EPISTEMOLOGICAL ASPECTS OF SYSTEMS THEORY RELATED TO BIOLOGICAL EVOLUTION

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Contents

Summary

The thermodynamic description of systems is used to understand the dynamics of biological systems and ecosystems.

The foundations of non-equilibrium thermodynamics are analyzed in order to gain a deeper insight of the evolution of living systems, with special reference to their supramolecular structures. From an epistemological point of view we deal with a real “gestalt” shift in the scientific paradigm: from a mechanistic to an evolutionary approach.

Thermodynamics and biological evolution introduce the concept of the undirectional flow of time and shift our “Gestalt“, focusing on the relations and evolution of structures rather than on single species and molecules. All natural processes are irreversible. Time, like entropy, is a natural trend. The time stored in relations and events has created biodiversity.

The limits of classical sciences in describing evolving systems are discussed in terms of irreversibility and complexity.

The non-equilibrium processes and the consequent inclusion of time in non-linear equations are the basis of a new evolutionary physics described in terms of probabilities.

A move towards an evolutionary view of physics means pursuing the unification of the sciences and the humanities. Science has given too much space to space, ignoring time. In history, in human affairs, and in ecology, the role of time is fundamental: memories are certainly more important than kilometers.

1. Integrating Epistemology of Thermodynamics and of Biological Evolutionary Systems

Time per se does not exist; the sense of what has been done in the past, what is in the present, and what will be, is embodied in things themselves. (Lucretius, De rerum natura)

The voice that spoke was certainly that of our master; he knows how to connect traces of things here and there. He observed the stars and traced their positions and orbits in the sand; he kept a watch on the sea of air and never tired of considering its clarity, movements, clouds, and lights.

He enjoyed connecting distant things. Now the stars would be men to him, now men stars, stones animals and clouds plants. (Novalis, The Disciples of Sais)

A blade of grass is energy manifesting as matter, the material grass. The spirit of grass is that invisible force that produces the species grass, and that manifests to us in the form of real grass. (Iroquois cosmogony)

1.1 Entropy and Biological Evolution

More than a hundred years ago, in 1886, Ludwig Boltzmann, 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 branch of science that deals with energy flows in biological systems is bioenergetics. In bioenergetics and in biophysical chemistry the role played by relations, understood as structures that organize themselves and transmit information to other structures, is evident.

As pointed out by Stebbins when introducing the concept of *relational order,* in biology the systematic ordering of the basic components or units of any structure is correlated with similar orders in other similar structures, enabling the structures to cooperate in specific functions, such as the synthesis of sugar by photosynthesis. Relational order helps organisms to carry out chemical reactions and to cause coordinated movement of their parts (thermodynamics and kinetics).

A systemic and evolutive point of view is therefore fundamental in environmental physical chemistry. A milestone in this direction is the concept of negentropy, introduced by Schrödinger.

Many regard 1944 as the year in which biophysics was founded, with the publication of Erwin Schrödinger's "What is life?". Winner of the Nobel Prize for Physics and father of quantum mechanics, in this publication he expresses his thoughts on biological problems. He introduces the concept of negentropy, emphasizing that it is a negative variant of entropy from an initial value (the birth of the individual, the origin of life, the beginning of biological evolution) and not of absolute negative entropy, since the Third Law of Thermodynamics does not conceive of an entropy value less than zero. "How would we express in terms of the statistical theory the marvelous faculty of a living organism, by which it delays the decay into thermodynamical equilibrium (death)? We said before that it feeds on negative entropy, attracting, as it were, a stream of negative entropy upon itself, to compensate for the entropy increase it produces by living and thus maintains itself on a stationary and fairly low entropy level."

When Schrödinger says that an organism feeds on negentropy, he simply means that its existence depends on an increase in entropy in the rest of the universe. This holds for open thermodynamic systems (living organisms) and for closed systems (the planet Earth). Obviously it is not true for isolated systems, fated to "thermal death" by entropy increase. Schrödinger's statement contains the key to the origin of life on Earth, the history of biological evolution, with its key protagonist, photosynthesis.

The relations between entropy (and negentropy), evolution, and Boltzmann's H theorem are complex and intriguing. Although we have already introduced Schrödinger's concept of negentropy (and there will be some repetition in what follows) it is important to give a complete picture of the scientific basis of energy flows in the biosphere and bioenergetics in general, in order to understand the role of entropy in nature and the role of thermodynamics in biological evolution (see *Entropy Systems Theory*.)

1.2 Biosphere, Entropy, and Dissipative Structures

Harold Morowitz states the problem in the following way. Evolution implies a hierarchical trend towards increasingly complex living systems. The Second Law of Thermodynamics states that the universe, or each isolated section of it, tends towards maximum entropy. Statistical mechanics and kinetic theory tell us that maximum entropy implies maximum disorder in the framework of the constraints of the system. Hence when we think about evolution in this context (Boltzmann's H theorem), we think of evolution towards increasingly disordered states of the system.

This idea is strikingly at variance with our knowledge of biology. Clearly the trend of living organisms is towards the creation of order where previously there was disorder: it is the trend to organize and self-organize. Life seems to contradict the Second Law of Thermodynamics. The solution to this apparent contradiction between biological and physical theory, Morowitz states, lies in the realization that the Second Law of Thermodynamics applies to systems close to equilibrium, whereas the surface of the Earth, the matrix of biological evolution, belongs to a different class of physical systems. Systems in equilibrium must be either adiabatic (isolated) or isothermal. However the biosphere is quite another type of physical system, in contact with various sources and sinks, and with matter and energy flowing through it from the sources to the sinks.

Let us consider the following flow diagram, due to Morowitz:

$$\underset{\text{(sun)}}{\text{energy source}} \rightarrow \underset{\text{(biosphere)}}{\text{intermediate system}} \rightarrow \underset{\text{(outside universe)}}{\text{sinks}}$$

Let us now consider the system divided into two parts:

1. source (s) + sink (s)
2. intermediate system (int)

According to the Morowitz's approach:

$$dS_s + dS_{\text{int}} \geq 0 \tag{1}$$

where S_s is the entropy of source + sink and S_{int} is the entropy of the intermediate system. The flow of energy from the source to the sink will always involve an increase in entropy:

$$dS_s > 0 \tag{2}$$

whereas the only restriction placed by the Second Law of Thermodynamics on dS_{int} is that:

$$-dS_{\text{int}} \leq dS_s \tag{3}$$

so that the entropy of the intermediate system (in our case the biosphere) can decrease if there is an energy flow. A flow of energy provides the intermediate system (the Earth's surface) with quantities of energy for the creation of states far from equilibrium; that is, far from thermal death. The further the non equilibrium system is from equilibrium, the more ordered it is. The ordered state of a biological system would decay, if left to itself, towards the most disorderly state possible. This is why work must continuously be done to order the system. As we have seen, this requires a hot source and a cold sink, the sun and outer space.

The decrease in entropy (negentropy) in the biosphere depends on its capacity to capture energy from the sun and to retransmit it to space in the form of infrared radiation (positive entropy). If retransmission is prevented—in other words, if the planet were shrouded in an adiabatic membrane (greenhouse effect)—all living processes would cease very quickly and the system would decay towards the equilibrium state, that is, towards thermal death. A sink is just as necessary for life as a source.

Morowitz continues that all biological processes depend on the absorption of solar photons and the transfer of heat to the celestial sinks. The sun would not be a negentropy source if there were not a sink for the flow of thermal energy. The surface of the Earth is at a constant total energy, re-emitting as much energy as it absorbs. The subtle difference is that it is not energy per se that makes life continue but the flow of energy through the system. The global ecological system or biosphere can be defined as the part of the Earth's surface that is ordered by the flow of energy by means of the process of photosynthesis.

The physical chemistry mechanism was elegantly described by Nobel Prize winner *Albert Szent-Györgi* as the common knowledge that the ultimate source of all our energy and negative entropy is the sun. When a photon interacts with a particle of matter on our globe, it raises an electron or a pair of electrons to a higher energy level.

This excited state usually has a brief life and the electron falls back to its basic level in 10^{-7}–10^{-8} seconds, giving up its energy in one way or another. Life has learned to capture the electron in the excited state, to uncouple it from its partner and to let it decay to its fundamental level through the biological machinery, using the extra energy for vital processes.
All biological processes therefore take place because they are fueled by solar energy. Morowitz notes that it is this tension between photosynthetic construction and thermal degradation that sustains the global operation of the biosphere and the great ecological cycles.

Living systems therefore need a continuous flow of negative entropy from outside to maintain their structures and a sink for giving up an even greater amount of positive entropy. *Ilya Prigogine*, winner of the Nobel Prize for Chemistry, calls these non equilibrium structures in open systems *dissipative structures*. Systems far from equilibrium produce structures, provided they are maintained far from equilibrium by being open. The flow of energy causes changes in dissipative structures, which reorganize towards a higher level of complexity.

The biosphere is a special kind of system. It is a closed system that exchanges energy but practically no matter and is in contact with a permanent and practically infinite heat source (the sun) and with a cold sink (outer space), also permanent and practically infinite, to which it gives up its degraded heat. The biosphere is a steady state system because the source and sink are fixed and the flows from the source to the sink are constant in time so that the parameters of the system (temperature, pressure, and so forth) are practically independent of time. This makes life possible, and is the reason why large changes induced artificially by man—in periods that are brief on the scale of biological time—are so dangerous.

The difference between a system in equilibrium and one in a steady state is that the latter exchanges energy and/or matter with external sinks. The stationary state and non equilibrium states are not characterized by maximum entropy.

The steady state is one in which the flow of energy maintains the system as far as possible from equilibrium. The biosphere, a steady state system far from equilibrium, is a necessary rather than accidental state.

Now we can look at some of the relations connecting the origin of life, biological evolution, entropy, and the Earth.

(a) The entropy of the universe is increasing (Second Law of Thermodynamics), whereas the entropy of the Earth has decreased in the course of evolution by dispersing positive entropy into space.
(b) If we think of the evolution of a system in terms of statistical mechanics, we think of evolution towards more and more disordered states (Boltzmann's Theorem H) with high entropy values, whereas biological evolution proceeds towards more complex and ordered forms with low entropy values.
(c) A living system feeds on negentropy, directly or indirectly via photosynthesis.
(d) The thermodynamic equilibrium state (immobility, non differentiation, death) is

characterized by an entropy maximum whereas in the steady state (dynamicity, diversity, life) a flow of energy keeps the system as far as possible from equilibrium. The biosphere is a steady-state system.

(e) The origin of life is related to the metabolic capacity to extract negative entropy from the environment.

(f) The Earth lives because of negentropy, not DNA. The earth cannot reproduce itself and its life is associated with stochastic and irreversible processes occurring in the biosphere. The Earth "plays dice", because this is an intrinsic characteristic of biological evolution, the entropy function and the evolution of the energy-matter system.

Obviously, this game of dice obeys certain rules determined by the constraints of the planet and by its history. An event occurs in a stochastic manner because it is preceded by others. There are historical, genetic, and environmental constraints. Evolutionary events proceed in a manner that depends on time: they show a sense of 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.

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

The role of thermodynamics in scientific construction boils down to prescribing relations and identifying constraints; thermodynamics is the science of what is possible and is to physics as logic is to philosophy. Entropy is the enigma of thermodynamics because it has the intrinsic properties of time irreversibility, quality, and information that other thermodynamic functions lack. This is why entropy is a central concept in biology and ecology.

In his sixth memorandum to the *Naturforschende Gesellschaft* of Zurich, Clausius wrote: 'To express how much the molecules of a body are separate from each other, let us introduce a new quantity that we shall call the "disgregation" of the body.' Clausius included this quantity in the entropy function.

In 1859 Charles Darwin writes "The Origin of Species" in which a new evolutionary paradigm is presented; in the same years Clausius formulates the second law of thermodynamics. If Darwin tells us that evolution increases the organization of life, how can this match Clausius' theory which claims that it is the production of disorder that accompanies the increasing complexity of nature? This contradiction has been magnificently overcome by Ilya Prigogine, the first to observe that non equilibrium can be a source of order.

Irreversible processes may lead to a new type of dynamic state of matter called dissipative structure. These structures manifest a coherent, supermolecular character which leads to new, quite spectacular manifestations such as, for example, biochemical cycles involving oscillatory enzymes. How do such coherent structures appear as the result of reactive collisions? Can thermodynamics give us an answer?

The classical formulation due to Clausius refers to isolated systems exchanging neither energy nor matter with the outside world. The second law then merely ascertains the existence of a function, S, which increases monotonically until it is reached its maximum at the state of thermodynamics equilibrium:

$$\frac{dS}{dt} \geq 0 \tag{4}$$

Prigogine has extended this formulation to systems which exchange energy and matter with the outside world. He distinguishes in the entropy change dS two terms: the first, d_eS is the transfer of entropy across the boundaries of the system; the second, d_iS is the entropy produced within the system:

$$dS = d_iS + d_eS \tag{5}$$

The second law assumes that S production inside the system is positive (or zero). For isolated systems d_eS=0 so the previous equation leads back to the classical second law. For open systems we can imagine some evolutions that lead to steady-states where dS=0 with:

$$d_eS = -d_iS \tag{6}$$

When this condition is verified order can appear out of disorder. Self-organizing systems are able to adapt to the prevailing environment, and they react to changes in the environment with a thermodynamic response.

The simplest example of a self-organizing system is the Bénard instability. A thin layer of liquid is subjected to a difference in temperature between its lower surface, which is kept heated, and its upper surface, which is kept at room temperature. For a small temperature difference that is near equilibrium the heat is transferred only by conduction; that is, through collision between the molecules. Above a well-defined threshold of temperature difference, there appears in addition to be a transfer of heat by convection.

This means that the molecules then participate in collective motions that correspond to vortices dividing the layer of liquid into regular cells. If we further increase the difference of temperature, the motion becomes less regular. We have a transition to turbulence and spatio-temporal chaos.

Far from equilibrium, we witness the emergence of new states of matter with properties in sharp contrast with those of equilibrium states.

We can conclude, with Prigogine, that irreversibility plays a fundamental constructive role in nature. It is therefore necessary to display the roots of irreversibility in our basic description of nature.

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Biographical Sketches

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