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BICENTENNIAL PROGRAM IN SCIENCE AND TECHNOLOGY

The World Bank

Dynamics, Singularities and Geometry of Matter out of Equilibrium

Macroscopic physics is the physics of great amounts, of the order of the Avogadro number, of the elementary constituents of matter and as such it is the physics of every day life, which is the physics of the vast majority of the phenomena with which we are in direct contact. In fact the world we observe around us is a consequence of the laws of macroscopic physics and technology is mainly applications of macroscopic science. Historically science started trying to explain the direct observation of nature and the impressive construction of mechanics was one of the first great successes of this period. Our subject in this proposal is directly in the line of this classical mechanics and in the ulterior appearance of thermodynamics whose necessity was imposed by new observations of simple natural phenomena. This classical thermodynamics of the XIX century is valid for *equilibrium systems,* i.e. systems whose interactions with the external world allowed them to go for long times to thermodynamic equilibrium. It was developed much before the acceptance by the scientific community of the “atomic hypothesis”, and central concepts for our comprehension of macroscopic systems, such as *entropy*, were introduced. The very existence of the first and second law of equilibrium thermodynamics showed that macroscopic systems could be described by collective variables, *gross or macroscopic variables*, representing macroscopic behaviors, and that these variables obeyed laws which are quite independent of the detailed microscopic structure of matter.

Classical thermodynamics was at the origin of the industrial revolution putting in this way in evidence the central role of technological progress in the changes of human society. However, a great quantity of macroscopic phenomena are not described by equilibrium thermodynamics since their interactions with the external world does not allow them to reach thermodynamic equilibrium, and a new world of possibilities are open for their behaviors in several areas of science such as fluid mechanics (convection, vortex dynamics, turbulence), magnetism (domain dynamics, magneto-hydrodynamics), nonlinear optics (Laser, solitary waves, optical memory), solid physics (solidification patterns, crack dynamics and defects), liquid crystal (electroconvection), chemical reaction (Belousov-Zhabotinsky reaction), biological population dynamics (dictyostelium discoideum), biological patterns (morphogenesis), medical science (heart dynamics), econo-physics (Financial modeling), etc.

The central activity today is the understanding of the behavior of macroscopic systems far from thermodynamic equilibrium and it is pursuing this ambitious objective that new central concepts have been incorporated to the description of nature: *self-organization, instabilities and bifurcations, coexistence of states, generic behaviors, defects, robustness, pattern formation,* and so on. The interest of the scientific community in these new aspects started to grow significantly only in the last two decades, following the route of the pioneering work of Scott Russell, Faraday, Poincaré, Rayleigh, Bénard, Taylor, Reynolds, von Kármán, Andronov, Fisher, Kolmogorov, Turing, Landau, Prigogine, etc.

There is no general theory for non-equilibrium systems except when they are confined and their dynamical description can then be reduced to ordinary differential equations. In this case, we know that for long times their behavior is roughly of 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 strange attractors (chaos).

We do not have this simple picture for extended systems, which are certainly the most interesting ones since complex space inhomogeneities and spatio-temporal behavior can arise. For instance, in a classical experiment like the Rayleigh-Bénard convection a fluid layer is heated from below, above certain threshold of temperature gradient, evolves towards periodic structures (rolls). Increasing the temperature gradient the system exhibits complex behaviors characterized by zigzag instability, appearance of dislocations, boundary domains and spatio-temporal chaos.

The macroscopic description is now done in terms of partial differential equations and we do not have a qualitative mathematical theory of these equations, and a direct consequence is the great variety of spatio-temporal structures and behaviors observed in the macroscopic everyday world. In fact, one can say that the rhythms and spatial structures observed in nature should correspond to robust behaviors of these equations. Quoting Feynman in Lectures of Physics, we summarize the spirit of our project: *“The next great era of awakening of human intellect may well produce a method of understanding the qualitative content of equations. Today we cannot. Today we cannot see that the water flow equations contain such things as the barber pole structure of turbulence that one sees between rotating cylinders. Today we cannot see whether Schrödinger’s equation contains frogs, musical composers, or morality – or whether it does not. We cannot say whether something beyond it like God is needed, or not. And so we can all hold strong opinions either way.”*

Individually each member of this group has particular abilities in theoretical dynamical systems, fluid mechanics, stochastic processes, interactive numerical simulations, and one of us is purely experimentalist. Our aim is to join experimental, numerical and theoretical skills and capacities of our group. The collaborative nature of this group is essential due to the complexity of the

Dynamics, Singularities and Geometry of Matter out of Equilibrium that we wish to understand. Therefore, we have the firm conviction that we must work together in order to achieve significant progress in this theme. More precisely, we intend to peruse the problems of localized structures, fracture, dynamic response in phase transitions, avalanches, fluidized beds, suspensions, acoustic interactions in two phase media, interface dynamics, elastic plates, pattern formation, noise effects, reaction diffusion systems, instabilities and bifurcations, and singularities.