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Editorial

Instabilities and Non-equilibrium Structures. On the occasion of the 60th birthday of Pierre Coullet

M.G. Clerc[1], S. Rica[2,3,a], and J. Tredicce[3]

[1] Departamento de Física, FCFM, Universidad de Chile, Blanco Encalada 2008, Santiago, Chile
[2] Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Avda. Diagonal las Torres 2640, Peñalolén, Santiago, Chile
[3] INLN, CNRS-UNSA, 1361 route des Lucioles, 06560 Valbonne, France

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The natural world we live in captivates us with a plethora of disparate and seemingly unrelated phenomena manifesting hidden and profound relations. It is precisely the exploration of those relations that has allowed us to unveil the innermost working mechanisms of nature. Indeed, we live in a world full of marvels that are an endless source of fascination and motivation of scientific endeavor. It has been a long path that led us from the state of mere perplexity, in front of the myriad of complex phenomena we are confronted with, to reach an understanding of the basic rules that mandate the behavior of the basic "simple" structures of matter that construct nature as a whole.

Ironically, the key to understand a large number of phenomena does not rely on the implementation of such rules. In our quotidian scale, matter is composed of large amounts of elementary constituents. The behavior of matter at such large scales is dictated by organizational principles that seize control over the microscopic constituents. Not unlike a complex choreography – rich in patterns and synchronicity – that can be staged by instructing the performers to follow simple rules, the large-scale behavior of matter can be conceived as the consequence of the organization between its constituents. For example, the molecules composing a fluid under a thermal gradient display tremendously complex behaviors, such as molecular chaos, at a microscopic scale. However, at a mesoscopic or macroscopic scale, they generate coherent structures, such as convection rolls or eddies, which possess a characteristic length at least eight orders of magnitude larger than the size of their elementary constituents. In a similar fashion, the behavior of billions of electrons and atoms, which interact microscopically following certain constraints and rules, is orchestrated to manifest a richer new phenomena, like magnetism or superconductivity. In this way, emergent behavior pervades through different aspects of nature, from the quantum to the classical realms, showing how order emerges from seemingly disordered, incoherent or disconnected behavior. The search for the basic emergent principles that describe the behavior of macroscopic matter has been an important field of condensed matter physics. However, the emphasis has been focused on the properties of systems at (or near) equilibrium, where the tools of statistical (classical and quantum) mechanics have proven to be astonishingly successful. Despite the impressive progress achieved, nowadays it is clear that understanding matter out-of-equilibrium is a great challenge to science and engineering. This general subject was studied in great detail in a recent report of the Office of Science of the Department of Energy in the United States, which was reported in Physics Today of July 2008, entitled *"Grand challenges of basic energy sciences"* [1]. The report pointed out five grand challenges, two of them being precisely:

(i) *"How do remarkable properties of matter emerge from complex correlations of the atomic or electronic constituents and how can we control these properties?"*; and
(ii) *"How do characterize and control matter away – especially far away – from equilibrium?"*.

To have a basic understanding of non-equilibrium phenomena would allow us to make significant progress in these subjects. This progress would be also a necessary condition for great advances in our ability to conceive and develop new materials with specific mechanical, electromagnetic and optical properties, and also to perform breakthroughs in the understanding in many other areas, ranging from turbulence in our atmosphere and earthquake and tide prediction to the control of complex structures in superfluids and condensates. In order to put in perspective this ubiquitous position of out-of-equilibrium systems we should recall that all natural and most human-caused phenomena occur away from equilibrium. Non-equilibrium systems can range in scale from the microscopic (such as nanostructures and bacteria in the nanometer scale) to the macroscopic (such as seismic fault

[a] e-mail: sergio.rica@gmail.com

zones in the kilometer scale), and away-from-equilibrium processes occur on time scales ranging from femto-seconds (in chemical reactions or optical systems) to millennia (in planetary formation processes).

The search of the emergent complex behaviors of macroscopic systems in extreme out-of-equilibrium conditions is a primary goal of nonlinear science [2–5]. These systems are characterized by behaviors which are a balance of energy and nonlinear saturation. Due to the colossal and complex mission to understand nonequilibrium systems progress in this area has been a constant amalgam of theoretical, numerical and experimental efforts.

When a system is weakly out-of-equilibrium it can be characterized by the appearance of regular patterns (rolls, squares, hexagons, quasi-crystals, etc.) described by few dominating modes. The evolution of these modes can be described by means of simple and universal physical pictures drawn upon the behavior of collective degrees of freedom, generally referred to as "order parameters" [2–5]. In particular, when systems operate at more extreme conditions out-of-equilibrium, self-organizing systems are characterized by the appearance of defects that are largely responsible for the diversity of forms and properties of these systems. Conversely, our knowledge of systems far from equilibrium is scarce and it has been a central subject of research recently. It has been in the pursuit of the understanding of complexity that new central concepts have been incorporated into the description of nature such as order parameter, spontaneously broken symmetries, self-organization, instabilities and bifurcations, coexistence of states, defects, robustness, pattern formation, synchronization, cooperative effects of noise and so on. In the vast majority of cases, a whole new world of possibilities is open for the behavior of systems out-of-equilibrium which develop in all areas of science, ranging from fluid mechanics (convection, vortex dynamics, turbulence) to magnetism (domain dynamics, magneto-hydrodynamics), from nonlinear optics (lasers, solitary waves and optical memories) to solid state physics (solidification patterns, crack dynamics and defects), from liquid crystals (electroconvection) to chemical reactions (Belousov-Zhabotinsky reaction), from biological population dynamics (dictyostelium discoideum) and biological patterns (morphogenesis) to medical sciences (heart and neuronal dynamics) and even econo-physics (financial modeling). This list can go on, as daily out-of-equilibrium systems are modeled and described theoretically, numerically and experimentally, in order to harness them into every-day-life applications.

A fact that cannot be bypassed is that a general theory for the dynamical behavior of out-of-equilibrium systems has not yet been developed (and probably it does not exist) except when they are confined, that is when their spatial behavior is bound. This leaves the temporal evolution remaining, and their dynamical description can be reduced to ordinary differential equations of a few variables. In this case, we know that for long times their behavior can be roughly characterized into three types: stationary, periodic or quasi-periodic, or chaotic. This qualitative classification is a consequence of the existence of a qualitative geometric theory of ordinary differential equations, which tells us that their possible attractors are fixed points (stationary), limit cycles (periodic) and invariant tori (quasi-periodic), and strange attractors (chaos), respectively. Such a simple picture does not exist for partial differential equations for instance.

Let us conclude by pointing out the pertinence of this area of knowledge. A coherent understanding of out-of-equilibrium systems is of paramount importance from both a fundamental and application point of view. Fundamentally new and adequate concepts to describe non-equilibrium emergence phenomena arise currently in the scientific community. New ideas and approaches need to surface, supported by new experimental and numerical studies. This statement is founded by the fact that the usual tools used to describe systems at or close to thermodynamic equilibrium have proven to be inadequate to describe correctly the complex behavior and dynamical properties of strongly forced out-of-equilibrium systems: life (and the biological, chemical and physical processes it carries) is a straightforward attack against the "thermodynamic way of thinking", that predicts a uniform, isotropic and stationary cosmos around us. Hence, human life can be viewed as the seminal example of an extreme out-of-equilibrium system.

This volume contains contributions on fluid mechanics, pattern formation, chemical reactions, non linear dynamics, sociological models, etc.

The first section is dedicated to the *emergence of coherent behaviors in non equilibrium systems*. The first article by Shipman et al. [6] considers the universal nature of Fibonacci patterns, patterns which are observed in various plants, such a sunflowers, pines or in the cactus spines. The second article by Meyra et al. [7] treats similarity laws in botanic, in particular the case of the hydraulic conductivity of xylem vascular systems. The third article, by Rojas et al. [8], studies the Faraday instability of a shallow viscous fluid and compare the predictions of the model with the morphology of the experiments. The article of Escaff [9] considers the interaction of fronts in systems with a nonlocal spatial kernel that may decay faster or slower than an exponential function. The ability to control and manage localized structures in the context of forced fluid is discussed in the article by us (MGC) [10]. Synchronous states are characterized in a two pulse-coupled electronic piecewise linear oscillator in the article by Rubido et al. [11]. Next, Mancini and Vidal [12] analyze numerically the dynamics of two driven coupled chaotic systems, in the framework of fluid convection in a small container with square symmetry.

The second section is devoted to the *transfer of energy and kinetics*. The role of fluctuations and noise present several challenges, and applications. In this sense, as an application of stochastic thermodynamics, Moreau et al. [13] study in practice the efficiency of engines in a non-equilibrium stationary state showing a new upper bound for the well known Carnot efficiency. On the other hand, scaling laws for the steady spectrum of wind excited waves on the sea are derived in the article of Pomeau and

Le Berre [14]. Next, Sonnino computes the effect of dissipation and the stationary distributions in plasmas [15].

The last section is devoted to the *complex behaviors and robust phenomena*. The influence of external fluctuations with memory on the carbon monoxide oxidation on iridium(111) is presented in the article of Cisternas et al. [16]. It is worth mentioning that this chemical reaction is currently playing a key role in the process of catalysis in the combustion. The article of dell'Erba et al. [17] investigates the stochastic resonance in the transition between Bloch fronts of opposite chiralities and derives a scaling law in terms of an effective nonequilibrium potential. The effects of diffusing opinions on a prototype model for continuous opinion dynamics is presented in the article by Pineda et al. [18]. Masoller and Atay [19] study the transitions to synchronization in delayed coupled automata. Finally, the article by Goles and Rica [20] considers the irreversibility in explicit reversible automata systems.

In the last contribution, Tresser [21] attacks one of the most controversial subjects in microscopic physics: the violation of Bell's inequalities in quantum mechanics and in quantum optics in particular. He tries to show us that locality is not the source of all the contradictions obtained in Bell's theory.

This topical issue has a very special character since it appears on the occasion of the 60th birthday of Professor Pierre Coullet of the University of Nice-Sophia Antipolis, author of many seminal papers on the subject. Because of this we were able to assemble a selection of original contributions from some of the most important scientists in the field of Nonlinear Physics.

Pierre Coullet was born in 1949 in Nice, where he grew up and undertook all of his studies. He became a CNRS researcher in 1975, and Professor at the Université de Nice-Sophia Antipolis in 1987. Today he is vice-president of the Université de Nice-Sophia Antipolis. Pierre Coullet's scientific work concerns more than 150 published papers in areas ranging from dynamical systems to extended systems such a liquid crystals, optics, etc.

Pierre has a very different view as well as a very deep understanding of the underlying physical mechanisms. However, Pierre's most relevant characteristic is, perhaps, the desire to experience the newer in science, in technology and in life. He has realized innovations since his early scientific age. In the mid 80s he switched from the study of finite dimensional dynamical systems to the understanding of partial differential equations. Very soon he understood that the qualitative behavior of partial differential equations requires intensive numerical simulations. He brought the first couple of Apple Macintosh computers to the Laboratoire de Physique Théorique at Parc Valrose. The first study concerned the complex Ginzburg-Landau equation, with the aid of his former students Lionel Gil and Jocelyne Lega. Later, in the search of the best, he got a few *Sun sparc* workstations and he drove his team (in particularly Kjartan Emilsson) to the development of interactive numerical simulations, which may be recognized as a revolutionary innovation. The main purpose of an interactive numerical simulation (instead of simulation running in batch) is that the user may interact, changing parameters for instance, with the routine that simulates a physical system governed by elementary rules like partial differential equations. This tool provided an important step forward in the qualitative understanding of the behavior of partial differential equations. It will be unpractical to list the direct or indirect new ideas generated by this kind of tool. Today most of his followers (including two of us MGC and SR) use interactive numerical simulations in their research. As a general principle, Pierre always gets the last technological release or gadget or everything he could use to solve a problem or express an idea in a better way.

This is only an example to describe one aspect of Pierre's character. We all wish to Pierre a good continuation in his fruitful activities and in his continuous journey towards the new and the best.

Finally, we have the pleasure to acknowledge Pierre Collet and Yves Pomeau for the following tribute to Pierre Coullet originally in french that we translate into english.

Tribute to Pierre Coullet. *D'après Pierre Collet et Yves Pomeau. After his studies at the Université de Nice, Pierre prepared his Ph.D. under the supervision of Enrique Tirapegui on the renormalisation group in field theory, and then his "thèse d'état" with Jean Coste as advisor. This research led him, in a rather unexpected way, to explore the ideas of fixed points of a functional equation creating a completely original field: although the bifurcation of a limit cycle by period doubling was well known, the discovery by Pierre and Charles Tresser of an infinite sequence of period doubling in a finite interval of the control parameters with its universal properties, was completely unexpected. This research has opened a new field in the theory of bifurcations and dynamical systems. These beautiful theoretical works have led to numerous applications and experimental studies. The experiments in fluid mechanics realized on this occasion have, naturally led to the study of spatially extended systems. He is one of the first to have understood that nonlinear optics is also concerned by this approach and, in particular, he predicted the existence of a turbulent regime mediated by optical vortices.*

His remarkable scientific works have earned him national and international recognition: prix Langevin from the société française de physique (1990), prix C.S. de Freycinet from the académie des sciences (1991), the médaille d'argent du CNRS (1993), foreign fellow of the academia chilena de ciencias (Chile, 1999), the Humboldt prize (Germany, 2000), the Holweck prize from the SFP and the IOP (2001).

Remaining the same, a creative and productive researcher, Pierre has invested a lot of time in the training of young scientists and the teaching of physics, including school teachers and the general public. His passion for the history of science has led to a reconsideration of classical problems in optics and mechanics with a modern view point.

He has put a lot of energy in successfully managing the research at the Université de Nice. Staying at the forefront of international research collaborations with a large number of activities, he managed to keep his friendly and optimistic mood.

We wish you, dear Pierre, to continue on this path of a man and a researcher with equal inventiveness, enthusiasm and beautiful discoveries.

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