of "complex" systems - such as liquids, amorphous systems, or glasses - whose behavior is dominated by disorder. At the same time the theory of dynamical systems has elected as one of its main subjects of study the characterization of deterministic chaos - i.e., of the phenomenon by which systems described by few degrees of freedom, whose dynamics is determined by a simple-looking evolution equation, exhibit a behavior which is not globally predictable. I should also like to mention the related emergence of a "global" point of view in ecology and the trend affecting immunology, where stress is shifting from the consideration of the immune response - with its associated emphasis on antigen-antibody interactions - to the immune system - with emphasis on the structure of the adiotypic network.

It is not clear, however, if these parallel trends do correspond to increasing interest in a common aspect which could be called "complexity". Dictionaries carry several definitions of the word. "Complex" means: (i) composed of interconnected parts; compound; composite; (ii) characterized by a very complicated or involved arrangement of parts, units, etc.; (iii) so complicated or intricate as to be hard to understand or deal with (*The Random House Dictionary*). In what sense are the subjects just mentioned "complex"? One would be tempted to answer, in meaning (iii). But with this kind of negative definition one would not understand whether there is a true peculiarity in the observed trends - since it is the usual endeavor of science at any time to move on towards the problems which at any given time appear "to be hard to understand or deal with". On the other hand, meanings (i) and (ii) surely do not apply to deterministic chaos - which deals with the complex [meaning (iii)?] behavior of simple systems.

Challenged by the recurring references to the birth of a science of complexity and puzzled by considerations of the kind just explained, we thought to resert to a simple minded (though rather "physicalistic") approach. If complexity could be consistently <u>measured</u>, its place among physical concepts could hardly be disputed. (In fact the physical nature of temperature remained a puzzle for almost two centuries, but its relevance was assured by the existence of reliable experimental methods.) This idea prompted us to call for an International Conference on "Measures of Complexity", which, promoted by the University of Rome "La Sapienza" and with the collaboration of the Cassa di Risparmio di Roma, took place at the Dipartimento di Fisica dell'Università "La Sapienza" from September 30 to October 2, 1987. The present volume contains the Proceedings of the Conference. The question asked to the speaker was to identify a manner of quantitatively characterizing complexity within each of their own disciplines and - if possible - to compare it with the corresponding ones of other disciplines.

We all know that a kind of complexity measure exists in information theory: the Shannon entropy H. Larger or lesser complexity of a message corresponds to smaller or larger values of H. This approach makes sense in the typical environment of information theory, when one considers that a receiver collects a message (one among several possible messages) sent through a noisy channel. But within the approach the most complex message consisting of N symbols belonging to an alphabet of C characters is the completely random sequence. We have the expectation however that the complexity random sequence (in which the character at each point is chosen independently of any other point and with equal probability among the possible ones) is of complexity comparable to the trivial one, composed of identical characters.

One aspect is conspicuously absent from the typical thought experiments of information theory: the meaning of the message. But it is this meaning that we strive to identify when we attempt to decode the messages which Nature sends us. In this sense we can say that a random sequence is one to which we attribute no meaning. If one is able to identify the random and nonrandom components of a phenomenon (or of a message), it is possible to measure complexity by means of the information necessary to reproduce, not the details of phenomenon - but its probability distribution. In this way, e.g., chaotic attractors duly appear more complex than the trivial or the completely random ones. On the other hand the identification of meaning is not obvious when one deals with the characterization of biological structures.

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Francesco Guerra Luca Peliti Angelo Vulpiani

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