COMMITTEE I
Unity of Science: Organization and
Change in Complex Systems

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SELF-ORGANIZATION AND EVOLUTION THROUGH FLUCTUATIONS AND INSTABILITIES

by

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EXTENDED ABSTRACT

In the past few decades there has been an enormous progress in our understanding of the behavior and evolution of matter under equilibrium and nonnonequilibrium conditions. In the latter case a real breakthrough did happen in the study of the selforganizing features of inanimate and living matter through fluctuations and instabilities. Instabilities lead systems driven away from equilibrium to new steady states or to time periodic (cyclic) behavior and even to turbulence (or, on occasion, deterministic chaos). All these states have been called *dissipative structures* by Ilya Prigogine. Synergetic behavior is the key feature of these structures, as emphasized by Hermann Haken.

Among the new concepts recently introduced are bifurcation of solutions in systems under controllable constraints, multistability of states for one and the same set of values of the constraints, emergence of organization, ordering, cooperative behavior,... in a continuous or discontinuous way, with or without bias, emergence of chaotic behavior under purely deterministic constraints, etc. The main thrust came from systematic and rather sophisticated experimental and theoretical studies of Bénard convection, the Belousov-Zhabotinskii reaction and the laser.

Once more in the history of the sciences, concepts that originate in the natural sciences seems to provide clues for our understanding of Nature and the human culture far beyond expected by the practitionners of physics, chemistry, etc. Thus *Unity of Sciences* emerges nowadays as a matter of fact.

1. INTRODUCTION

How life originated and how it evolved on Earth? These are some of the fascinating questions to which modern science, in the present century, has provided partial though definite answers. Answers that in the past few decades do not reflect any longer a specific ideology but that are rather the products of carefully controlled experiments and detailed model studies. There are, however, lots of unanswered questions about important details and thus we cannot claim having obtained a homogeneous body of knowledge comparable to the Newtonian one. We are in fact, in a period of transition, a period of fertile yet fragmentary and on occasion contradictory scientific development. But we begin to see the emergence of a new paradigm that tends to replace the Newtonian one. Now we also see as *a matter of fact* a new approach to Science that incorporates man and so a Science that embraces in a natural way man and nature together,thus embracing all disciplines from physics, chemistry, biology... to economy, sociology, etc.

Nowadays the study of prebiotic or biological evolution is not merely related to the study of evolution of inanimate matter (magnets, fluids, fluid flows, turbulence, lasers, etc). It is in fact quite related to the study of human (individual or societal) behavior, economic growth and crisis, and the humanities at large.

How this has come about?. What are the building blocks (concepts, ideas, models) of this rather recent approach to Nature and Man?

There has been, *on the one hand* , the extraordinary development of the statistical mechanics of cooperative (critical) phenomena and equilibrium phase transitions (melting, crystallization, vaporization, ferromagnetism,...) that culminated in the ideas of K.G. Wilson (1982 Nobel Prize in Physics). *On the other hand,* there has also been an extraordinary development of the methods in nonlinear mathematics applied to non-equilibrium thermodynamic systems. A wealth of knowledge has accumulated since the pioneering and seminal ideas of L.Onsager (1968 Nobel Prize in Chemistry) and I. Prigogine (1977 Nobel Prize in Chemistry).

And *thirdly*, there has been an extraordinary achievement in our experimental and theoretical study of nonequilibrium cooperative, synergetic phenomena like Bénard convection, the laser action or the evolution of chemical and biochemical processes (like the Belousov-Zhabotinskii reaction: the oxidation of malonic or other acid in the presence of Cerium or other catalyzers). H. Haken has played an enormous influence upon such development. Alltogether these three lines of research have led to new unifying concepts, models, etc. whose usefulness go far beyond their original context.

2. EXAMPLES IN THE NATURAL SCIENCES AND A BIT OF VOCABULARY

Consider the case of a horizontal liquid layer heated from below and either open to the ambient air or enclosed between, say, two copper plates. For low enough values of the (bottom minus top) temperature difference the actual state for the system is the state of rest with a steady nonequilibrium linear vertical temperature profile. Yet for all values of the rate of heating the liquid explores not only this motionless state but many other possible states including numerous convective modes and turbulence. The actual state is however the rest for it is the only stable one. If we keep increasing the rate of heating we observe that past a certain *threshold* value the system evolves to steady cellular convection (Bénard convection). Whether one or another pattern of convection (rolls, polygonal cells,...) develops is a matter of boundary conditions, i.e., depends on the constraints at the boundaries, or on the specific kind of fluid dynamics envolved. However, there is a universal finding as the major result of theory and experiment is that through *fluctuations* the system explores as many as possible states to finally through instability establish itself in a particular one. This actual state reached past a certain threshold value of the temperature difference across the layer is the *bifurcated* state from the state of rest. Moreover, in terms of a suitably chosen (dimensionless) quantity or control parameter the critical (threshold) value is universal, i.e., it does not depend on the liquid for a given geometry (set-up) or for a chosen liquid it does not depend on the geometry.

The bifurcation from rest to cellular convection or to more complex behavior is a form of non-equilibrium *phase transition*. The new state is a specific *dissipative structure*. This bifurcation can be continuous, soft, direct or else it can be discontinous, hard, inverted with metastability and hysteretic phenomena. The terminology is a straightforward though not always fully justified *verbatim* take over from the jargon invented by L.D. Landau (1962 Nobel Prize in Physics) for equilibrium thermodynamics and statistical mechanics. Here, the system is not at equilibrium but rather it is in one of its available non-equilibrium dynamic states along its "evolution". When reached it is stable.

Cellular convection is one among the possible and actual states of the liquid layer heated from below. Another possibility is oscillatory convection , i.e., a state of time periodic variation of the velocity and temperature or any other measurable quantity. Oscillatory periodic motions are also the typical pulsed behavior of a laser like T. Maiman's 1960 ruby laser (the first to be operated) or of a laser with an intracavity absorber. Generally, oscillatory states arise when there is competition between two or more agents, two or more constraints or there are two or more largely separate time scales in a way that a recurring relaxation process develops.

Another possible and on occasion actual state of a system driven away from equilibrium is *turbulence* or in a more restrict situation *deterministic chaos*. We speak of these cases when all time (or space and time) correlations in the system decay as time proceeds (when time goes to infinity). In more technical words when the power spectrum of all time signals in the system show broad band noise (well above instrumental noise). Note that the power spectrum of steady cellular convection is a spike centered at the origin (a time independent signal has an "infinite" period and thus it correponds to a zero frequency motion). On the other hand a periodic (or a quasi/almost periodic state) has always a power spectrum with a discrete (finite or not) set of spikes well above the noise level.

At present, there is a tremendous impetus in the study of deterministic chaos, i.e., "turbulence" generated not in stochastic/random elements but rather a *deterministic* consequence of the complexity (sophistication) of the system (feedback loops, autocatalysis, nonlinear evolution laws, high enough dissipation,... or non-integrability in a conservative system). Deterministic chaos is generally linked to time dependent *albeit* aperiodic states lying on "volumes" of *fractal* (non-integer) dimensionality, i.e., on "space" that almost, but not quite, fill a volume and as a matter of fact have *zero volume*. A system evolving towards such a state, called in the jargon a *strange attractor*, shows extraordinary *sensitivity* to the values given at the *initial time* in its evolution towards the attractor. Moreover, although the laws of the system may be purely deterministic, there is no possibility of predictability in the sense of Newton's paradigm. This lack of predictability of the future of the system is well known by our fellow meteorologists.

Finally, still another possibility for a complex system is to have multiplicity of possible states for one and the same value of the constraints. This is not for a different instant of time but rather at the same time. *Multiplicity* of steady states (steady patterns, for instance) or of oscillatory periodic states. The actual state to be attained among the two or many possible ones depends strongly on fluctuations and external noise or external forces and eventually on aspects of its "history"; for some complex systems, initial conditions may eventually be not forgotten at all. This contrasts with classical simple systems where the past is generally irrelevant for its future.

3. WHERE DO WE STAND AND FUTURE OUTLOOK: FROM PHYSICS TO OTHER DISCIPLINES LIKE ECONOMY, SOCIOLOGY AND SO ON.

The more the ideas exposed in the preceding Sections penetrate in other disciplines or become part of the culture of our fellow colleagues in the soft sciences, say, the more it becomes apparent how useful they can be to them. Consider, for instance, the evolution of clima on Earth. It has recently been shown that glaciations and the related climatic phenomena have an apparent chaotic evolution and the same appears to be some stock market data (time periodic states are also known in Economy). What about the propagation of fashion, or the spread of a rumor or of a disease ?. What about political revolutions and the evolution of human behavior before and near election days ?. Fascinating questions in the realm of human sciences that are not far from similar questions asked about the behavior of inanimate matter.

I do not know if in the near future,trandisciplinary concepts defined in Physics would prove really useful in other sciences. But I do believe that we are facing the downfall -as useless- of the allmighty and deeply rooted Newtonian paradigm that has been during several centuries -with great success- the explicit or implicit support of all sciences, hard (natural) or soft (humanities including economy).

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