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LA OPOSICIÓN ENTRE EL AUMENTO DE LA ENTROPÍA Y LA GENERACIÓN DE UNA COMPLEJIDAD CRECIENTE PUEDE ABORDARSE DESDE UNA PERSPECTIVA INFORMACIONAL

The opposition between entropy increases and the generation of increasing complexity can be approached from an informational perspective

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Abstract

This paper deals with the discussion between two points of view justified by thermodynamics, the tendency to increase entropy, given by the second law, and the tendency towards increases in complexity, given by the tentative fourth law. I argue these two perspectives can be reconciled from the perspective of information processing systems. I discuss how living systems counteract entropy through stored chemical free-energy, which is used for generating structural or informational constraints. Taking cellular and ecological systems as models of open far from equilibrium systems, the formulation of a tentative fourth law of thermodynamics is examined. The second and the tentative fourth laws of thermodynamics explain why the propensity to approach a state of equilibrium with respect to local restrictions promotes further impositions of structural constraints that enhances its distancing from equilibrium at a global scale.

In consequence, while a complete equilibration of the universe will never be attained, the trend towards increasing complexity expresses with growing intensity, hence, cosmic evolution and the evolution of life on earth can be understood as the outcome of two antagonistic and complementary tendencies, first, towards the dissipation of energy gradients, generating complex organizations, and second, to the degradation of these organizations when no energy flows are available. Therefore, information from the prospective of the processing systems decrease their uncertainty about their surroundings, enabling them, to select following functional criteria one among the immense accessible trajectories that, by canalizing energy flows maximizes its conversion into chemical energy that is invested in building and sustaining increasingly complex structures.

Keywords: Information, Structural constraints, Tentative fourth law, Complexity

Resumen

Este artículo aborda la discusión entre dos puntos de vista justificados por la termodinámica, la tendencia al aumento de la entropía, dada por la segunda ley, y la tendencia al aumento de la complejidad, dada por la tentativa cuarta ley. Argumento que estos dos puntos de vista pueden conciliarse desde la perspectiva de los sistemas de procesamiento de la información. Analizo cómo los sistemas vivos contrarrestan la entropía mediante la energía química libre almacenada, que se utiliza para generar restricciones estructurales o informativas. Tomando los sistemas celulares y ecológicos como modelos de sistemas abiertos alejados del equilibrio, se examina la formulación de una cuarta ley tentativa de la termodinámica. La segunda y la cuarta ley tentativa de la termodinámica explican por qué la propensión a acercarse a un estado de equilibrio con respecto a las restricciones locales promueve nuevas imposiciones de restricciones estructurales que potencian su alejamiento del equilibrio a escala global.

En consecuencia, si bien nunca se alcanzará un equilibrio completo del universo, la tendencia hacia una complejidad creciente se expresa con intensidad cada vez mayor, de ahí que la evolución cósmica y la evolución de la vida en la Tierra puedan entenderse como el resultado de dos tendencias antagónicas y complementarias, en primer lugar, hacia la disipación de gradientes de energía, generando organizaciones complejas, y en segundo lugar, hacia la degradación de estas organizaciones cuando no se dispone de flujos de energía. Por tanto, la información perspectiva de los sistemas procesadores de información disminuye su incertidumbre sobre el entorno, permitiéndoles, siguiendo criterios funcionales, seleccionar una entre las inmensas trayectorias accesibles que, canalizando los flujos energéticos maximice su conversión en energía química que se invierte en construir y sostener estructuras cada vez más complejas.

Palabras clave: Información, Restricciones estructurales, Cuarta ley tentativa, Complejidad

1. Introducción Energy and Epigenetic Landscapes

In biology, Waddington [i] showed that unstable high totipotent cells shift to more stable differentiated cells, as illustrated by the metaphor of epigenetic landscapes (EL). A passage from high potency unstable states to lower energy more stable states that according to Simondon1 [ii] requires a transducer, exemplified by continuous electric relay that operates as a modulable resistance between a potential energy and its concrete mode of actualization through time. The transducer, works as the mediator between the unstable high free-energy domain to the concrete realized entities with lower free-energy content. In this case the transducer would be the cell itself, undergoing differentiation that modulates the steepness of the EL and smooths the energy barriers that open the way down the canalized pathways. The discharge of energy from a field of potetialities is modulated all the way, till it reaches a metastable state, thus it is irreversible and so requires time. The potential is represented as the differences of height between the peak and any region located in a valley, though the dynamics of this irreversible process is modulated by the changing topography of the EL.

This a process that does not only runs downhill as energy gradients breakdown, reaching metastable states, but as more energy is captured by the transducers or processing information systems, it can also run uphill towards potentiation. In this processual viewpoint what matters is not only the definition of the states that are in fact attained, but mostly how they came to be, and the potential future that is enabled, because the process of energy transformation never ends. Time plays a decisive role since not all potential energy can be discharged and transformed into realized concrete forms at the same time. Information processing involves both a decrease of the potential as it crystalizes into concrete ordered forms (actualization), yet there are no stable organized structures, but dynamic transient organizations in permanent tension. Information processing like transduction is mediated by the very same entities that develop and evolve by means of establishing new types of interactions between their own disparate constitutive parts and between them and other entities undergoing similar processes of morphogenesis.

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[1] Transduction is Gilbert Simondon's key concept for understanding processes of differentiation and of individuation in several fields, including scientific disciplines, social and human sciences, technological devices, and artistic domains. Originating in the sciences and crucially developed in its philosophical implications by Simondon, transduction refers to a dynamic operation by which energy is actualised, moving from one state to the next, in a process that individuates new materialities.
Paulo de Assis (2018).

The topology of the surface of epigenetic and energy landscapes curves, creating folds that open up new paths. The existence of a real potential or virtual reality is fundamental since it provides the possibility of becoming, by shifting phases from one state to the next. "An organism is always more than its organized and fully differentiated reality. This excess signal a virtual reality that can be observed at the embryonic stage" (Beistegui 2012, 170) [iii].

All throughout the discussions that follow below, energy transformations are illustrated with the image of an energy landscape, a tridimensional model that associates possible states with their free-energy content (Figure 1). The higher the free-energy, the more numbered, short lived and unstable conformations exist for a given entity, conversely, the lower the free-energy, the more reduced the number of states that can be attained and the more stable they are. Thus, peaks in the landscape stand for high energy levels populated by a number of highly unstable states, and valleys stand for low energy levels populated by a reduced number of stable states. The landscape also helps to illustrate the energy barriers that have to be surmounted by a given structure in order to pass from one state to another. It is also postulated that there is a spontaneous tendency to pass from unstable to stable states, that is visualized as a transition from potency to act (realized in concrete metastable structures), that requires an increment of entropy by reduction of a free-energy gradient. Thence, entropy increases as free-energy landscape tends to flatten. Moreover, the free-energy landscape representation serves also to illustrate that if energy is available in the surroundings, detected and harvested, a multiplicity of many different systems acting simultaneously can catch it up, and the net accumulative effect will show up as new arising peaks.

2. INFORMATION IS THE MORPHOGENETIC PRINCIPLE OF NATURE

Organisms are thermodynamic systems best suited to model energy transformations. This proposal appears in several authors such as Prigogine and Stengers [iv], Brooks and Wiley [v], Swenson [vi], Chaisson [v] Schneider and Kay [viii], Schneider and Sagan [ix], among others. In these models, living systems are explained as integrated "totalities"[2], though structurally constrained and plastic enough to functionally couple with their environment in order to capture energy flows, for further conversion, storage and efficient use. Therefore, living systems can be explained by resorting to thermodynamic notions such as entropy, self-organization, density of energy flow and restrictions. However, in addition to thermodynamics, an integrated informational approach from the prospective of the living systems is needed. Information will be approached as that which drives the passage from potentiality to forms (actualized information) and the reverse from actualities to emerging new potencies that enable new more complex organizations.

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[2] "Kantian wholes" according to Kauffman.

These dynamics can be understood as being regulated by an informational transaction between opposite tendencies expressed in the second law (energy gradient equilibration and structural decay), and, the tentative fourth law of thermodynamics (emergence of more complex organizations that enable new possibilities). Clearly, I am not making a conventional use of the notion of information, in the sense of Shannon as a measure of ignorance or entropy by an external observer in order to specify one message among all the different probable messages that can be emitted by a given source. Instead, I stress the information gain that ensues when an agent is prompted to choose between at least two alternative responses [x], information that is used by the processing agent to detect accessible energy gradients.

Self-organization is the outcome of energy flows that are made accessible by information processing. Dissipative structure is a term defined by Prigogine and Stengers, in order to designate the organized patterns visualized in chemical reactions far from equilibrium. The study of chemical reactions like Belousov-Zhabotinski in which the concentration of the chemical involved were measured during a certain time, showed the existence of bifurcations in the trajectories at points of high instability. Self-organization requires an intense and permanent flow of energy and matter under conditions of openness and non-equilibrium, which spontaneously crystallizes into a specific structural arrangement. The emerging system adopts a structure that stabilizes between the thermal thresholds defined by the conditions to which the system is subjected. As energy flows intensify, systems move further away from equilibrium, reaching unstable critical points where one of at least two different accessible alternative conformations turns up. Unstable critical points lead to bifurcations that allow access to new contingent and unpredictable configurations. Energy flows enable self-organization, but do not specify the type of organization generated. The specific form that a system takes depends on the restrictions adopted in its strivings to maintain a local organization that is functional fit with the environment. Restrictions that are exerted upon the lower levels, make them more prone to harvest energy from accesible gradients.

To talk about energy gradients means that there is a free-energy budget difference between the states of high potential “source” and a low potential “sink”. Any living systems as it breaks down the chemical bonds of carbohydrates, glucogen and lipids (chemical stored energy), its internal entropy lowers because of the gain in realized structural organization by means of high chemical energy flow (metabolism). The supply of high potential energy that can be converted or stored into new structural arangements, is asured as long as energy gradients are accesed and captured. There is a choice at each unstable critical point that reduces the uncertainty that the living system faces, as it progresses toward more stable states of minimal entropy. At this bifurcation point, whenever any system chooses between two equally likely alternatives, the world gains a bit of structural information. In other words, information processing guides the choice of route from potential (unbound energy) to actual definite forms (stored energy). The permanent reorientation of energy flows involves a diversity of agents that interact in a specific environment, trying to define the structural adjustments and actions to be carried out.

In accord to the above guidelines, an integrated notion of information should address the intrinsic potentiality of nature, which would be to generate and propagate a maximum diversity of organized forms, by means of interactions that generate an increasingly dense network of systems that permanently enhance the potential (vitality) of nature. Actualized information refers to the organizations currently existing in the present, which at the same time constitutes a growing potential of what may be in the future. The imprints of the past are incorporated in existing structures (i.e. evolutionary ancestral body plan) that enable an unforeseen future. The future exists virtually as an immeasurable potential for a multitude of yet undefined events, whose actualization results from the informational transactions that are taking place at the present. In other words, the forms that are possible and accessible in the immediate future are being hatched through successive transactions and sustained feedbacks from the micro to the macro and vice versa, giving rise to a reality plenty of unanticipated situations.

Thus, informational processes meet conflict since entities, in greater or lesser degree of individuation, face the possibilities of being destroyed and absorbed by the lower levels of organizations, or the opposite, to get integrated into higher order wholes. Following Lupasco [xi], when a particular state is achieved or actualized, an opposite state is potentialized alternately and reciprocally, given that none reaches the total presence or absence. Thus, it is installed a tension between potencies that tend to be actualized, and actualized forms that tend to be potentiated.

Information processing must be understood as the modulating factor between these two opposing tendencies, an irreversible tendency towards thermal equilibrium or increasing entropy, manifested as flattening of energy gradients (thermal death), and a tendency towards increasing complexity, self-organization and higher distancing from thermal equilibrium. Information guides processes toward the production of a diversity of more or less stable individualized systems within every level of organization (actualization of a potential), but also enables new dynamics and interactions that lead to the emergence of more complex levels of organization (potentiation of actualities). In biology, we have that information processing is not limited to the production of individualized forms along ontogenies following the genetic instructions encoded in DNA, but, also to their integration at microbial, cellular, multicellular, organismic, communal and ecosystemic scales. In consequence, information expresses the transactions between these antagonistic drives, as it is processed by organized systems that permanently adjust and interact.

Therefore, evolutionary processes exhibit two seemingly opposite tendencies: 1) the emergence of more complex forms, and 2) the individuation, stabilization and eventual decay of these forms. Forms are individualized and integrated with each other by generating more complex organizations and as they stabilize and diversify. Accordingly, Darwinian evolution by natural selection favors individuals that interact in order generate new types of symbiotic associations, ontogenies and ways of coupling to the surrounding environment. Each emergency enables new types of interactions between previously individualized forms, expanding the world of what is possible and so giving rise in due time to new forms that become new niches for other possible living systems. These evolutionary logic shows the reciprocity of the part/whole relationship. Existing forms configure and modify the environment that made them possible through the very actions they implement, so that parts and wholes are intimately associated.

Parts incorporate information of the whole that contains them, while the whole is modified by the parts that make it up, thus, the whole contributes to its own transformation by constraining its constitutive components.

3. The Tension between spontaneous Self-organization and the Increase of Entropy.

Strictly speaking, the increase in entropy refers to the degradation of the available energy gradients that can be illustrated as a current of water flowing downstream along a path that bifurcates to attain more stable sates. However, this current can also flow up hill to reach higher potency that will be further actualized in a diversity of stable states. The way down to metastable states is accounted by the second law, while the way up to unstable states is accounted by the tentative fourth law [xii]. (Table 1)

From Boltzmann´s mechanical-statistical interpretation of the second law, entropy is the spontaneous tendency of organized systems to disintegrate into their components, increasing molecular disorder. But the important thing is to understand that any organization depends on the net energy flow-through. When systems are in conditions of openness and interaction with others, they can cling to accessible sources of energy, resulting in a growing organization, but when they approach to isolation and closure, the energy flow through decreases and systems equilibrate. Displacements toward the state of equilibrium take place with respect to the environment formed by the less complex entities that allowed its emergency, so that when the organization decays, its components breakdown and are absorbed by the lower levels, so that the state of maximum molecular disorder cannot be attained. The hypothetical thermal death of the universe is an extrapolation of thermal process occurring in condition of isolation and adiabatic closure.

Research on how to maximize energy that can be extracted from a combustion machine led to the formulation of the second law by Rudolf Clausius. Prior research by Sadí Carnot had established that for an ideal machine, isolated from heat fluxes and without friction, minimizing entropy dissipation would optimize the efficiency of energy conversion into mechanical work. A machine would have 100% efficiency only in the ideal case where it did not give up heat to the environment. Therefore, efficiency was defined as the proportion between the amount of net work performed over the heat transferred that depends on the thermal gradient in which it operates, i.e., for steam engines, maximum efficiencies are low (<< 40%) because heat waste is considerable.

The ideal thermal machine was thought of as a closed (adiabatic) mechanical system that imposes restrictions on gas expansion so that it is driven to push a non-friction plunger, operating on a thermal gradient, maintained by the chemical energy released in the combustion. Combustion releases the chemical energy stored in the carbon bonds characteristic of hydrocarbons, in a long biogeochemical process. This release requires atmospheric oxygen that was generated by water hydrolysis as a byproduct of photosynthetic activity carried out by bacteria for thousands of millions of years. Decontextualizing the steam machine of the geobiological history responsible for carbon fixation and the production of oxygen has made us to forget the importance of processes of chemical energy storage. The Industrial Revolution was made possible by the combustion machine, and it generated a strong dependence on non-renewable fossil fuels, the capture of which has served as an excuse for countless wars motivated by the desire to control energy sources. If we compete fiercely for increasingly scarce resources in a Darwinian way, fatalism associated with entropy (shortage of available energy) becomes evident and threatening.

But this hopelessness is relieved when we model systems that are far from equilibrium, where flows of matter and energy are so widely distributed that they are reinforced to generate “dissipative structures”, or stationary states that are located in compartments that temporally stabilized the organized structure. Out of the whole solar energy entering the system, a great part dissipates as heat into the environment, but a minimal part is used to maintain the organization of photosynthetic bacteria, making them more steadfast to capture the available energy with more efficiency and so on in a positive unharnessed autocatalytic process.

Processes of self-organization, to the extent that are positively reinforced, allow the growth and propagation of the organized systems, but they can also lead to an exhaustion of the primary chemical sources, and reach a point where the system breaks down. For this reason, energy gradients are consumed in building up structures that act as energy barriers that prevent the diffusion of catalysts and the depletion of primary resources. For example, catalytic cycles of self-reinforcing reactions, such as those devised by Manfred Eigen [xiii], and the self-catalytic ensembles postulated by Stuart Kauffman [xiv] to explain the origin of organic life, are helpful; but it is also essential to consider the formation of internal compartments, by means of membranes that prevent the diffusion of catalysts, needed for the efficient use of energy.

The idea that irreversible processes lead to entropy increases that tend to a thermal death, would not have prevailed if the study of energy transfers had been based on the study on energy flows through cells and ecosystems, instead of the combustion machines. Unfortunately, this research program was not interesting in the XIXth century, when the Industrial Revolution was on the fast track towards industrialization and the ensuing mechanization of productive processes. The inexorable thermal death predicted by the second law was questioned by James C. Maxwell, when he stated the following paradox. If a hypothetical being or "demon" located within a chamber at constant volume and pressure could gather information about the position and speed of individual molecules and, if it could use this information to control their passage between two compartments, it would achieve the separation of fast (hot) molecules from slow (cold) molecules into different compartments. The point to remark here is that for Maxwell, if informational restrictions are imposed upon the free diffusion of molecules, an orderly system is generated in apparent opposition to the stipulations of the second law. Briefly, the point to stress is that Maxwell anticipated a general scheme that connects information with constraint enforcement and the ensuing generation of order. The paradoxical point was that in conditions of adiabatic isolation and closure the energy invested in building up the restrictions would not be available.

Joseph Kestin [xv] formulated a unified principle of thermodynamics according to which, when the constraints that act upon an isolated system located some distance from equilibrium, are eliminated one by one, it reaches a single state of equilibrium that is independent of the order in which constraints are removed. For instance, in a process of diffusion of gases at constant volume, the average length of the paths that can be traveled by individual molecules as they approach equilibrium, decreases as the occupied places restricts their diffusion. Thus, as entropy increases, the tendency to expand and the propensity to change decreases. In the case of the container box of particles that move at random (modeled by Boltzmann as an equilibrium state of maximum entropy), the loss of usable energy is due to molecular diffusion in all possible directions.

Josiah Willard Gibbs (1870), following Kelvin, defined free-energy, or enthalpy, as a thermodynamic potential, that is, an extensive state function with energy units that measures the amount of usable energy to perform a work. The change in free-energy is defined as $\Delta F = \Delta E - T\Delta S$, a formula that divides the energy content of a system into two components: on the one hand, energy available to perform work (E), and on the other, entropy (S) or energy not available to perform work. Noteworthy, the contribution of the entropic term tends to zero as the absolute temperature decreases. The change in Gibbs free-energy provides useful information about the spontaneity of a chemical reaction, though it cannot be applied to individual molecules. However, biochemists have shown that within the cells, energy is stored in the chemical bonds of the organic molecules (sugars, carbohydrates, lipids, etc.). and the molecules of ATP (adenosine tri-phosphate) are known as the energy currency of the cells.

Erwin Schrödinger [xvi] investigated how organisms are not affected by the entropy that they must generate in order to live, a concern that led him to assert that to stay away from thermal equilibrium (to grow, to develop and to reproduce) they must capture negentropy (negative entropy), that is energy stored in the chemical bonds of organic matter. In fact, living beings are poised at a stationary state sustained by an intensive ongoing anabolic and catabolic processes. Organisms are thus, characterized as systems that do not equilibrate with their environment, since they are organized in such a way that they capture, transform, and use all available forms of energy to reach far from equilibrium states.

Furthermore, the study of cellular processes of storage and management of energy reserves, allowed Collin McClare [xvii] to distinguish between stored energy (high quality energy) and equilibrium energy (entropy)3 . The first is an energy stored chemically in cell compartments that is readily available to perform the work needed to remain in non-equilibrium distribution, for instance, in active molecules the states of higher energy in outer electronic orbits are more populated than those of lower energy. The second, thermal energy, mostly represented by molecular vibrations that equilibrate between 10^{-9} to 10^{-10} seconds, though usable "slowly" with moderate efficiency, it inevitably ends up being thermally equilibrated with the environment, and thus, achieves a temperature-dependent Boltzmann distribution. The concept of stored energy introduces a precision to the concept of free-energy, because it is defined with respect to a characteristic time interval, and so allows its applicability to individual molecules, cell compartments, cells and organisms, since every level in the organic hierarchy can be characterized by its own temporal scales.

According to McClare [xviii-xix] organisms are not thermal machines, but isothermal systems that depend on the flow of chemical energy that can be stored and used, when necessary, as macromolecules act as 100% efficient chemical machines. A cell is a highly heterogeneous organized system composed of micro space compartments in which, various processes in stationary states take place, at time scales ranging from 10^{-14} to 10^{-12} seconds, so rapidly and efficiently, that they do not have time to equilibrate. Thus, processes of energy release by rupture of chemical bonds are used to synthesize other biomolecules within the cell. Consequently, molecular machines, perform work (W) by direct transfer of energy stored within the same system and so promote the integration of processes at different time scales. The end result is cell efficiency in the use and storage

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[3] In other words, it is needed to investigate the flows and transformations of energy into organized systems such as living beings. For this reason, various authors have chosen to distinguish energy according to quality, using the notions of exergy and entropy. The first corresponds to high-quality energy that can be used by the system under certain conditions of the environment, and the second corresponds to low-quality energy, which cannot be used to perform work, and which is therefore dissipated to the outside. That is, poor quality energy dissipated by one system can be used and degraded further by another system until its ultimate dissipation in heat energy at equilibrium.. In this work I will prefer the term "stored energy", instead of "exergy" in order to avoid terminological confusions.

of energy, keeping compartments stationary and minimizing thermal dissipation. For example, photosynthesis results in amazingly fast and efficient energy transfers away from equilibrium: 1) Molecular resonance energies have been estimated at the order of 10^{-14} seconds in the first step of photosynthesis in the green photosynthetic bacterium named *Chlorobium tepidum*. 2) Separation of positive and negative charges in chlorophyll molecules at the reactive center formed by the Fenna-Mathews-Olson complex (FMO) [16] takes place in less than 10^{-13} sec. 3) The energy absorbed by hundreds of thousands of chlorophylls at the chlorosome is transferred, and part of it dissipates by generating vibrations of this protein, creating an energy landscape that funnels the absorption of excitations in the reactive center with almost 100% efficiency.

Consequently, Mae-Wan Ho [xx] highlights the two main conclusions that can be derived from the second law. 1) In thermal equilibrium, it is impossible to convert dissipated energy as random molecular motion into stored energy. 2) The energy stored in the molecular bonds is specifically released and becomes another so quickly that it does not have enough time to contribute to the dissipation of entropy.

This view implies that every organized system like a cell operates as an ecosystem, where the flow of energy transactions in the ideal case tends to reach states of minimal dissipation to the outside, as a result of the fact that compartments within the system efficiently take advantage of energy. The point to emphasize is that, in effect and because of the second law, spontaneous processes tend to degrade energy gradients, but given the systemic nature of the organization, unprofitable energy in one compartment is exploited by another component within the same system, therefore, external dissipation of entropy is minimal. In other words, the internal use of energy is maximized by catalyzing the system to greater degrees of structuring and organization.

On the other hand, the study of energy flows in ecosystems prompted Howard Odum [xxi] to show that each structure is characterized by being a specific way of storing and using energy[4]. Consequently, the value of stored energy in all the productions of nature and technology, can eventually be estimated in solar energy equivalents, or the amount of energy needed to produce a particular form, assuming that solar radiation was the only available source. Odum roughly estimated, in terms of solar radiant energy, the energy invested in the construction of each level of biological structuring, taking into account all the energy transformations that have supported the biosphere and have accumulated into organized structures for billions of years, including human technology in the past thousands of years. Solar energy that has entered the planet is very abundant, however, it has a very low quality or transformative power in the sense that most of it is lost as entropy. In this sense, the amount of stored energy (*emergy*) constitutes a factor that allows to rank

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[4] Odum coined the term "emergy" in order to refer to stored energy. Also, he used the term "exergy" to denote the energy that can be used by systems organized under certain environmental conditions. Both terms "emergy" and "exergy" refer to free-energy, the former places the accent in its storage and the latter in its usage.

the different forms of energy flowing through ecological systems. Let us remember that energy quality refers to its efficient use by a user in the economic system of living nature.

Odum [xxii-xxiii-xxiv] also argued that in ecosystems there is a process aimed at maximizing the energy incorporated in any given structure, which determines the transformations toward higher quality forms of energy and their storage in structures of increasing complexity. This principle of maximum empowerment stipulates that the systems that prevail are those that develop the most effective and beneficial work with incoming energy sources through a cooperative systemic organization.

According to Sven Erik Jørgensen [xxv], free-energy (*exergy*) is invested in work, keeping the system as far away as possible from thermodynamic equilibrium, so generating gradients. This proposal gave rise to the debate on whether a fourth law of thermodynamics should be formulated, since it was no longer just a question of recognizing that entropy increases, but that these increases take place at the fastest possible rate. In other words, systems tend to move far away from equilibrium as quickly as possible, resulting in highly ordered structures. According to Jørgensen and his group [xxvi-xxvii-xxviii], systems tend to use available free-energy (exergy) to stay away from equilibrium, and as more free-energy is available, they move even faster from equilibrium, resulting in the rise of new energy gradients. At unstable critical points, where there is more than one way accessible, the system chooses the one that allows the most efficiently work under existing conditions, thus taking the fastest path possible, leading to the generation of more complex structures. While the second law highlights the depletion of available energy, the fourth law allows to focus on the wealth generated as potential, represented in high quality stored energy that can be further invested in the generation of organized structure and biomass production. Consequently, the fourth law heralds the trend towards developing more complex networks wherever energy is used and reinvested in feedback cycles that stabilize restrictions and thus facilitate the uptake of more energy-matter.

This thesis conflicts with the more widespread interpretation of the second law of thermodynamics, which establishes an increase of entropy in the universe by dissipating energy as heat waste and brings with it the decay of organized systems approaching a state of equilibrium, in which all structures are degraded to be absorbed by the lower level of poor free-energy content. The difference is that, for Jørgensen, energy gradients degrade as quickly as possible, to be used and invested in the construction of highly organized systems that store free-energy. Colloquially, we would say that while the second law sees the glass of water half empty and gradually running out, the fourth sees it half full, and being rapidly refilled. Accordingly, the second law sees the systems in a phase of decay or gradual approximation to equilibrium as some forms are actualized, whereas the tentative fourth law sees them in their stage of accelerated growth and expansion.

The second law defines an arrow of time towards disorder because of the mechanical and random movements of the constituent particles of matter free of restrictions.

But we must never forget that particle dispersion conceived by Boltzmann is an idealized model formulated for expanding rarefied gases in conditions of closure, a situation that does not apply to real systems composed of interacting particles and submitted to flows of energy matter. In the absence of energy matter flows, the most likely configurations at the macroscopic level correspond to the homogeneous state of equilibrium with the environment, whereas in the presence of energy matter flows, the most likely configurations correspond to far from equilibrium heterogeneous organized forms.

The difference in behaviors between closed systems in near proximity to equilibrium and open systems that move away from it, is expressed in the formulation of the tentative fourth law of thermodynamics. Accordingly, entropy increases as the degradation of energy gradients proceeds, but given that this process takes place at the fastest possible rates, it leads to a maximization of stored energy and use efficiency, giving rise to a far from equilibrium organized states that are supported by their coupling to new energy sources. Consequently, the fourth law prescribes the generation of systems of growing complexity.

The tentative fourth law corresponds to the way energy transactions take place in ecological systems, considering that, 1) processes of energy storage support the generation of structures that reinforce energy uptake and efficiency of their use. 2) Living systems operate in conditions of openness to the surrounding environment, which allows for the permanent exchange and recycling of basic constituent materials. 3) Organized systems are stabilized by constraints imposed by negative feedback cycles from the environment to the system. 4) Cooperative work between the various constituent subsystems is essential to optimize the use of energy.

According to Crawford Holling [xxix], ecological processes do not follow a linear path of potential growth, but a four-stage cycle. 1) Exploration and exploitation of available resources by pioneer species. 2) Conservation and consolidation of species with greater structural complexity. 3) Relaxation and degradation of the organization by external and internal causes. 4) Reorganization of available resources and enhancement of a new cycle. The new cycles produce a total increase in biomass and structure in the ecosystem, generating a greater number of feedback loops and metabolic pathways, coupled altogether to provoke a decrease in entropy dissipation in relation to biomass. However, increasing the efficiency of energy transactions results in an increase in the amount of structural information, manifested in ever greater species and genetic diversity.

It goes without saying that in the advanced technological societies of the present, these principles are not fulfilled, since the prevailing global economic order does not favor a highly decentralized energy acquisition, cooperation, recycling of materials, or diversification of energy sources, let alone the maintenance of the ecological networks that have evolved over billions of years.

4. Information processing leads to the implementation of structural constraints

The Maximum Power Principle of Odum, finds a complementary version in the proposal of Rod Swenson [xxx-xxxi], who formulated the Principle of Maximum Production of Entropy, according to which systems take the path that maximizes the production of entropy, in the fastest way according to present restrictions. Consequently, the path that globally maximizes entropy by the dissipation of energy gradients, is the same one that minimizes its production locally by generating ordered structures or low entropy states.

In the case of a set of self-catalytic reactions, in which some molecules facilitate the formation of more complex ones, depending on an external supply of simpler molecules, reaction rates tend to increase exponentially until simple reactants are exhausted by dilution and diffusion in the environment, so that the attained organization can no longer propagate itself. But if two or more self-catalytic processes are coupled, there is a reciprocal constriction between them [xxxii-xxxiii], that would give rise to reaction cycles that stabilize and propagate, reinforcing itself in the form of Eigen´s hypercycles or just Kauffman´s catalytic self-organized networks. An emerging system can only gain some autonomy over the environment, if there is a supply of the simplest primary molecules provided by the environment, and retained in microcompartments that prevent their diffusion in order to facilitate the propagation of the organization of the entire self-catalytic set. Similar mechanisms have been described to explain the reproduction of viruses within cells [xxxix]. Likewise, organisms create an immediate environment or a niche, so that they can use the stored energy to thrive despite adverse and unexpected pressures from the external environment.

The words restriction and constraint have a negative connotation associated with impairment, absence, unfinished status, but, on the other hand, it can also be seen in its positive aspect as equivalent to the conditions under which order and organization is maintained. The synergistic coupling of two or more self-organizing catalytic processes, facilitates the establishment and stabilization of restrictions that keep systems away from the equilibrium condition, making it possible to propagate the organization. In other words, energy is invested in the construction of structural constraints which, in turn, make the work carried out by the release of energy more efficient. In this way, systems evolve toward maximum empowerment. For example, a combustion of a certain volume of fuel can occur under non-restrictive conditions, as in the case of a Molotov cocktail that causes an uncontrolled and destructive explosion, preventing its use, since it abruptly dissipates its chemical energy without being harnessed for usage (maximum dissipation of entropy to the environment). Otherwise, if the same amount of fuel were burnt in an idealized Carnot machine, under conditions of adiabatic isolation and frictionless isothermal expansion, it would result in a 100% efficient work transformation, without entropy dissipation, in a quasi-static process that would take an extremely long time, given by a sum of infinite reversible steps, to complete the expansion-contraction cycle.

Although highly efficient, this process is not useful either, because organized systems require rapid energy transformation for use as needed, in order to gain in autonomy. The optimization of the energy use by an organized system, takes place at a point in which the restrictive constraints create a suitable environment or ecological niche protected from external influences, so that the work output is used and invested to store energy and control its usage in order to feed continuous growth and development. Thence, energy is chemically stored for use in the generation of new restrictions that favor the maximization of its utilization in the execution of tasks and functions in the available niches that as they are created and occupied, open new possibilities for other systems, resulting in energy transformation cycles where entropy dissipated into the environment is minimized, tending at the limit to a value close to zero.

Local maximum reversible and efficient transfers of energy take place as energy is upgraded within the organized system with respect to the basal level of the environment. The idea of autonomous agents as self-referential isothermal engines that depend on chemical energy gradients has been discussed by Kauffman [xxxv], [xxxvi]. Organized systems evolve to the state in which they maximize their ability to execute useful work, but paradoxically, in order to achieve the state of maximum conversion of energy into usable work, systems must destroy the energy gradients at the fastest possible speed. Interestingly, restrictions prevent them from exhausting external energy sources, once they have become dependent on internally stored energy.

According to Ulanowizc [xxxvii] and Kauffman [xxxviii-xxxix], among others, there is a tendency of nature to generate systems of increasing complexity without therefore having to accept that the increase in complexity must necessarily proceed by a specific route with a predefined purpose in advance. The fourth law states that “the biosphere maximizes the average secular construction of the diversity of autonomous agents and the ways how these agents make a living and propagate further” [xl]. Therefore, processes go through the path that degrades gradients as quickly as possible, which is defined by a multitude of factors that converge in space-time. The spatiotemporal distribution of living agents and their structural properties mirrors the history of the interaction between living systems and the environment. But this history must be irreversible and non-ergodic because the space of possible accessible states growths much faster than the number of realized states. Thus, the probability of returning to a state previously realized in the past is for all practical purposes zero. For systems like living cells, organism and biospheres whose phase space grows extraordinarily faster than exponential, it cannot be stated beforehand which are the ones that are actually to be realized in the next evolutionary step. For this reason, Kauffman [xli] coined the term “adjacent possible”, which refers to the set of states that are accessible at defined given time. Accordingly, potential information refers to the set of all configurations that can be accessed in one evolutionary step at a given time and place, among all imaginable configurations.

When talking about the set of realized chemical entities in a delimited region of the universe, the adjacent possible is the set of new chemicals that can be produced in the next reaction step as a result of the interactions. New chemical entities which exhibit properties that did not exist previously, will come into being. Yet, information processing rules the choice among the options that are really possible and accessible. In other words, organized systems, in their interactions with the environment, evaluate physical disturbances as possible informational signals that guide the choice of appropriate options. In this way, every one of the increasingly complex and diverse forms that emerge face a greater number of possible alternatives, some of which will eventually be realized, further enhancing the dynamics of evolution. The point however is to understand that the space of available options (adjacent possible) increases at much faster rate than the space of realized configurations. Thus, the free-energy landscape will pull up towards higher energy states that have become the most likely to occur, instead of having to try at random, every single configuration one at a time. This problem motivates the formulation of an expanded notion of information processing [xlii], as the factor that guides the decisions of energy-consuming agents, and thus, redirects the flow of available energy by imposing restrictions on a diversity of systems chaotically distributed over an energy landscape that would otherwise tend to flatten.

Information processing should be understood as the controlled imposition of restrictions to ensure the maintenance and propagation of the organization. Ontogenetic development is driven by an intense flow of energy that takes place far from thermal equilibrium. Following Stanley Salthe [xliii-xliv], it is possible to distinguish three stages through which any developing system go: a) Juvenile stage (openness, free of restrictions), b) Mature stage (regulated and partially opened, restrictions play a positive role) and c) Senile stage (closure, restrictions play a negative role). These stages were inferred by estimating the density of energy flow per unit mass relative to time throughout development. In phase (a), at the initial youth stage, the system has not yet been defined as a new entity, resulting in a sharp increase in the net flow of energy per unit of mass through the system, so boosting an irreversible process of individuation. At this stage, growth is very rapid but it cannot continue indefinitely because it would deplete the available energy.

For this reason, the system adopts restrictions that characterize the stage (b) of maturity. This stage is characterized by a grow of internal organization, establishing a steady state with respect to the new incorporated restrictions, associated with a maximization and stabilization in the density of energy flow. In this way, the developing system is individualized and becomes autonomous, while being functionally adapted and specialized. The flexibility of the system allows to explore and use various energy gradients, while structural constraints play a positive role in enabling, directing and channeling a diversity of pathways that are available for energy use. In the terminal stage (c), the developing systems become rigid and hardly respond to external stimuli due to the decrease in energy flow density. So structural restrictions play a negative role and prevent the use of new energy gradients, causing the individual to lose autonomy and flexibility.

The traditional view of entropy as the antithesis of information has been questioned [xlv-xlvi- xlvii], gaining acceptance the contrary idea that as the first one increases, the second also grows, leading to an increase in structure, order and organization, moving further away from the fully randomized configuration, widening the gap between the possible and the actual. This phenomenon takes place precisely because restrictions channel the flow of usable energy and allow its storage by generating structures that go through the stages of growth, maturity, decay and disintegration. To increase entropy is to deplete the energy that sustains that order and therefore induces degradation. But as discussed above, before draining this power, systems generate internal compartments, and explore new available energy gradients that will allow them to growth and propagate their organization. If it is not possible to build up new energy gradients by storing energy, systems are maintained to the maximum degree of organization allowed by available energy flows. Yet, in case of complete depletion they are assimilated by the environment formed by the systems of lesser complexity that preceded them.

Moreover, according to Rod Swenson [xlviii], information and entropy go hand in hand, given that organizing processes increase the entropy of the universe in a much faster and more effective way. As organizational complexity increases, constraints move the systems away from equilibrium, causing the reverse tendency to achieving equilibrium more strongly. But as profitable sources of energy are destroyed, systems invest it in building structures that move the universe further away from equilibrium by means of the imposition of new restrictions. In this way, as ever more complex forms emerge, the opposite tendency to degrade them increases. The point is that living beings are endowed with an ability to detect energy gradients, that are to be converted into higher quality of stored energy, an activity that leads to the creation of new gradients.

The effort of science to develop technologies that diversify access to higher-quality energy sources to store and use it efficiently through more complex technological devices, is consistent with the way nature operates. What goes against nature is to believe that there is only one source of energy available, and that the dominant technology must manage its flow in a centralized way. It also goes against the way nature works to dissipate gradients from source to sink, without investing in the buildup of constraints that favor the maintenance and propagation of the organization. By contrast, the diversity of life forms is due to the diversity of energy gradients that can be used and dissipated in a wide variety of decentralized ways. Human beings are energy-degrading on an intensive scale, but problems arise when this energy sources are captured by few and released dropwise for use from a centralized source, and even worse, not constructively invested with high efficiency, minimizing external dissipation. Technological societies of the present have not yet incorporated the necessary restrictions for the use of the various energy sources between the different compartments or regions in which we are artificially divided according to political zones of influence.

Technological societies must be reorganized in the way cellular and ecological living systems operate. It is therefore urgent to overcome the dependence of fossil fuel, in order to give priority to the exploitation of a diversity of sources with greater efficiency in their storage and conversion. In addition, social modes of cooperation must be promoted, so that energy stored in the products of one sector are made available to another without the production of waste or non-recyclable materials. Energy, in the economy as in nature, must flow cyclically in its mature and stable phases, approaching zero dissipation, while the exponential growth phases must be based on the cooperative work of a huge number of microsystems that permanently harvest and store the energy that contribute to the empowerment of the whole ecosystem, so promoting the emergence of a more complex level of organization. Rapid growth stages due to the collective permanent harvesting, storage and usage of energy, must lead to lasting periods of stability and homeostasis.

5. LIFE IS A FLOW OF ENERGY CONTROLLED BY INFORMATION

Eric Chaisson [xlix] considered that Shannon-inspired measures on the content of information in bits were not interesting in addressing physical, biological and technological evolution. Instead, the focus should be placed on energy, understood as the source of the organization at different levels, as Lotka and Odum had initially pointed out [l-li] [lii-liii-liv]. Chaisson soon realized that although a star has a lot more energy, estimated in absolute values than a bacterium, the latter is more complex. Accordingly, he defined a Φ parameter, -total energy flow per unit of mass per unit of time-, which measures the free-energy used per second per unit of mass (ergs/sec/gm), i.e., the energy available to build structural and functional complexity. The Φ parameter does not measure total energy, but the density of its flow. His results show that the estimated Φ value for the sun (Φ = 2) has roughly two orders of magnitude less than a plant (Φ = 900). That is, although the sun uses energy based on nuclear fusion, it is surprisingly, a much less energy dense system and so less complex, compared to a plant that uses chemical and quantum processes in photosynthesis. That is, much more energy flows through the same mass per unit of time in a plant than through an equivalent mass of the sun.

Chaisson reported relative values dependent on system mass, composition and efficiency. He showed that nature is apparently governed by a principle of optimizing energy use. Consequently, evolution is governed by what he called the "principle of energy compression," according to which energy flows (harvested, stored, transformed, used, degraded) by complex adaptive systems form an emerging hierarchy of developmental systems, ranging from galaxies to human societies, including our technological systems. The complexity of an emerging system would be a function dependent on Φ, that in the case of the known universe describes an exponential growth curve from the inflationary expansion approximately 300,000 years after the big bang to the present, 14 billion years later.

Open systems, far from the thermodynamic equilibrium, capture and use energy, which they invest in the formation of restricted structures that channel and guide the flow of energy [lv- lvi]. In this sense, Φ is not only a measure of structural complexity, but also of system's adaptive responsiveness. The complexity of a structure can be estimated as a function of the energy density or the rate at which free-energy circulates per unit of mass. The constructive capacity of the system and its complexity is directly proportional to the density of the energy flow (erg/sec/gr) [lvii], which has increased throughout cosmic history at an exponential rate[5]. That is, information should be understood as the ability to channel energy by unit of mass and time, generating and maintaining structures necessary to ensure increases in complexity. As a result, the ability to process the information increases.

Every new level of organization that emerges accumulates and compresses the relevant information contained in less complex previous systems so that it can cope with more complex and demanding environments by executing more complex tasks and functions. Consequently, new systems contain the relevant information of precursors incorporated into their structure, so that as more complex levels emerge, new potential information can be actualized in future situations. In this sense, the total information of the universe grows with complexity, as well as the tendency of systems to stay as far away as possible from thermal equilibrium. The alleged opposition between constructive impulses to increasing complexity (growth of both potential and actualized information) and a degrading tendency towards absorption by the less complex systems (maximum entropy and absence of free-energy), reflects a profound characteristic of nature in which opposing forces or tendencies operate simultaneously across all levels of organization. The state of any given system is the result of the informational transactions made by the organizing systems in order to relieve this tension.

Therefore, the lower levels optimize the capture, storage and use within the restrictive conditions imposed on them by the emerging higher system. In other words, maximizing the power or work exercised by an organized system, is the outcome of a compromise between opposing tendencies to restore global equilibrium, moving as far away as possible from it at the local level. In the exploration of the space of possible configurations, a maximum action (energy use) that allows to orient all resources toward the search for the paths leading to the faster degradation of the energy gradients is observed. The information gathered by the organizing systems allows to detect the

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[5] The average density of estimated energy rates in [erg/s/g] and age in giga-years for human society (aged 0 giga-years old) has been estimated Φ = 500.000 [erg/s/g], in Φ = 40.000 for animals (aged 0.5 giga-years old), in Φ = 3,900 for plants (aged 3.0 giga-years old), Φ = 75 for the geosphere (aged 4 giga-years old), Φ = 2 for the sun (aged 5 giga-years old), and Φ = 0.5 for the milky way (aged 12 giga-years old).

energy gradients to be used, we are thus inevitable trapped in a non-tautological circular process, like a spiral that opens and widens, diversifies and reintegrates continuously in a wholly unpredictable manner.

The alleged opposition between entropic and organizing tendencies leads to an understanding of the hierarchical organization of nature through the magnifying glass of an ontology of processes, in which these tendencies act simultaneously, one described by the second law (decreasing available free-energy) and the other one by tentative fourth law (increasing access to free-energy) thus, generating complex forms. As explained, information regulates the restrictive settings that direct the flow of energy and guides the election at unstable points where trajectories bifurcate. Consequently, the energy flow available in the surroundings promotes the generation of more complex systems that are plastic enough to redirect and channel the flow of energy in various ways by imposing restrictions that increases the density of energy flow.

Therefore, natural selection has favored the autonomy of living beings or agents that collectively negotiate the effects of these opposing impulses, thus promoting morphogenetic processes as greater densification of the energy flow is achieved. Meanwhile the higher efficiency of the lower levels represented in the transformation of solar energy made by photosynthetic bacteria and its transformation by microbiome, is enhanced. Living systems do not evolve according to premises defined by initial conditions and an invariant law, on the contrary, they gain and create information, maximize their potential for action and modify themselves, so channeling processes oriented to the achievement of configurations that were not predetermined by the initial conditions.

Conclusions

The cosmological consequence of this approach would be the need to acknowledge the existence of two opposing and complementary tendencies in the universe: the first toward the generation of ordered forms of growing complexity (fourth law of thermodynamics) and the second toward increase of dynamic disorder (second law of thermodynamics).

As explained so far, life exists as a local organization maintained by a highly dense flow of energy, because the universe as a global system tends to move toward thermodynamic equilibrium and in doing so gets further away from it. In the same way, the universe also faces restrictions given by gravitational forces that condense matter in certain regions, preventing its homogeneous dispersion. Moreover, according to Lee Smolin, the appearance of black holes gives stability to the universes that contain them, making them more like living organizing structures than a dispersive Boltzmann gas. In this sense, the origin of life meant the emergence of more efficient routes for the capture, storage and use of energy gradients through the generation of highly organized structures.

Analyzes based on the second law are paradoxical, if one does not consider that life must ensure the maintenance and conservation of the dissipative pathways, developing innovative strategies for efficient capture and usage of energy gradients. This objective is achieved by minimizing the overall production of entropy through the reuse of energy by other agents that couple with each other, resulting in highly integrated symbiotic and ecological networks of interaction. Living systems are organized systems with structural and genetic memory, that facilitate the propagation of dissipative processes, thanks to the fact that energy, as it is consumed, is invested to boost growth, development and reproduction, while becoming available to potential predators. If we view the earth as an open thermodynamic system, terrestrial life manages to capture a small fraction of solar radiation, that is transformed into energy stored in chemical bonds. However, while solar energy is of very low quality and dissipates mostly in the environment, the stored chemical energy is of high quality, allowing a high efficiency in its use by intracellular enzymatic systems, promoting metabolism and self-organization, as explained by the tentative fourth law [lviii-lix-lx].

As I have shown, the tendency to form stationary states away from equilibrium does not lead to global equilibrium (thermal death), but rather to a departure from it. These complex dynamics underpins the ecological interpretation of the second law, which led to the formulation of the fourth law. Most of the scientific community consider the latter to be a specification of the second, and therefore it would not be necessary to formulate it. For my part, I argue that far from equilibrium open systems like living systems are more general, while near to equilibrium closed systems like thermal machines, are very specific and artificial cases. From an informational perspective that places creative evolution as a central aspect, the fourth law must be accepted, to the extent that it allows to imagine the universe as a process of emergency and permanent degradation, where information rules a dynamic opposition between tendencies toward increasing complexity and the opposite tendency to systems' degradation that are swallowed by the lower levels or organization.

In this perspective, the role of Darwinian natural selection would be no other than to preserve and favor systems sufficiently plastic to respond to the sudden changes in the environment, in other words, those that process information more efficiently. We must discuss what is meant when we say that a living system can incorporate information from the environment. This problem refers to the circularity and reciprocity of relations between organisms and the environment. While the latter imposes restrictions on the structure in growth and development, the living system does not suffer passively from this imposition, but according to its perceptual system (set of sensory structures that allow it to probe the environment according to certain thresholds of sensitivity) and organizational structure (internal processing modules, connected to motor effector structures) defines the type of structural adjustment or modification to be adopted, as well as the action to be implemented.

A structure has incorporated information from the environment when in its adjusting gains stability, becoming more constrained in that environment. Structural accommodations are constraints that lower the entropy of macromolecular component subsystems; however, these lower-levels of organization (genetic and molecular) do not determine the phenotypic structural states, but rather make them possible. Information has an intrinsic value to the extent that it helps the organizing system to detect energy gradients that can be used. The idea of information as formulated by Shannon has been reduced to set of binary elections made by observers located at the higher level, in order to reduce the uncertainty about the lower levels, without any consideration for its meaning and value. The idea of information processing must include the using system and so, it is best understood as the contingencies faced by any living systems that strive to buffering the tension between lower and higher levels of organization by choosing the corresponding structural adjustments and the actions to be executed in order to efficiently capture and employ energy.

Living systems select few among the many possibilities given by the lower complex levels and the rife alternatives offered by the surrounding environment. There is a tendency of nature to generate systems of increasing complexity without therefore having to accept that this increase should proceed through a specific route with a predefined purpose. On the contrary, I argue for the existence of multiple ways to increase complexity, but the definition of which are the ones that take place, is due to a multitude of factors that contingently converge in a specific space-time situation. The metaphor of informed choice made by the organized system, is used to explain the transit from the immense potential options and those that in fact take place.

This choice is a preference made by living systems, rather than a random elimination of other alternatives. Information as a generative process of increasingly complex and diverse forms, faces a greater number of possible choices at each step, some of which are eventually accomplished, further enhancing the evolutionary dynamics of the universe. As I have claimed, information guides the decisions faced by the agents in order to direct the flow of available energy, feeding a potential as restrictions are imposed on systems composed of subsystems that would otherwise tend to be evenly distributed. The choice in question is the result of information transactions that actualize potencies, while potentiating actualities, thus triggering a process of antagonist and complementary tendencies: 1) towards increasing complexity, and 2) to the degradation and subsumption by lowers level of organization. Information is the transactional buffering that regulates this tension by the action of organized living systems.

To end up there is not a single overarching arrow of time, but a multiplicity of processes going on at different places in the universe, while some of them might have attained levels of organized complexity unthinkable for us, others might be just emerging and beginning to expand, and surely many are decaying and breaking apart and being swallowed by black holes.

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Table 1. The table shows the contrasting characteristic between the second law of thermodynamics and the tentative fourth law as discussed in the text.

Appendices

Table 1. The table shows the contrasting characteristic between the second law of thermodynamics and the tentative fourth law as discussed in the text.

Second Law	Fourth Law
Entropy (low quality energy)	Free-energy, high quality energy
Carnot, Clausius, Boltzmann	Odum, Jorgensen, Kauffman
Modeled studying efficiency of thermic machines	Modeled studying ecosystems and cell energy transactions
Degradation of energy gradients, decreasing potency	Rise in complexity, increasing potency, creation of new energy gradients
Closure and isolation, low energy flow	Openness and interaction, high energy flow
Local Equilibrium	Global Distancing from Equilibrium
Structural decay and absorption by lower levels	Structure buildup and emergence of higher levels of organization
Arrow of time => thermal death	Arrow of time => increasing organization

Figure 1

A two-dimensional profile of energy gradients is depicted. in which the "Y" axis stands for free-energy content and, "X" axis for time. Figure (a) represents the passage from potency to its actualization as a stable state by a single discharge of energy contained in the input. Figure (b) shows how the previous process can be more complex as more energy is incorporated all along and so new intermediary states are passed through. Figure (c) shows a case in which a low free-energy state can be potentiated by incoming energy that pushes the attainment of stable high energy states.