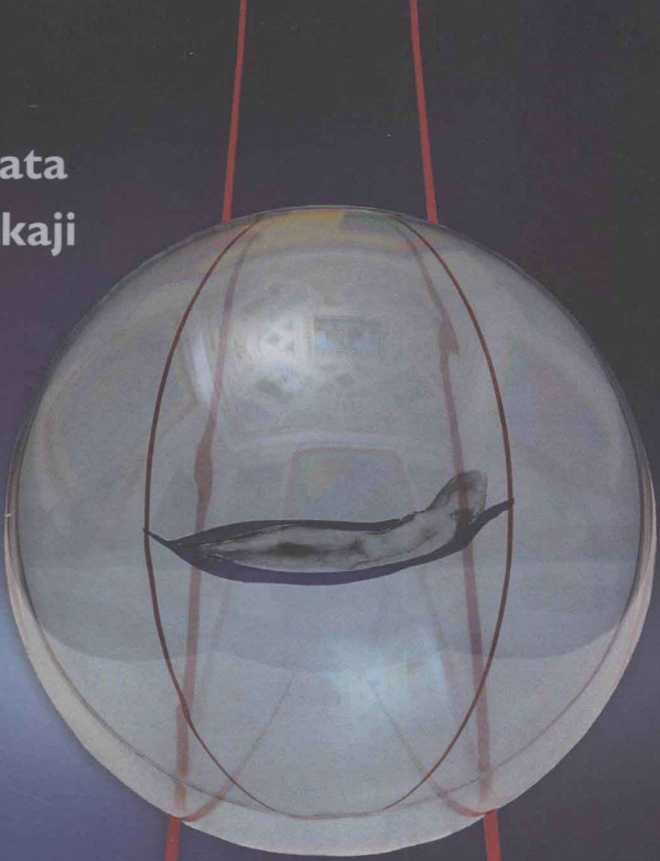
Ignazio Licata
Ammar Sakaji
editors



Physics of Emergence and Organization

World Scientific

Physics of Emergence and Organization

editors

Ignazio Licata

Institute for Scientific Methodology, Palermo, Italy

Ammar Sakaji

Ajman University, Abu Dhabi

World Scientific

NEW JERSEY · LONDON · SINGAPORE · BEIJING · SHANGHAI · HONG KONG · TAIPEI · CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

PHYSICS OF EMERGENCE AND ORGANIZATION

ISBN-13 978-981-277-994-6
ISBN-10 981-277-994-9

Printed in Singapore by Mainland Press Pte Ltd

Physics of Emergence and Organization

Foreword

Gregory J. Chaitin
IBM Research, P O Box 218,
Yorktown Heights, NY 10598, USA
chaitin@us.ibm.com
http://www.umcs.maine.edu

When I was a child the most exciting field of science was fundamental physics: relativity theory, quantum mechanics and cosmology. As we all know, fundamental physics is now in the doldrums. The most exciting field of science is currently molecular biology. We are being flooded with fascinating data (for example, in comparative genomics), and the opportunities for applications seem limitless.

A mathematician or physicist looking with admiration at the exciting developments in molecular biology might be forgiven for wondering how theory is faring in this flood of data and medical applications. In a way, molecular biology feels more like software engineering than a fundamental science. Nevertheless there are fundamental questions in biology. Here are some examples:

a) Is life pervasive in the universe, or are we unique?
b) What are consciousness and thought, and how widespread are they?
c) Can human intelligence be greatly amplified through genetic engineering?

These are extremely difficult questions, but as the articles in this special issue attest, the human being is a theory-building as well as a tool-using animal. The desire for fundamental understanding cannot be suppressed.

Someday we will have a theoretical understanding of fundamental biological concepts. In order to do that we will probably have to drastically change mathematics and physics. This is already happening, as the notions of complexity, computation and information develop and spread.

What the mathematics and physics of complex systems may ultimately be like, nobody can say, but as the articles in this issue show, we are starting to get some interesting glimpses. The only thing I can safely predict is that the future is unpredictable. There will no doubt be a lot of surprises.

Preface

It was Philip W. Anderson in his famous 1972 paper *More is Different* who first threw doubts upon the reductionist approach as the fundamental methodology in Physics. Since then, the problem to build a Theory of Emergence has grown more and more as a matter of great importance both in Physics and in a broad interdisciplinary area. If, initially, emergence could be framed within a naïve, "objective" world scheme and thus easily seized by mere formal and computational models, today widespread, epistemological awareness has rooted the idea that the most genuine and radical features of emergence cannot be separated from the observer's choices. In this way, the fundamental lesson of Quantum Physics extends to the whole theoretical field transversally crossing old and new subjects. A general theory of the observer/observed relationships thus represents the ideal framework within which the connections among different areas can be discussed. Such kind of theory can actually be regarded as an authentic "Theory of Everything" in systemic sense and can go side by side with the more traditional unified theories of particles and forces.

From the Physics viewpoint, the matter implies many fundamental questions connected to the different ways in which classical and quantum systems exhibit emergence. The formation and evolution of structures find their natural, conceptual context in the theories of critical phenomena and collective behaviors. It is getting clear that information takes on different connotations depending on whether we consider a phase transition from the classical or quantum viewpoint, as well as that the connection between Physics and computation finds its deepest significance in regarding physical systems as systems performing effective computation. This is the reason why the recent researches on Quantum Computing are just one eighth of an iceberg which will lead not only to new technological perspectives, but — above all — to a different comprehension of the traditional questions about the foundations of Physics. Another relevant problem concerns the relationships among the different description levels of a system in that complex and not completely colonized middle land represented by the mesoscopic realm, where Physics meets the other research fields. Among such questions, one emerges as the most drastic: whether to extend the syntax of both Quantum Theory and Quantum Field Theory in order to build a general theory of the interaction between the observer and the external world, or whether such action will rather lead to include Quantum Theory itself as a particular case within a more general epistemological perspective.

This project has been conceived within the yearly tradition of the Special Issues of Electronic Journal of Theoretical Physics. We intended to give birth to an open space hosting quite different conceptions so as to offer the researchers a significant state of the art scenario in such exciting topics. Such a project would have never turned into a book without the fruitful discussions with my friend Ammar J. Sakaji, who shared both the conceptual choices and hard work.

I would also like to thank the authors who perfectly grasped the spirit of our project and have presented precious contributions — our debate will not stop! I extend my thanks to the EJTP Editorial Board, and Teresa Iaria whose artwork on science and art relationships has provided the cover image. Finally, a warm acknowledgement to all my friends and colleagues who — during these years — have developed these topics with me ... I am glad I can say that all of them are — directly or indirectly — present in this volume.

Ignazio Licata
November 2007

Contents

Emergence and Computation at the Edge of Classical and Quantum Systems

Ignazio Licata

ISEM, Institute for Scientific Methodology, Palermo, Italy
ignazio.licata@ejtp.info

The problem of emergence in physical theories makes necessary to build a general theory of the relationships between the observed system and the observing system. It can be shown that there exists a correspondence between classical systems and computational dynamics according to the Shannon–Turing model. A classical system is an informational closed system with respect to the observer; this characterizes the emergent processes in classical physics as phenomenological emergence. In quantum systems, the analysis based on the computation theory fails. It is here shown that a quantum system is an informational open system with respect to the observer and able to exhibit processes of observational, radical emergence. Finally, we take into consideration the role of computation in describing the physical world.

Keywords: Intrinsic Computation; Phenomenological and Radical Emergence; Informational Closeness and Openness; Shannon–Turing Computation; Bohm–Hiley Active Information
PACS(2006): 03.50.z; 03.67.a; 05.45.a; 05.65.+b; 45.70.n; 45.05.+x; 45.10.b; 03.65.w; 03.67.a; 03.70.+k; 89.75.k; 89.75.Fb

1. Introduction

The study of the complex behaviors in systems is one of the central problems in Theoretical Physics. Being related to the peculiarities of the system under examination, the notion of complexity is not univocal and largely interdisciplinary, and this accounts for the great deal of possible approaches. But there is a deeper epistemological reason which justifies such intricate "archipelago of complexity": the importance of the observer's role in detecting complexity, that is to say those situations where the system's collective behaviors give birth to structural modifications and hierarchical arrangements. This consideration directly leads to the core of the emergence question in Physics. We generally speak of emergence when we observe a "gap" between the formal model of a system and its behaviors. In other words, the detecting of emergence expresses the necessity or, at least, the utility for the creation of a new model able to seize the new observational ranges. So the problem of the relationship among different description levels is put and two possible situations arise: 1) phenomenological emergence, where the observer operates a “semantic” intervention according to the system's new behaviors, and aiming at creating a new model—choosing the state variables and dynamical description—which makes the description of the observed processes more convenient. In this case the two descriptive levels can be always—in principle—connected by opportune “bridge laws”, which carry out such task by means of a finite quantity of syntactic information; 2) radical emergence, where the new description cannot be connected to the initial model. Here we usually observe a breaking of the causal chain (commonly describable through opportune symmetries), and irreducible forms of unpredictability. Hence, the link between the theoretical corpus and the new model could require a different kind of semantics of the theory, such as a new interpretation and a new arrangement of the basic propositions and their relationships.

Such two distinctions have to be considered as a mere exemplification, actually more varied and subtler intermediate cases can occur. The relationships between Newtonian Dynamics and the concept of entropy can be taken into consideration as an example of phenomenological emergence. The laws of Classical Dynamics are time-reversal, whereas entropy defines a “time arrow”. In order to connect the two levels, we need a new model based on Maxwell–Boltzmann statistics as well as on a refined probabilistic hypothesis centered, in turn, on space-time symmetries—because of the space-time isotropy and homogeneity there do not exist points, directions or privileged instants in a de-correlation process between energetic levels. So, a “conceptual bridge” can be built between the particle description and entropy, and consequently between the microscopic and macroscopic analysis of the system. But this connection does not cover all the facets of the problem, and thus we cannot regard it as a “reduction” at all. In fact in some cases, even within the closed formulation of classical physics, entropy can decrease locally, and after all the idea to describe a perfect gas in molecular terms would never cross anybody's mind!

Another example regards the EPR-Bell correlations and the non-locality role in Quantum Mechanics. Within the Copenhagen Interpretation the non-local correlations are experimentally observed but they are not considered as facts of the theory. In the Bohm Interpretation the introduction of the quantum potential makes possible to bring non-locality within the theory. It should not be forgotten that historically the EPR question comes out as a *gedanken experiment* between Einstein and Bohr about the "elements of physical reality" in Quantum Mechanics. Only later, thanks to Bohm analysis and Bell's Inequality on the limits of local hidden variable theories, such question developed into an experimental matter. Nor Einstein neither Bohr would expect to observe really the "ghost-like-action-at-a-distance". It is useful to remember that in Bohm theory the introduction of non-locality does not require any additional formal hypotheses but the standard apparatus provided by the Schrödinger equation. Besides, if on one hand the new interpretative perspective provides a different comprehension of the theory, on the other hand it puts some problems about the so-called "pacific coexistence" between Restricted Relativity and Quantum Mechanics.

In both of the briefly above-examined cases we can see how the phenomenological and radical features of emergence are strongly intertwined with the development dynamics of physical theories and how the general problem of emergence points up questions of fundamental importance for the physical world description, such as the updating mechanism of the theories and the crucial role of the observer in choosing models and their interpretations. In particular, it is worth noticing that the relationship between the observer and the observed is never a merely "one-way" relationship and it is unfit to be solved in a single direction, which would lead to epistemological impoverishment. This relationship has rather to be considered as an adaptive process in which the system's internal logic meets our modalities to acquire information about it in order to build theories and interpretations able to shape up a system's description.

The problems related to the emergence theory, conceived as a general theory of the relationships between observing system and observed system, will be here taken into consideration, and will be tested on some evolution models of both classical and quantum systems. Finally, we will develop some considerations about the logic limits of the theories and the computability role in describing the physical world.

2. The Observers in Classical Physics: Continuous Systems

For our aims, an informational or logical closed formal system will be intended as a model of physical system such that: 1) the state variables and the evolution laws are individuated; 2) it is always possible to obtain the values of the variable states at each instant; 3) thanks to the information obtained by the above mentioned two points, it is always possible to connect univocally the input and the output of the system and to forecast its asymptotic state. So, *a logical closed formal system is a deterministic system* with respect to a given choice of the state variables.

Let us consider a classical system and see how we can regard it as logical closed with respect to the observation procedures and its ability to show emergent processes. To be more precise, the values of the state variables express the *intrinsic* characteristic properties of the classical object and they are not affected by the measurement. Such fact, as it is known, can be expressed by saying that in a classical system the measurement made on all state variables are *commutative* and *contextually compatible*, i.e. all the measurement apparatuses connected to different variables can always be used without interfering one with the other and without any loss of reciprocal information. This assumption, supported by the macroscopic observations, leads to the idea of a biunivocal correspondence between the system, its states and the outcomes of the measurements. Hence, the logic of Classical Physics is Boolean and orthocomplemented, and it formalizes the possibility to acquire complete information about any system's state for any time interval. The description of any variation in the values of the state variables, at each space-time interval, defines the *local evolutionary* feature of a classical system, either when it is "embedded" within the structure of a system of differential equations or within discrete transition rules.

The peculiar independence of a classical system's properties from the observer has deep consequences for the formal structure of classical physics. It is such independence which characterizes the system's *local, causal determinism* as well as the principle of *distinguishability of states* in the phase space according to Maxwell–Boltzmann distribution function. This all puts very strong constraints to the informational features of classical physics and its possibility to show emergence.

The correspondence between the volume in a classical system's phase space and Shannon information via Shaw's Theorem (Shaw, 1981) allows to combine the classification of the thermodynamic schemes (isolated, closed, open) in a broader and more elaborate vision. Three cases are possible:

a) *Information-conserving* systems (Liouville's Theorem);
b) *Information-compressing* systems, ruled by the second principle of thermodynamics and consequently by the *microscopic principle of correlation weakening* among the constituents of the system individuated by the Maxwell-Boltzmann statistics (see Rumer & Ryvkin, 1980). These systems, corresponding to the closed ones, have a finite number of possible equilibrium states. By admitting a more general conservation principle of information and suitably redefining the system's boundaries for the (b)-type systems, we can connect the two kind of systems (a) and (b), and so coming to the conclusion that in the latter a passage from macroscopic information to microscopic information takes place;
c) *Information-amplifying* systems which show definitely more complex behaviors. They are non-linear systems where the variation of a given order parameter can cause macroscopic structural modifications. In these systems, the time dependence between the V volume of the phase space and the I information is given by: $dI/dt = (1/V)\, dV/dt$. The velocity of information production is strictly linked to the kind of non-linearity into play and can thus be considered as a measure of complexity of the systems. Two principal classes can be individuated: c-1) Information-amplifying systems in polynomial time, to which the dissipative systems able to show self organization processes belong (Prigogine, 1994; Haken, 2004); c-2) Information-amplifying systems in exponential time; they are structurally unstable systems (Smale, 1966), such as the deterministic chaotic systems. Both the information-amplifying types belong to the open system classes, where an infinite number of possible equilibrium states are possible.

Despite their behavioral diversity, the three classical dynamic systems formally belong to the class of logical closed models, i.e. because of the deep relationships between local determinism, predictability and computation, they allow to describe the system by means of recursive functions. If we consider the evolution equations as a local and intrinsic computation,we will see that in all of the three examined cases it is possible to characterize the incoming and outgoing information so as to define univocally the output/input relationships at each time (Cruchtfield, 1994). In dissipative systems, for example, information about the self-organized stationary state *is already contained* in the structure of the system's equations. The actual setting up of the new state is due to the variation of the order parameter in addition to the boundary conditions. Contrary to what is often stated, even the behavior of structural unstable systems — and highly sensible to initial conditions — is asymptotically predictable as strange attractor. What is lacking is the connection between global and local predictability, but we can always follow step-by-step computationally the increase of information within a predefined configuration. Our only limit is the power of resolution of the observation tool and/or the number of computational steps. In both cases we cannot speak of intrinsic emergence, but of emergence as *detection of patterns*.

3. The Observers in Classical Physics: Discrete Systems

The discrete systems such as Cellular Automata (CA) (Wolfram, 2002) represent interesting cases. They can be considered as classical systems as well, because the information on the evolution of the system's states is always available for the observer in the same way we saw for the continuous systems. On the other hand, their features are quite different than those of such systems in relation to emergent behavior.

The Wolfram–Langton classification (Langton, 1990) identifies four fundamental classes of cellular automata. At the λ parameter's varying — a sort of generalized energy — they show up the following sequence:

Class I (evolves to a homogeneous state)→ Class II (evolves to simple periodic or quasi-periodic patterns)→Class IV (yields complex patterns of localized structures with a very long transient, for ex. Conway *Life Game*)→Class III (yields chaotic aperiodic patterns).

It is known that cellular automata can realize a Universal Turing Machine (UTM). To this general consideration, the Wolfram–Langton classification adds the analysis of the evolutionary behaviors of discrete systems, so building an extreme interesting bridge between the theory of dynamical systems and its computational facets.

The I, II, III classes can be directly related to the information-compressing systems, the dissipative-like polynomial amplifiers and the structural unstable amplifiers, respectively.This makes the CA a powerful tool in simulating physical systems and the privileged one among the discrete models. The correspondence between a continuous system and the class IV appears to be more problematic. This class looks rather like an intermediate dynamic typology between unstable systems and dissipative systems, able to show a strong peculiar order/chaos mixture. It suggests they are systems which exhibit emergence *on the edge of chaos* in special way with respect to the case of the continuous ones. (Bak *et al.*, 1988).

Although this problem is still questionable from the conceptual and formal viewpoint, it is possible to individuate at least a big and significant difference between CA and continuous systems. We have seen that information is not erased in information-compressing systems, but a passage from macroscopic to microscopic information takes place. Therefore, the not time reversal aspects of the system belong more to the phenomenological emergence of entropy at descriptive level than the local loss of information about its states. In other words, for the conservation principle and the distinguishability of states, the information about any classical particles is always available for observation. It is not true for CA, there the irreversible erasing of local states can take place, such as in some interactions among *gliders* in *Life*. The situation is analogous to the middle-game in chess, where some pieces have been eliminated from the game. In this case, it is impossible to univocally reconstruct the opening initial conditions. Nevertheless, it is always possible to individuate *at least one computational path* able to connect the initial state to the final one, and it is possible to show, thanks to the *finite* number of possible paths, that one of such paths must be the one that the system has actually followed. Consequently, if on the one hand the erasing of information in CA suggests more interesting possibilities of the discrete emergence in relation to the continuous one, on the other its characteristics are not so marked to question about the essential classical features of the system. In fact, in more strictly physical terms, it is also possible for the observer to locally detect the *state erasing* without losing the global describability of the dynamic process in its causal features.

Some interesting formal analogies between the unpredictability of structural unstable systems and the *halting problem* in computation theory can be drawn. In both cases, there is no correlation between local and global predictability, and yet the causal determinism linked to the observer's possibility to follow step-by-step the system's evolution is never lost. Far from simply being the base for a mere simulation of classical systems, such point illuminates the deep connection between computation and classical systems. Our analysis has provided broad motives for justifying the following definition of classical system: *a classical system is a system whose evolution can be described as an intrinsic computation in Shannon–Turing sense.* It means that any aspect of the system's "unpredictability" is not connected to the causal structure failing and any loss of information can be individuated locally by the observer. All this is directly linked to what we called the classical object's *principle of indifference* to the measurement process and can be expressed by saying that *classical systems are informational closed with respect to the observer.*

Such analysis, see in the following, is not valid for the quantum systems.