SELF-ORGANISATION IN NONEQUILIBRIUM SYSTEMS: TOWARDS A DYNAMICS OF COMPLEXITY

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1. INTRODUCTION

Complex behaviour made its appearance in the physical sciences in a modest, low-key fashion. For a long time, in the mind of most physicists and chemists, complexity was associated with biological order and its multiple manifestations, for example at the level of evolution, embryogenesis and population dynamics. Physical sciences on the other side were aiming at a description of nature in terms of laws of universal validity. And to this end they were utilising simple models to which, hopefully, the description of more complicated systems could be reduced. This feeling has been repreatedly expressed by some of the greatest scientists of our century. Thus, for Einstein "the physicist must content himself with describing the most simple events which can be brought within the domain of our experience; all events of a more complex order are beyond the power of the human intellect to reconstruct with the subtle accuracy and logical perfection which the theoretical physicist demands .... The general laws on which the structure of theoretical physics is based claim to be valid for any natural phenomenon whatsoever. With them, it ought to be possible to arrive at the description, that is to say, the theory, of every natural process including life, by means of pure deduction, if that process of deduction were not far beyond the capacity of the human intellect".

True, from time to time some fissures were appearing, threatening the status of this magnificent edifice: the discovery of the erratic behaviour of turbulence flows by

M. Hazewinkel et al. (eds.), Bifurcation Analysis, 3–12.

Reynolds, the periodic precipitation phenomena known as Liesegang rings, or the oscillatory behaviour of certain chemical oscilliations. The usual reaction to the challenge, however, was either to regard such phenomena as curiosities and even artifices, or to convince oneself that they did not really belong to the realm of physical sciences being rather parts of engineering, materials science, biology or geology.

The last twenty years have witnessed a radical departure from this monolithic point of view. We are still in the middle of this reconceptualisation, but we can already perceive a new attitude in the description of nature. In brief, this new attitude corresponds to a "rediscovery of time" at all levels of description in science. The two great revolutions in physics of this century are quantum mechanics and relativity. Both started as corrections to classical mechanics, made necessary once the role of the universal constants, c (the velocity of light) and h (Planck's constant), was discovered. Today both have taken an unexpected "temporal" turn: quantum mechanics deals in its most interesting part with the description of unstable particles and their mutual transformations. Similarly, relativity started as a geometrical theory, but today this theory is mainly concerned with the thermal history of the early universe. More striking from our point of view is the fact that radical changes are taking place in fields reputed to be classical and well established like dynamics or chemistry. Simple, high-school examples of mechanical systems are now known to present unexpectedly complex behaviour. A periodically forced pendulum on the borderline between vibration and rotation gives rise to a rich variety of motions, including the possibility of random turbulent-like excursions from its equilibrium point. Chemical reactions, usually thought to reach rapidly a stationary state of uniform composition, can generate a multitude of self-organisation phenomena in the form of spatial structures, temporal rhythms, or propagating wave-fronts.

As a result of these discoveries the interest towards macroscopic physics, the physics dealing with phenomena in our scale, is increasing enormously. One of the most striking aspects of this revival is the realisation that the distinction between "simple" and "complex", between "disorder" and "order", is much narrower than usually thought: complexity is no longer confined to biology, but is invading physical sciences as well. The description of the phenomena arising in this context is the subject of a new discipline, which may be called tentatively the dynamics of complex systems.

The aim of this article is to describe some of the avenues along which progress is likely to occur in this new discipline. But let us first sketch briefly its present status.

2. THE DYNAMICS OF COMPLEX SYSTEMS

A first facet of the dynamics of complex systems corresponds to thermodynamics. It is indeed necessary to characterise the onset of order and complex behaviour at the macroscopic level from the standpoint of the theory of irreversible processes. This approach started in the 1940's, after Onsager's pioneering work in the theory of fluctuations, when experimental evidence was still scarce, and culminated in the late 1960's in the discovery of the concept of dissipative structure. The existence of such structures reflects the fact that irreversibility, dissipation, and distance from equilibrium can act as source of order. No simple extrapolation of the equilibrium like behaviour can thus be expected far from equilibrium: new dynamical states of matter like chemical oscillations or regular convection cells, which would be inconceivable under equilibrium conditions, become possible in this range. Realising this is a surprise comparable, say, to the one that would experience intelligent beings accustomed to live in a high temperature environment at the view of a beautiful crystal!

More specifically irreversibility and dissipation confer to physical systems the property of asymptotic stability, that is to say, the ability to damp the effect of disturbances acting on them. Thanks to this property, which is absent in conservative systems like those one deals with in mechanics, sharp and reproducible configurations of matter can be sustained. On the other hand, the distance from equilibrium allows the system to fully "reveal" the potentialities hidden in the feedbacks and other nonlinearity of the kinetics, and thus to undergo transitions to dynamical behaviour.

Despite the conceptual importance of the above considerations, it is clear that at some stage of the analysis additional information coming from the mathematical structure of the evolution equations is necessary. In this way we are led to the fascinating, and still largely unexplored world of dynamical systems. As it turns out the onset of complex behaviour can be associated with a mathematical concept of a great generality, the bifurcation of new branches of solutions from some "reference" state. Moreover, bifurcation is by no means a unique event. Rather, it is the beginning of a complex sequence of transitions which may lead to symmetry-breaking and space-time order, to a high multiplicity of solutions and the concomitant ability of regulation and switching, but also to an erratic time evolution commonly referred to as "chaos" (cf. Figure 1). This marks in fact the onset of what was long known as turbulence in fluid dynamics. The new fascinating aspect is, however, that such behaviour is no more confined to a single field but, rather, invades such different disciplines as chemistry, optics, or metallurgy.

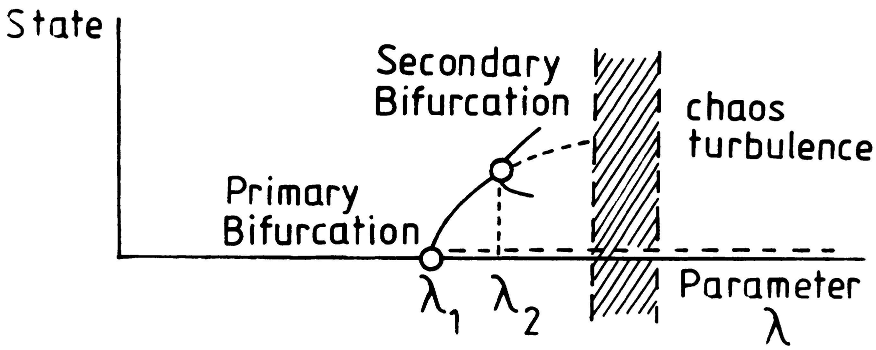

Figure 1.

It is striking to see such radically different kinds of behaviour embedded in a single description. On the other side we have the first bifurcation branches, which reflect the appearance of strict regulations and controls ensuring order. It is tempting to associate such regimes with biological order. And on the other side we have turbulent chaos, reflecting the collapse of an order encompassing the system as a whole. One can hardly avoid the feeling that such states should provide the physico-chemical basis for understanding pathological behaviour and disease. In short, we are witnessing both an incredible specificity and diversity of nonequilibrium states as well as a deep unity in the basic concepts involved in their description.

The generality of the phenomenon of bifurcation in nonlinear dynamical systems leads us quite naturally to a third facet of complex systems, namely the stochastic analysis of fluctuations. Indeed, bifurcation is basically a "decision making" process. But because of the multiplicity of choices at the "decision" point a selection mechanism is necessarily involved. Now all physical systems possess such a mechanism, in the form of random fluctuations that are generated spontaneously around the deterministic evolution. Thanks to them the state space is continuously scanned, and the evolution is directed toward the appropriate outcome. This adds therefore a ubiquitous historical dimension in the description of the system.

The fourth, but by no means the least important facet of complex systems is, naturally, experiment. After a laborious induction period we have witnessed an explosion of experimental results in the last ten years. New sophisticated techniques, many of them based on laser spectroscopy, have increased both the precision and range of space and time scales that could be explored. Moreover, a new set of quantities, related to the distance from equilibrium, have imposed themselves as key control parameters in the experimental technology. The residence time of initial products in a chemical reactor is a typical example.

The message resulting from these experimental investigations is, once again, that different systems present similar sequences of transitions; and simple behaviour coexists side-by-side with a variety of complex phenomena ranging from sharp periodicities to chaos. It suffices to modify some of the externally controlled parameters to see all these behaviours come into existence and parade in the laboratory! Moreover, many of these transitions occur in situations of great interest in applied sciences like, for instance, heterogeneous catalysis. In this respect it is worth noting that even reactions having a very simple kinetics can give rise to complex dynamics if they take place in a sufficiently complex environment such as the surface of a catalyst.

Several characteristic features of the present state of dynamics of complex systems become obvious from the above brief presentation. Both macroscopic theories and theories dealing with fluctuations are needed to understand complexity, as both "chance" and "necessity" are cooperating in the emergence of new types of behaviour. The systematic use of probabilistic concepts, longtime confined to quantum mechanics, is therefore making its entrance in the study of macroscopic phenomena. More generally after a period of parallel practically unrelated developments, the thermodynamic and statistical theory of irreversible processes, the theory of dynamical systems and the new experimental techniques become now parts of a vast interdisciplinary effort in which intense cross-fertilization between different ideas and methods begins to take place. Complex behaviour no longer appears to be a singularity in the otherwise uneventful history of a physical system. Rather, it is realised that it is deeply rooted into physics, that it may emerge and disappear repeatedly as the conditions vary, and even that it can coexist with the more familiar simple static behaviour.

3. PERSPECTIVES

After this brief summary let us look forward to the future developments in the field of complex systems. It seems to us that the most exciting discoveries are still ahead of us.

From the standpoint of nonlinear dynamics and bifurcation phenomena it would not be unfair to qualify our present knowledge as some sort of "taxonomy", the art of systematics prevailing in botany and zoology before the advent of molecular biology! This is largely due to the global character of most of these phenomena, as a result of which the problems remain highly nonlinear and thus intractable. True, from time to time some beautiful regularities emerge and inspire unexpected progress: the discovery of universality in bifurcation cascades leading to a doubling of the period in certain classes of discrete time mappings is a striking example. Still, the vast majority of transition phenomena remains poorly characterised. How these global phenomena can become amenable to a local analysis utilising perturbation theory is a major challenge of the coming years. The experimental discovery that different types of complex behaviour are possible in narrow ranges of parameter values gives some hope that such a local view of complexity might become a reality.

Mastering the mechanisms of bifurcation cascades will undoubtedly allow us to have a new look at the particularly fascinating problem of biological order. It is already clear that the fact that matter may possess properties usually ascribed to life like sensitivity, choice, history, narrows the gap between "life" and "non-life". But can one go one step further toward an understanding of generation of life? Manfred Eigen made an important contribution in this direction by showing that populations of biopolymers endowed with the ability of self-replication and autocatalysis can evolve to states of increasing complexity, which may be thought of as precursors of the genetic code. One major question remains open however, namely, how can self-replication and autocatalysis come about. Prebiotic chemistry gives some interesting clues by showing that, at the molecular level, small amino-acid and nucleotide chains are capable of cooperative behaviour. It will be a challenge of the coming years to understand how out of such elementary subunits a supermolecular organisation capable of utilising autonomously the resources of the environment, like a bioenergetic pathway, can emerge. It is difficult to avoid the feeling that bifurcations and self-organisation in nonequilibrium conditions should play a key role in this venture.

As we repeatedly stressed the occurrence of bifurcations reveals the new potentialities of matter under nonequilibrium conditions. On the one side we know that matter is capable of coherent behaviour at the macroscopic scale. But on the other side, because of the multiplicity of regimes that can be observed we realise that statistical considerations should be present in physical sciences, including branches reputed to be eminently deterministic like chemistry. Let us mention a new and still practically unexplored aspect of this duality, suggested by recent studies of fluctuations in nonequilibrium systems. It appears that in systems characterised by nonlinear kinetics internal differentiation may take place not only in the space of the parameters (as it usually happens in bifurcation) but also in time, as the system follows the course of its otherwise deterministic evolution. It suffices for this that the rate of change of the variables switches from low to high values at some characteristic "ignition" moments. What is happening then is that, because of fluctuations, different parts of the system perceive different "ignition" times and consequently some of them evolve ahead of others. This phenomenon of "bifurcations unfolding in time" shows therefore the enormous plasticity of matter when the evolution occurs under highly nonequilibrium conditions. It should play an important role in the understanding of phenomena involving sudden transients, like combusiton of explosions.

So far we have been concerned primarily with the mechanisms generating complex behaviour in physico-chemical systems. It is clear, however, that modelling complexity and evolution as a sequence of bifurcations in which fluctuations provide the mechanism of selection is a picture extending far beyond the range of physics and chemistry. Concepts developed in connection with the dynamics of complex systems are thus likely to be in the forefront in the extensive transfer of knowledge that is going to take place in the forthcoming years between physics and chemistry on the one side and environmental, biological or human sciences on the other.

Let us illustrate on a representative example how we view this problem of transfer of knowledge. Consider the problem of climatic variability. In the first half of the present century mankind has experienced a particularly mild and predictable climate. It is now established, however, that this was an exception in climate's long turbulent history. On all known scales, ranging from one season to tens of thousands of years, climate has experienced massive changes. In an overpopulated and energy-thirsty society like ours the possibility that such changes can indeed take place constitutes a major question to be faced, if not to be mastered. Whence the recent interest in modelling climatic change.

The first problem arising is whether climatic change is a phenomenon intrinsic to the earth-atmosphere-cryosphere-biosphere system, or whether it is an externally driven process. To be specific take the example of glaciations of the quaternary era, which are certainly the most dramatic climatic episodes of the last two million years. These phenomena occurred with a relatively well-defined average periodicity of the order of 100,000 years. This happens to be precisely the periodicity of variation of the eccentricity of the earth's orbit, as a result of which the solar energy received on the earth's upper atmosphere slowly varies with a relative amplitude of about 0.001. We arrive therefore at an apparent paradox: on the one side, the correlation between the two periodicities is impressive and on the other side, the amplitude of the external forcing acting on the climatic system is too small to trigger a major change.

It is here that the utilisation of concepts stemming from the dynamics of complex systems permits us to arrive at a coherent picture. Climate dynamics is modelled by a set of highly nonlinear balance equations, which as a rule admit multiple solutions. One of them corresponds to present-day climate, and others to glacial-like climates. Both types of climate are possible and compatible with all known constraints, in other words, they both constitute stable solutions of the climatic equations. Which one will be preferred? We know from the theory of complex systems that fluctuations provide the selection mechanism. So let us study the influence of fluctuations under the action of a periodic forcing representing the 100,000 year cycle of orbital variations. The result is very surprising: because of the fluctuations the weak orbital signal is amplified drastically and entrains the whole system into a 100,000 year cycle corresponding to massive climatic changes reminiscent of quaternary glaciations. In this way we arrive at a synthesis between external and interally generated mechanisms of climatic change.

4. CONCLUDING REMARKS

We have seen that the study of matter under nonequilibrium conditions introduces new concepts and, in particular, shows the constructive role of irreversible phenomena in nature. We are convinced that the modifications that we have to impose in our description of matter as a result of these discoveries will not be restricted to macroscopic physics. Important repercussions have to be expected also in the extreme scales of natural phenomena, particle physics and cosmology. As already mentioned in this article, our view of the physical world is shifting from a mechanistic, reversible description to a thermodynamic one in which notions such as entropy, instability, evolution, will play an ever increasing role. Signposts in this direction are the theory of black holes in cosmology and the gauge theories of unified interactions in elementary particle physics.

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