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THERMODYNAMICS AND LIFE: AN EVOLUTIONARY POINT OF VIEW

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ABSTRACT
The complexity we observe in life forms, in their development and in biological evolution, is the result of the temporal and spatial constraints of a long evolutionary history made up of relations accumulating in time. This work assumes that space and time belong to different logical types: the first being reversible and conservative and the second irreversible and evolutionary. Time and space are reciprocally irreducible quantities. We refer to the thermodynamics of the Nobel laureate in Chemistry, Ilya Prigogine, to perform a new point of view of life, in terms of evolutionary thermodynamics.
Keywords: Dissipative Structures, Evolution, Information, life origins, Macrostates, Microstates,Tempos.

1 INTRODUCTION ON PRIGOGINE RESEARCH

The historical–scientific moment that we are living in seems to be searching for, once again, a definition for a concept that has had *complex* consequences. The concept we will be talking about in this work is that of *dissipative structures*, as its 'inventor', Ilya Prigogine, has named it. The magnitude of Prigogine theory can be understood only if time is considered in its closed relation with life and evolution [1–4].

The comprehension of irreversible phenomena has undergone a revolution, thanks to the study of dissipative structures, of those systems, that is, far from equilibrium and open to the exterior, in which fluctuations of energy can produce *order out of chaos*.

The last 60–70 years have seen a continuously increasing need for a non-linear science in order to explain many of the realities that surround us, most of all the characteristics inherent in living beings. The theory of irreversibility is presented not only as a link between the inanimate and living but also as a possible bridge between *two cultures* [4], scientific and humanistic.

Ilya Prigogine was one of the pioneers of the Complexity Theory. The introduction of the dissipative structure concept and his whole thermodynamic theory leaded to mistrust in the idea of a nature working in simple ways. It is the complexity of irreversible processes that allow the raising and the maintaining of life.

It is from the basic concept of non-equilibrium system, which seems to be the absence of physical order, and the II thermodynamics principle that a new kind of order arises: similar to the order of biological evolution.

The work of Prigogine underlines the 'new' role of time:

> Time is no more opposing man to nature but on the contrary marks his belonging to an inventive and creative universe.

2 DISSIPATIVE STRUCTURES

A dissipative system or structure is a thermodynamically open system operating far from thermodynamic equilibrium and that exchanges energy, matter and information with the environment that surrounds it. In virtue of the exchanges with the exterior, the system manages to organize itself within. That is, it is characterized by the spontaneous breaking of symmetry, both spatial and temporal,

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and by the formation of complex structures, sometimes chaotic, in which the interacting particles show long-range correlations and interactions.

The innovation introduced by the Belgian scientist was that a new kind of order can originate from a chaotic, homogeneous system. A revolutionary thought that gives chaos, up to that moment avoided as an argument not well defined scientifically, a new role: that of moulding, in time, an ordered reality.

Therefore, dissipative structures maintain their non-equilibrium thermodynamic state, thanks to a continuous dissipation of energy towards the exterior. The order produced by this dissipation generates new order and new organization (autocatalytic structures), but if the flow of energy is interrupted or diminished, the structure can collapse and may not return to its initial state (irreversibility).

The instability called 'Bénard's' can give an idea of how a stationary state leads to a phenomenon of spontaneous organization [4]. While Bénard's cells' instability has a simple mechanical origin and the behaviour of the flow is predictable in some of its aspects, this is not the case in chemical systems, such as in the Belousov–Zhabotinsky reaction [2], in which 'the fate of the fluctuation that disturb [them] depends on the detailed mechanism of the chemical reaction' [4]. Condition of being far from equilibrium is necessary, but not sufficient.

Biological cells, as complex systems, can be understood as dissipative structures, but with a higher complexity degree than simple reaction–diffusion systems. They are collective autocatalytic systems, which maintain themselves as entities capable of reproducing themselves and undertaking an evolution.

Human sphere, as the relation in the centre of which there is man, works as a dissipative system, capable of maintaining a state of non-equilibrium thermodynamics, at the cost of a continuous flow of energy that originates from food ingested and that must be continuously dissipated. The consumption of this energy maintains internal regulation of vital processes, which means individual state of order, and performs the entire human sphere organization (human tools, projects and activities).

3 TEMPOS

The concept of monodirectional time comes from the II thermodynamics principle and the consequent concept of entropy: every natural process in an isolated system is irreversible; so, *time* must be irreversible, in physics. Prigogine introduced the basis of a double view of time: linear for inanimate physics and complex, non-linear inside a living system. Anyway, in both these cases, time is always monodirectional.

A notable impulse to the theory of dissipative structures, demonstrating its relevance in practice as well, has been given by the discovery of the so-called oscillating reactions in chemistry and biochemistry. In particular, the new concept introduced by Prigogine helps us to understand many facts inherent in biology and, more specifically, living organisms as open thermodynamic systems.

3.1 A short history of time concepts

The history of the concept of 'time' is spread during centuries. The earliest recorded philosophy of time was expounded by Ptah-Hotep, who lived around 2350 BC (he was the Great Vizier of Faraon Djedkare Isesi). He wrote: 'Do not lessen the time of following desire, for the wasting of time is an abomination to the spirit' ([5]; the original Prisse Papyrus is shown at the Louvre, Paris). During centuries, the concept of time was used repeatedly by philosophers (cyclic time, linear time, unreal or internal time), but the physical concept of time was reinterpreted first by Newton. Aristotle already analyzed the *time problem* [6]: he noted that time was the measure of movement, in the prospective of *before* and *after*.

Aristotle failed to assign a system reference for the before and the after, other than human internal perception. This trouble was overcome when experimental evidence of unanimated irreversible processes was found.

Lucretius wrote that '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'.

> *Tempus item per se non est, sed rebus ab ipsis consequitur sensus, transactum quid sit in aevo, tumquae res instet, quid porro deinde sequantur* [7].

With almost all classical scientists after him, Newton believed time and space form a container for events, which is as real as the objects it contains.

> Absolute, true, and mathematical time, in and of itself and of its own nature, without reference to anything external, flows uniformly and by another name is called duration. Relative, apparent, and common time is any sensible and external measure (precise or imprecise) of duration by means of motion; such a measure – for example, an hour, a day, a month, a year – is commonly used instead of true time [8].

Newton introduced dynamics with all its consequences: the objective of classical physics was to describe everything in terms of immutable laws. Just linear laws and casual events: but universe is not so simple. Fortunately, there is irreversibility and non-linear events. Time concerning biological growth or societies evolution is not the same time describing motion of planets or of the ideal pendulum. Newtonian science has not the possibility to integrate this fundamental idea [9]. In dynamics, time is the measure of the mutation, not the direction this mutation follows.

Physical dynamics, concerning thermodynamics phenomena, from Newton to Einstein theories lays to the first principle of thermodynamics, but putting a reversible equivalence between causes and effects. The introduction of quantum mechanics equations in classical mechanics meant also the beginning of the use of an abstract language in dynamics, which makes the motion conception (and, hence, of the time) to arrive at its own truth. Infact, Hamiltonian equations (concerning the sum of kinetic and potential energies) are conservative and also reversible with respect to time, making their variables constant during the evolution in time, which they determine. In this kind of physical dynamics, all was assigned.

In the same historical moment of Quantomechanics introduction, Albert Einstein thought time as a physical spatiality: a consequence of the dynamical time concept. Also in General Relativity, the time (that is the space–time) is reversible.

The *time's arrow* concept was coined in 1927 by Eddington. From the 1928 book *The Nature of the Physical World* Eddington [10] states:

> Let us draw an arrow arbitrarily. If as we follow the arrow we find more and more of the random element in the state of the world, then the arrow is pointing towards the future; if the random element decreases the arrow points towards the past. That is the only distinction known to physics. This follows at once if our fundamental contention is admitted that the introduction of randomness is the only thing which cannot be undone. I shall use the phrase 'time's arrow' to express this one-way property of time which has no analogue in space.

Just few years before Eddington, Henry Bergson introduced its idea of time as consciousness states, having a vivacious debate with Einstein. Bergson thought that the time concretely lived is the real length to which the present psychic state maintains the process from which it comes, trough memory, but also constructs naturally something new. There is no continuity solution between consciousness states, but exists a continuous evolution, a lived moment that science cannot completely explain with stiff concepts. Similarly, for Leibniz and Kant, time was part of a mental measuring system (*time as a perception*). Hence, similarly to what Lucretius wrote, Bergson affirmed that 'if time were not an invention, it was nothing. Creativity is the prime mover of life and biological evolution' [11].

Mae-Wan Ho aptly described the relations between thermodynamics and Bergson:

> The second law of thermodynamics defines a time's arrow in evolution and in that sense, captures an aspect of experience which we know intuitively to be true. By contrast, the laws of microscopic physics are time reversible […].
>
> There is another sense in which time in physical laws does not match up to our experience. Newtonian time, and for that matter, relativistic time and tome in quantum theory, are all based on a homogeneous, linear progression – the time dimension is infinitely divisible, so that spatial reality may be chopped up into instantaneous slices of immobility, which are then strung together again with the 'time line'.
>
> Real processes, however, are not experienced as succession of instantaneous time slices like the successive frames of a moving picture. Nor can reality be consistently represented in this manner [12].

The existence of a *physical time* separated from a *philosophical time* is a problem studied by many philosophers, such as Heidegger, Bergson and Aristotle, as we have already explained. According to Prigogine, Heidegger found a very strong difference between future and past, underlining that it is not the time determining this difference, i.e. science cannot describe exactly Universe. Modern science developments demonstrate that time (that is its direction) is an essential element of the universe.

3.2 The Prigogine time paradox

The recognition that time is 'real' leads to what Prigogine calls the 'time paradox'. He asks how it is possible that the basic equations of classical and quantum mechanics are reversible with respect to time at the microscopic level, whereas at the macroscopic level the arrow of time plays a fundamental role? How can time emerge from non-time?

To solve this paradox, Prigogine [13] starts with Poincarѐ's theorem of 1889 introducing the distinction between integrable and not integrable systems. The latter lead to an alternative formulation of dynamics in probabilistic terms, both in classical and quantum physics. This description includes the breaking of time symmetry and incorporates the second law of thermodynamics.

Prigogine considers large Poincarѐ systems including multiple body systems involving collisions. He treats them in a way that implies the existence of chaos in the context of dynamic, always regarded as the stronghold of a deterministic description. Broken symmetry and irreversibility explode into dynamics. Prigogine writes of the inversion of the usual formulation of the time paradox. The usual attempt was to deduce the arrow of time from dynamics based on reversible time equations. He speaks of generalizing dynamics to include irreversibility. The divergences of Poincarѐ are eliminated by an appropriate time ordering of the dynamic states. In this way Prigogine introduces the concept of the natural time ordering of the dynamic states.

If we assume that time is real, it is necessary to move towards a new formulation of dynamics, including irreversibility. We call this attempt with the neologism of *ecodynamics* [1]. Constraints and time give rise to order out of chaos and the creation of *internal time* [13], expressed in terms of the relations between the various units which form the system. In a broader sense, internal time means information and creation of different forms.

Prigogine binds strongly the concept of time with that of entropy. In an open thermodynamic system, entropy can decrease if there is an energy flow. Note that the entropy variation of the whole system (the open subsystem plus its environment) can have only one sign, it can only increase (or remain fixed) in time. Its variation is monotone, and entropy cannot change sign with time.

The concept of entropy suddenly calls that of evolution (in ancient Greece: *Eντροπη′* meant *Evolution*). In modern physics, there is a more temporal and historical vision, nearer to humanistic sciences, which allows us to take in consideration casual events. Time is not even more just a human concept.

Prigogine actually introduced 'a formulation of theoretical methods in which time appears with its full meaning associated with irreversibility or even with "history", and not merely as a geometrical parameter associated with motion' [14].

In the Nobel lecture, he introduced three different time levels:

1. time associated to classic and quantistic dynamics
2. time associated to irreversibility through Lyapounov functions
3. time associated to the 'history' through fluctuation

Analogously, F. Braudel, the famous French historian, proposed the existence of three different 'histories' or time courses [15, 16]:

1. A story quite immobile, slow, relative to humans and their relations with the surrounding environment.
2. A second story, slowly beaten, social, concerning groups and individual.
3. Third, the 'traditional' history, not in the dimension of man as an individual, but as a flow of greater processes, on human relation on a major scale.

The analogy between this new physical time and the classical history concepts is evident. Far from equilibrium systems do not follow linear dynamics and can be described not by equilibrium logic, but through a narrative logic. The coherent activity of a dissipative structure is also a *history*, which has as a subject the emergence of global coherent logics integrating the small local histories. For these collective regimes of activity, Prigogine affirmed the need of three minimal elements: *irreversibility*, *probability* and *possibility* of the emergence of coherent novelties.

The concept of time concerns that of *correlation*. As pointed out by Prigogine, there is a natural time ordering of dynamical states: unstable atomic state first, followed by the emission of radiation. First we have binary correlations, then ternary correlations and, as time goes on, correlations including more and more particles.

Ecodynamics is the dynamics of the evolution of correlations. Transitions to higher correlations are 'future oriented' and transitions to lower correlations are 'past oriented'.

Natural evolution has to be regarded as a process characterized by a great increase in correlations, thus by increased negentropy [1], due to the fact that the biosphere is a 'closed' thermodynamic system exposed to a huge beneficial flux of energy from outside.

From the concept of correlation, it is shown that time appears to have a direction: the past lies behind, fixed and incommutable, while the future lies ahead and is not necessarily fixed. Yet the majority of the laws of physics do not provide this *arrow of time*. The exceptions include the second law of thermodynamics, which states that entropy must increase over time, in an isolated thermodynamics system, the cosmological arrow of time, which points away from the Big Bang, and the radiative arrow of time, caused by light only travelling forwards in time.

We can state that in every open system, far from the thermodynamics equilibrium, and with a discontinuity to the environment (to separate, to control, to maintain a gradient of some parameter, as a membrane, …), time and the negentropy flow allow macroscopic correlation to rise more and more.

4 INFORMATION, TIME AND EVOLUTION

Wicken [17] affirmed that 'thermodynamics is important because it contains information, entropy and evolution concepts'. Evolution and origin of life are not separate problems. According to Wicken, organisms are thermodynamic systems that maintain their non-equilibrium orders by degrading exogeneous free energy to entropy. For Prigogine, life is not sustained by atemporal determinate laws, but is immersed in the time flow. The limit of classical dynamics and even Einstein's theory of relativity lies in their attempt to exclude the dimension of time, placing their laws in the sphere of eternity. Time is an integral part of natural history and of the structure of matter. Thanks to these contributes, mainly by Prigogine, Tiezzi and Wicken, thermodynamics enter strongly in the science and research on life origin and evolution [1, 9, 16].

Thermodynamic links life with the surrounding inanimate nature, at least on an operational level. On an evolutionary level, thermodynamics contains also concepts of:

1. Variation
2. Constraints
3. Natural selection

These are all Darwinistic concepts. In Prigogine [16, 18], there is a likely explicit link with Darwinism:

4. The II thermodynamics principle leads to random directionality, which underlies variation in all its expression
5. Organizational typologies to achieve recourses are involved in Natural Selection
6. Thermodynamic regimes have a Bounded Stability, which creates limits to variations

Furthermore, Lotka and the 'energy flow ecologists' underlined with their work the natural selection principle and predicted evolutionary ways present in thermodynamics [19]. The evolutionary tendency towards complexity derives from the second law of thermodynamics and the set of physicochemical constraints provided by the biosphere [20]. Complexity generating processes provide the means by which thermodynamic information resulting from solar energy influxes can be dissipated.

As many authors have stated and as it descends from Prigogine theories, there exists a strong link between evolution and thermodynamics [21]. Wicken's research enhanced the relation of Prigogine theories with evolution and life.

Wicken persuasively argued that the second law is not just compatible with life but instrumental in its origins and evolution. He unveils the connections between autocatalysis – linked, self-perpetuating networks and thermodynamics, showing them to be woven from a single cloth, the same tapestry whose embroidery includes the origins of life, the reproduction and maintenance of species, the emergence of ecosystems and the evolution of life. Wicken defines life as 'informed autocatalytic organizations'. Hence, to better understand the linkage between Prigogine irreversible thermodynamic theory and self-organization, we refer to information theory. In the following paragraph, we emphasize Wicken's theory related to Prigogine far from equilibrium systems to build a bridge between origin of life, evolution, self-organization and information.

Introducing the Molecular Anamorphic Evolution Theory (namely, *anamorphosis*) [20–24], Wicken developed a parallel scheme that represents processes of increasing complexity and self-organization in terms of thermodynamic information. As he said: 'evolution is generally understood as the processes by which complex chemical and biological structures emerge with time from simpler structures. This integrative or 'anamorphic' tendency of matter to organize into structures of ever-increasing complexity is perhaps the most distinctive future of evolutionary process'. Considering life as 'informed autocatalytic organizations', he observed that the formation of living systems and their evolution are due to processes of energy and matter randomization, with 'randomization' meaning a random distribution, allocation or delivery of energy and matter inflows that allows complexity increase within a system.

We may apply this reasoning to the biosphere, which is a closed thermodynamic system: the continuous radiant energy inflow from an external source (the sun) demands an energy randomization, before part of the low-quality energy leaves the planet. Over millions of years, this has led to the emergence of new organized structures and to a higher diversification (life, evolution and biodiversity). The process by which complex chemical and biological structures emerge with time from simpler structures was named *Anamorphosis* by Wicken [25].

According to Wicken, the macroscopic thermodynamic information of a specific state can be written as follows:

$$I_{\mathrm{M}} = I_{\mathrm{w}} + I_{\mathrm{e}}, \tag{1}$$

where $I_{\mathrm{w}} = -k\ln w_{\mathrm{i}} = -S$ is the negentropic component of the chemical information and $I_{\mathrm{e}} = (E_{\mathrm{i}} - A)/T$ represents the energetic component. The latter relates to the entropy output from the system due to energy dissipation. In particular, I_{w} is given by:

$$I_{\mathrm{w}} = I_{\mathrm{th}} + I_{\mathrm{c}}, \tag{2}$$

where I_{th} is the thermal information and I_{c} is the configurational information. The former refers to the distribution of the state's thermal energy and the latter to the number of microstates in any possible configuration. In other words, these components are concerned with the reciprocal structuring and energetic relations among the elements in the macrostate (intra-molecules information) due to the increased differentiation of microstates and their inter-molecules information.

In particular, the thermal information I_{th} of a chemical system indicates its thermal energy non-randomness. In general, I_{th} increases with molecular size or with the number of small element involved in a macromolecule (meaning a reduction of distinct chemical entities) [20].

According to the principle of the second law of thermodynamics

$$\Delta I_{\mathrm{c}} + \Delta I_{\mathrm{th}} + \Delta I_{\mathrm{e}} < 0, \tag{3}$$

that is,

$$\Delta I_{\mathrm{th}} < -\Delta I_{\mathrm{e}} - \Delta I_{\mathrm{c}} \tag{4}$$

or

$$\Delta I_{\mathrm{th}} + \Delta I_{\mathrm{c}} < -\Delta I_{\mathrm{e}}. \tag{5}$$

This represents the thermodynamic limits to chemical information transfer between two different states. In terms of entropy, inequality (4) was presented by Harold Morowitz [26] through an energy flow diagram Source → System → Sink. The term ($\Delta I_{\mathrm{th}} + \Delta I_{\mathrm{c}}$) represents the information within the (intermediate) system and the term ($-\Delta I_{\mathrm{e}}$) corresponds to the disorder generated by the entropy dissipation to the external environment. According to Wicken's theory, a hypothetic formation of new chemical bonds and interactions corresponds to an energy randomization, which diminishes the number of chemical entities and increases their dimension. In this case, I_{th} increases ($\Delta I_{th} > 0$), while ΔI_e decreases, meaning that the energy inflow was used to increase complexity within the system and make order. For example, in an open thermodynamic system, a high-quality energy inflow will induce molecules to self-organize by increasing I_{th}, and I_e will decrease. To absolve the second principle, an energy randomization ($\Delta I_e < 0$) is required in order to make I_{th} increase. Due to inequality (4), the inverse is not possible.

This means that, due to the energy inflow, the small original molecules within the system achieve a more complex mutual arrangement, with new long-range interaction or with new bonds (i.e. giving rise to new and bigger molecules).

The increase of I_{th} and the consequent decrease of I_e are necessary but not sufficient conditions for anamorphosis. A reduction of I_c is possible when I_{th} increases: $-\Delta I_c$ represents a matter randomization [20], which is linked to variety and aperiodicity of elements (i.e. spatial and temporal configuration of basic small molecules). The matter randomization process is an energy dissipating process which decreases I_e by promoting two essential kinds of reactions for molecular evolution:

1. *Dispersive reactions* that form a lot of biomonomers and represent *divergent* phase of evolution
2. *Convergent*, *permutative reactions* that form new concatenation and interaction of molecules starting from the simpler pre-existing ones

In the case of inert substance, matter and energy randomization should bring a system to thermodynamic equilibrium, but the possibilities of interaction among similar and different molecules may drive a system towards a macrostate poorer in microstates [2]. This leads to the generation of complexity and organized systems.

As Wicken stated [20] (and as can be similarly deduced by Prigogine thermodynamics):

> sufficient conditions for the generation of aperiodic complexity are
>
> i. that one have a pool of monomers that can link in random fashion and
> ii. that there is an available kinetic mechanism for linkage
>
> Given these, matter randomization forces some degree of polymerization, the extent of which will depend on energetic and entropic considerations.

5 CONCLUSION

Complexity generating processes provide the ways by which thermodynamic information resulting from solar energy influxes can be dissipated. Natural selection converts the sequences of entropy generated in these processes into molecular information. The asymmetric tendency in evolution can be derived from the II thermodynamics principle that, given the particular set of physicochemical constraints under which it operates, leads naturally to progressively higher levels of complexity.

Finally, Wicken remarks on the meaning of ‘arrow of time’. The cosmological arrow generates randomness, whereas the evolutionary arrow generates complexity. A fully reductionist theory of evolution must demonstrate that the evolutionary arrow can be derived from the cosmological arrow. The formal connection is provided by information and non-linearity theory [20, 22]. The causal connection is provided by the natures of the randomizing reactions prescribed by the second law.

We can now emphasize the role of dissipative structure in nature:

> Our theory differs from other so-called thermodynamic theories in claiming that information takes precedence over energy when we consider the impact of the second law of thermodynamics on organisms. We can see this point when we consider the fact that it is the instructional information that determines the kinds of chemical reactions that will occur at a rate fast enough to maintain the steady state of an organism in a particular environment.
>
> In other words, instructional information is not only directly related to structural organization but also it determines how energy will flow through the organism [27].

Ecodynamics or ecological thermodynamics has to be based on a rigorous mathematical approach, but the equations have to be irreversible with respect to time, not based on a rigid intellectual framework but open enough to contain narrative elements.

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