Ecodynamics: the quest for evolutionary physics

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Abstract

The challenge for sustainable development needs a shift of paradigm towards an evolutionary point of view and also needs new modeling tools to investigate complex ecosystems and the related dynamics. This paper is an attempt to develop the new discipline of ecodynamics as a quest for evolutionary physics and ecoinformatics. Particular attention is devoted to goal functions, to the relation of conceptualizations surrounding matter, energy, space and time and to the interdisciplinary approach connecting thermodynamics and biology. The evolutionary dynamics of complex systems, ranging from open physical and chemical systems (strange attractors, oscillating reactions, dissipative structures) to ecosystems has to be investigated in terms of far from equilibrium thermodynamics (Prigogine). The theory of probability is discussed in light of new theoretical findings related to the role of events, also in terms of entropy and evolutionary thermodynamics.
Keywords: entropy, evolutionary thermodynamics, ecodynamics, probability.

1 Introduction

More than a hundred years ago, in 1886, Ludwig Boltzmann [1], one of the fathers of modern physical chemistry, was concerned with the relation between energy and matter in scientific terms. According to Boltzmann, the struggle for life is not a struggle for basic elements or energy but for the entropy (negative) available in the transfer from the hot sun to the cold Earth. Utilizing this transfer to a maximum, plants force solar energy to perform chemical reactions before it reaches the thermal level of the Earth's surface.

To live and reproduce, plants and animals need a continuous flow of energy. The energy of the biosphere, which originates in the luminous energy of the sun, is captured by plants and passes from one living form to another along the food chain. The energy captured by chlorophyll is stored in carbohydrates (molecules rich in energy), and by means of photosynthesis, a term that means "to make things with light". This radiant pathway that provides us with great quantities of food, fibers, and energy—all of solar origin—has existed for about four billion years, a long time if we think that hominids appeared on the earth only three million years ago and that known history covers only two thousand years. Our ancestor, the blue alga, began to photosynthesize, thus assuming a fundamental role in biological evolution.

The organization of living beings in mature ecosystems slows the dispersal of energy fixed by plants to a minimum, enabling them to use it completely for their own complex mechanisms of regulation. This is made possible by large "reservoirs" of energy (biomasses) and by the diversification of living species. The stability of natural ecosystems, however, means that the final energy yield is zero, except for a relatively small quantity of biomass that is buried underground to form fossils for the future.

Photosynthesis counteracts entropic degradation insofar as it orders disordered matter: the plant takes up disordered material (low energy molecules of water and carbon dioxide in disorderly agitation) and orders it using solar energy. It organizes the material by building it into complex structures. Photosynthesis is therefore the process that, by capturing solar energy and decreasing the entropy of the planet, paved the way for evolution.

It is important to emphasize that biological activity is a planetary property, a continuous interaction of atmospheres, oceans, plants, animals, microorganisms, molecules, electrons, energies, and matter, all part of a global whole. The role of each of these components is essential for the maintenance of life.

The relations and activities of the global biogeochemical system are life. The aim of science is to maintain these relations and characteristics; to live in harmony with nature, not to conquer it. This type of science comprehends complexity and uncertainty, and moves away from a deterministic-mechanistic view of the world in favor of a holistic and evolutionary view. It refers to the "clinamen" of Lucretius and to the "disciples of Sais" of Novalis rather than to the clockwork world of Descartes and the reversible time of Newtonian mechanics. It considers the constraints not as halters or chains but as conditions that create diversity and mutations, all of which amounts to biological evolution: constraints as sources of creativity and presuppositions for evolution.

The basic laws of physics from Newton to the present day have been time reversible; on the contrary, reality is constituted by phenomenological aspects: macromolecular organization, cellular differentiation, life processes, characterized by irreversibility of time. The reason for this lies in dynamical interactions that take place in complex systems. The analysis of reality requires major modification of current physical chemistry equations and theories. What is now clear is that complex systems and their behaviour can only be analyzed by means of relations including time as directional factor.

On one hand, the use of time-reversible classical and quantum physical chemistry approaches for studying matter at the molecular level and the behaviour of simple molecular systems has greatly improved man's understanding. On the other hand, we need new approaches and new time-irreversible theories able to describe the behaviour of complex systems.

As Thomas Khun [2] remarks, the passing of time often brings anomalies which existing theories are no longer able to explain. The divergence between theory and reality may become enormous and consequently a source of serious problems. This is exactly what is happening today between current scientific theories and the natural situation of the planet. For this reason the sustainability theory needs this type of approach.

In Khun's terms this means a shift toward a new paradigm. As Palomar in Italo Calvino's novel observed: “if the model does not succeed in transforming reality, reality must succeed in transforming the model”.

Based on the assumption that the interaction between biophysical constraints and evolution is not satisfactorily described by current scientific theories, this paper is an attempt to present a new model to be used in ecological physical chemistry as concerns entropy, energy and time fluctuations in biological and ecological systems.

The epistemology of the model derives from interdisciplinary cross-fertilization between physical chemistry, mainly thermodynamics, and ecology, mainly systems ecology. The logical consequence is a complete change of point of view or a "gestalt" shift in modelling the relationship between biophysico-chemical parameters and the global environment.

Professor Ilya Prigogine, Nobel prize winner in chemistry, founded the basis of this new discipline. I do like to call this new discipline Ecodynamics or Evolutionary Physics.

2 Steps towards ecodynamics

In the framework of evolutionary physics we deal with goal functions instead of state functions, the ecodynamic models have to be based on relations evolving in time; “far from equilibrium thermodynamics” (Prigogine) assumes upon itself the role of foundation of a new description of nature.

In his autobiography, Nobel prize winner Ilya Prigogine recounts his first studies on far-from-equilibrium phenomena:
“It is difficult today to give an account of the hostility that such an approach was to meet. For example, I remember that towards the end of 1946, at the Brussels IUPAP meeting, after a presentation of the thermodynamics of irreversible processes, a specialist of great repute said to me, in substance: ‘I am surprised that you give more attention to irreversible phenomena, which are essentially transitory, than to the final result of their evolution, equilibrium’.”
He adds: “As we started from specific problems, such as the thermodynamic signification of non-equilibrium stationary states, or of transport phenomena in dense systems, we have been faced, almost against our will, with problems of great generality and complexity, which call for reconsideration of the relation of physico-chemical structures to biological ones, while they express the limits of

Hamiltonian description in physics. Indeed, all these problems have a common element: time.”

Professor of physical chemistry at the University of Brussels, Ilya Prigogine was awarded the Nobel prize in chemistry in 1977. His studies opened a window on nature. For the first time in the history of physical chemistry, tools, methods, equations and models were developed to describe the essence of the evolutionary properties of nature. This was a true change of paradigm. This change in paradigm: a) implies that the intrinsic irreversibility of time has erupted in the basic equations of chemistry and physics; b) it sustains Pascal’s view that the whole is greater than the sum of its parts and hence negates the statement of Descartes that the world should be divided into the smallest possible parts in order to understand it; c) it suggests that form and aesthetics (and hence quality as well as quantity) play a role in the evolution of nature. Nature is therefore conceived as φυσισ (*physis,* the word from which *physics* is derived) in the original Greek sense, a nature in which time, relations and aesthetics play a fundamental role.

In the foreword of “The Essence of Time” [3] Prigogine wrote:

“The first part of this book deals with the passage ‘from a space to a time culture’. This is indeed an essential part of the scientific revolution we are witnessing at the end of the 20th century. Science is a dialogue with nature. In the past this dialogue has taken many forms. We feel that we are at the end of the period which started with Galileo, Copernicus and Newton and culminated with the discovery of quantum mechanics and relativity. This was a glorious period but in spite of all its marvelous achievements it led to an oversimplified picture of nature, a picture which neglected essential aspects. Classical science emphasized stability, order and equilibrium. Today we discover instabilities and fluctuations everywhere. Our view of nature is changing dramatically. At all levels we observe events associated with the creative power of nature. I like to say that *at equilibrium matter is blind, far from equilibrium it begins to ‘see’.*

Although quantum mechanics and general relativity are revolutionary, as far as the concept of time is concerned, they are direct descendants of classical dynamics and carry a radical negation of the irreversibility of time.

Irreversibility is not related to Newtonian time or its Einsteinian generalization, but to an ‘internal time’ expressed in terms of the relations between the various units of which the system is composed, as are relations between particles.”

This simply means that we no more deal with state functions, but rather with evolving ecodynamic functions.

Faced with the evolutionary character of nature and life, classical science (physics and chemistry) encounters three paradoxes:

- Prigogine’s time paradox [3];
- the paradox of negentropy that cannot be calculated on the basis of conservative, deterministic and purely quantitative terms (energy and classical entropy) but which must consider information, forms and quality;
- the probability paradox (probability is an aseptic, atemporal mechanistic concept) which has to account for events, emerging phenomena, choices made

by plants, animals and ecosystems, random fluctuations of evolutionary biology and the phenomena of far-from-equilibrium systems.

3 The Belousov-Zhabotinsky reaction

Prigogine introduces the concept of the arrow of time to describe irreversible changes. The main issue derived from the theory of dissipative structures is that the evolution and maintenance of open systems far from equilibrium are possible only if irreversible thermodynamic processes occur. Such processes dissipate energy and matter, increasing Entropy in the environment.

The evolutionary process is such that systems become more and more complex and organized. Biological diversity is the product of long-term interactions at a genealogical and ecological level: the genealogical interactions regard the dissipation of Entropy by irreversible biological processes; the ecological interactions regard Entropy gradients in the environment.

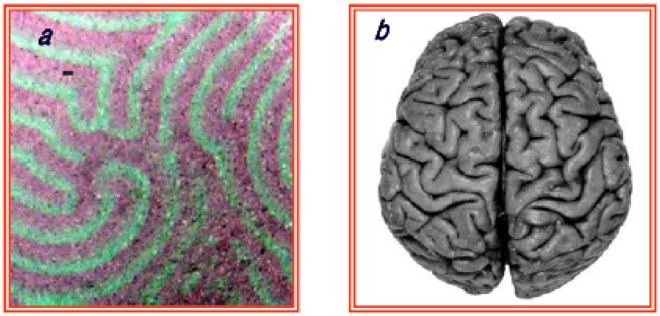

Figure 1: a) *Labyrinthine* chemical structure obtained with our reaction diffusion system (the Belousov-Zhabotinsky reaction) in lipid membrane b) Human brain.

There are also chemical systems that show phenomena of self-organization such as the formation of stationary spatial structures or periodic oscillatory states. Self-organizing chemical systems have been of relevant importance for the development of the theoretical biology, and nowadays they cover an important role in the evolution of systems biology. This science has been originated from the confluence between molecular biology, with its emphasis on individual macromolecules (DNA, proteins, enzymes…), and the molecular self-organization theories, in which thermodynamics plays the key role [4]. In his seminal work "*The Chemical Basis of Morphogenesis (1952)*" [5], Alan Turing theorized that tissues differentiation in the development of an organism starting from similar cells, could be due to a reaction-diffusion process in the cellar environment. This intuition remained only a theoretical speculation until 90s, when Dekepper's group in Paris found this kind of structure in an oscillating chemical system performed on a gel substrate [6]. Nowadays, the chemical pattern formation is deeply studied for its implications in biological systems, in particular a relatively simple chemical model can be used to explicate a lot of behaviors in cellar and tissue development. We performed a great number of experiments studying the Belousov-Zhabotinsky (BZ) oscillating reaction in membranes used as model for biological systems [7], and the figures 1 and 2 explain the similarities between the laboratory model and biological systems of several orders of complexity. The phenomenon is clearly related to the role of entropy in dissipative structures and to the input-output entropy flows.

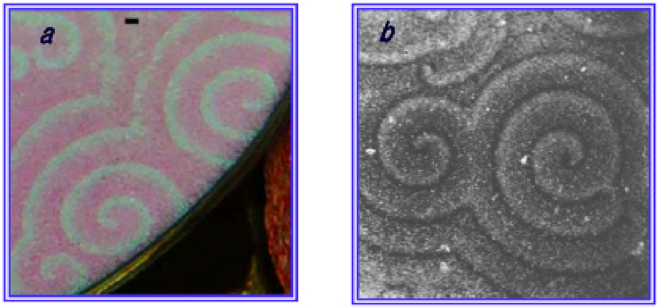

Figure 2: a) Spiral patterns obtained in our chemical systems; b) A colony of Dictyostelium Discoideum [8]. The spirals shown are caused by the movement of cells in response to cAMP waves periodically initiated by the aggregation center.

4 The entropy paradox: energy vs. entropy

In the far from equilibrium thermodynamics the role of entropy is fundamental. We may say that entropy exist *per se*, is a non-conservative function and is related to evolution. This conclusion is a big step because it overcomes the old dilemma of whether entropy was the shadow of energy or vice versa, and does not reduce the ingenious invention of entropy to a purely energy dogma. The First Principle formulates the concept of energy in a conservation framework; the Second formulates that of entropy in an evolutionary framework. This is where evolutionary biology and mechanics meet. Schrödinger's introduction of the concept of negentropy was an inspired one: a living system absorbs negentropy from the external environment, structuring itself and evolving on the basis of this interaction. In other words, energy and entropy can be related, as is done in classical thermodynamics and statistical thermodynamics, but from the point of view of time, the two concepts are irreducible and different. In an evolutionary Gestalt, entropy has an extra gear which is the key necessary for studying living systems and ecology. It is important to study flows of energy and matter, quantities which are intrinsically conserved; it is also important to study entropy flows, an intrinsically evolutionary and non conserved quantity. The appearance of a term of entropy production, or "source term" as Aoki [9] calls it, is the watershed dividing the evolutionary world from the special case of conserved energy and mass. *But if energy and mass are intrinsically conserved and entropy* *is intrinsically evolutionary, how can entropy be calculated on the basis of energy and mass quantities (entropy paradox)?* This question is still unanswered [10] and all we can do is to note that the ecodynamic viewpoint is different from that of classical physics and classical ecology.

Let us observe the different relations of energy and entropy vs. information. An energy flow can lead to destruction (increase in entropy, for example a cannon ball) or organization (decrease in entropy, for example photosynthesis). The same quantity of energy can destroy a wall or kill a man; obviously the loss of information and negentropy is much greater in the second case. Energy and information are never equivalent.

Entropy has the broken time symmetry of which Prigogine speaks. In other words, entropy has an energy term plus a time term that energy does not have. Entropy has an intrinsic temporal parameter. Energy obeys spatial and material constraints; entropy obeys spatial, material and temporal constraints.

If history and the succession of events are of scientific relevance, the concept of function of state should be revised at a higher level of complexity. The singularity of an event also becomes of particular importance: if a certain quantity of energy is spent to kill a caterpillar, we lose the information embodied in the caterpillar. But were this the last caterpillar, we should lose its unique genetic information forever. The last caterpillar is different from the nth caterpillar.

Stories take place in a setting, the details of which are not irrelevant to the story. What happens in the biosphere, the story of life, depends on the constraints of the biosphere itself. Hence it is important to have global models of the biosphere in terms of space, time, matter, energy, entropy, information, and their respective relations.

Table 1: The death of the deer.

Far from thermodynamic equilibrium	ENTROPIC WATERSHED	Towards thermodynamic equilibrium
m		m
E		E
S		$+\Delta S$
$-\Delta S$		$-\Delta S_{lost}$
information		Information lost

Finally if we consider the evolutionary transition from anaerobic to aerobic living systems, the ratio of energy to stored information is clearly different. The information that led to an evolution and organization of the two types of system is not proportional to the flow of energy.

Thus entropy breaks the symmetry of time and can change irrespective of changes of energy, being energy a conservative and reversible property, whereas entropy is evolutionary and irreversible *per se*. The flow of a non-conservative quantity, negentropy, makes life go and the occurrence of a negentropic production term is just the point that differs from analysis based on merely conservative terms (energy and matter).

The situation is explained in *table 1* "The death of the deer": mass and energy do not change, whereas entropy does. There is an entropic *watershed* between far from equilibrium (living) systems and classical systems (the dead deer or any inorganic-not living system).

We may conclude that in the far from thermodynamics equilibrium systems (biology and ecology) *entropy is not a state function, since has intrinsic evolutionary properties*, strikingly at variance with classical thermodynamics.

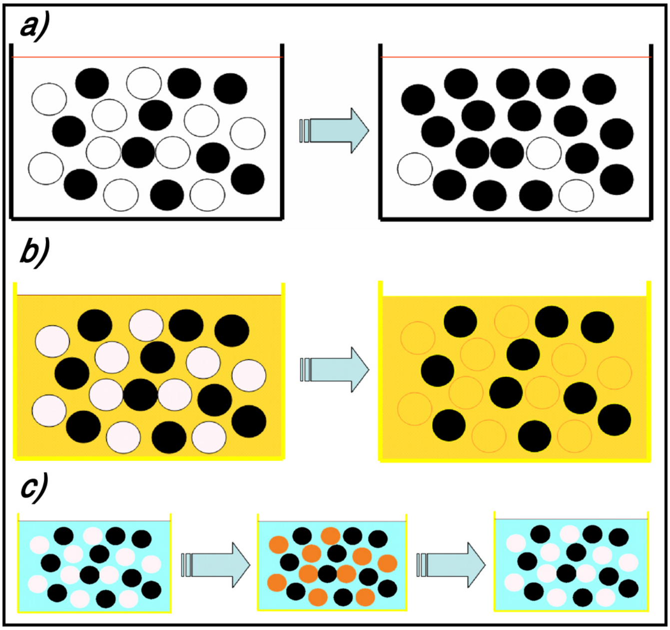

Figure 3: Unexpected events that may occur in living systems: a) oxidation; b) chameleon effect; c) oscillating reaction.

5 The probability paradox

An event occurs in a stochastic manner because it is preceded by others. There are genetic and environmental constraints. Evolutionary events proceed in a manner that depends on time: they show a direction of time; they are irreversible.

Past time has determined the constraints; the future is largely unpredictable, and always has a stochastic or probable element.

Previously unobserved events cannot be predictable; rare and extreme events may completely change the dynamics of complex systems.

Figure 3 shows the *emergence* of a probability paradox in the presence of events:

a) suppose that an oxidation (chemical event), unknown to the observer, arises in the classic “white and black spheres” game: the probability white/black is no more fifty-fifty (only if the oxidation is changing the white sphere to grey, I may know what happened),
b) suppose that an evolutionary event also occurs , related to the *“chameleon” effect* (sensible to the environment): again the probability is no more fifty-fifty; moreover the event’s interval depends on the “chameleon”;
c) suppose an oscillating event occurs, similar to the previously observed BZ reaction: the situation is more complex and depends on many parameters. Again the observer has no possibility to predict which sphere will be picked up from the container.

It is possible to conclude that in the far from equilibrium framework a classical probability approach does not apply and new models have probably to be developed for the Boltzmann’s relation S = k lnW.

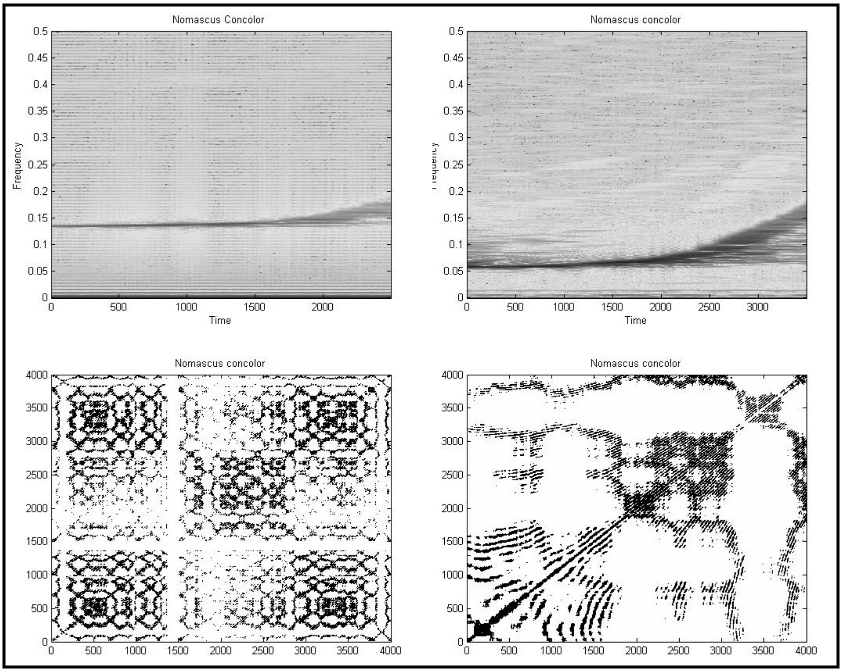

Figure 4: Recurrence Plot analysis of the calls of two different Nomascus Concolor gibbons. The spectrograms show two very similar signals, characterized by a light frequency modulation. On the contrary, the recurrence plots show completely different patterns.

6 Strange attractors

Because open ecosystems are self-organizing complex adaptive systems responding to current environmental conditions, we view the organizing principles as “orientors” or “attractors”

Again Prigogine underlines that the evolutionary dynamics of complex systems, (strange attractors, oscillating reactions, dissipative structures) has to be investigated in terms of far from equilibrium thermodynamics.

Figure 4 shows an experiment performed on gibbon vocalizations [11] . The comparison between the two lower figures (*recurrence plots of strange attractors*) is a clear *evidence of biodiversity* marked by *vocal fingerprint.* We have done similar experiments on Bat’s *vocal fingerprint* and on Sardinian deer [12]. Experiments on whales’ songs are in progress.

Again the role of Prigogine’s far from equilibrium thermodynamics is the theoretical basis of these calculations.

Biodiversity is strictly related to biological evolution and, also in this case, we have to refer to goal evolutionary functions: entropic change and flow is the key to understand the experimental results of the recurrence plots and a further incentive to develop new steps towards an evolutionary physics.

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