

# Thermodynamic Formulation of Living Systems and Their Evolution

Luis Felipe del Castillo, Paula Vera-Cruz

*Departamento de Polímeros, Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, Mexico, Mexico*

*E-mail: [lfelipe@servidor.unam.mx](mailto:lfelipe@servidor.unam.mx)*

*Received January 20, 2011; revised March 7, 2011; accepted April 2, 2011*

## Abstract

The purpose of this review article is to present some of the recent contributions that show the use of thermodynamics to describe biological systems and their evolution, illustrating the agreement that this theory presents with the field of evolution. Organic systems are described as thermodynamic systems where entropy is produced by the irreversible processes, considering as an established fact that this entropy is eliminated through their frontiers to preserve life. The necessary and sufficient conditions to describe the evolution of life in the negentropy principle are established. Underlining the fact that the necessary condition requires formulation, which is founded on the principle of minimum entropy production for open systems operating near or far from equilibrium, other formulations are mentioned, particularly the information theory, the energy intensiveness hypothesis and the theory of open systems far from equilibrium. Finally suggesting the possibility of considering the lineal formulation as a viable alternative; that is, given the internal constrictions under which a biological system operates, it is possible that the validity of its application is broader than it has been suggested.

**Keywords:** Entropy, Life, Evolution, Dissipative Structures, Negentropy Principle

## 1. Introduction

The application of thermodynamics [1] to biological systems and their evolution has offered important contributions [2] by describing the characteristics of animal evolution [3]. The basic aspect underlined is that the laws of thermodynamics can predict the feasibility of the processes and the relation between the variables [4].

Schrödinger established the first contributions to the field in 1944 [5], offering some ideas about the concept of negentropy or negative entropy to describe the common fact that physiological processes gradually generate an increase of the internal “order” in living organisms. In the sense that the action of living matter opposes the degradation of the organic constituents by effect of the irreversibilities [6,7].

Currently, the concept of order in relation to negentropy is ignored since a quantitative correlation has not been found. Alternatively, in biology the equivalence has been proposed with the concept of “organization” (regarding structure), originated in information theory as a more appropriate way to quantify the degree of structur-

ing (or contained information) of an organic system, as proposed by Brillouin in 1951 [8,9].

Schrödinger also applied the concept of negentropy to describe the evolution of species, which has received much attention [10]. Another related development can be attributed to Prigogine in 1946 [11], who applied the theory of linear non-equilibrium thermodynamics to describe the phenomenon of adaptation of species. He considered the organism as an open system in stationary state [7], which evolves in the direction that entropy production decreases, and reaches a minimum when the adaptation to the environment has concluded. With these first attempts, the phenomenon of adaptation was expressed in a thermodynamic language, involving both chance and necessity [12], thus being characterized as a teleonomic [13] phenomenon.

The present work describes the basic facts originated by the irreversibility in biological systems, and the relevant advances in animal evolution in terms of structure growth [14] and the introduction of stationary conditions (maturation process) [15]. Particularly, these two aspects are formulated in the negentropy principle, which estab-

lishes the necessary and sufficient conditions for the survival of a species when the environment has suffered a radical change that endangers its existence. The sufficient condition is negentropic growth and the necessary condition observes that the adaptation process (maturity) is the search and achievement of the stationary state in the habitat surrounding a species.

Afterward, the contributions to formulate the necessary condition for survival are discussed [11]. Particularly, the information theory, the energy intensiveness hypothesis, and the theory of self-organization of dissipative structures far from equilibrium.

## 2. Nature of Living Matter as a Thermodynamic System

Important efforts have been made to describe biological systems from the point of view of macroscopic sciences, particularly thermodynamics and statistical physics [16,17].

Biological systems are organized internally by constrictions. These are internal walls (membranes, epithelia, endothelia, interfaces, etc) and their role is to maintain separated two localities, each of them in equilibrium and specified by different local values of the thermodynamic variables; particularly, temperature, pressure or electrochemical potentials. Generalized flows occur through these constrictions, such as transport of mass, charge, calorific energy and momentum [18]. Since the constrictions hold the pressure differences, these flows occur under conditions of mechanical equilibrium, which is manifested by the absence of accelerations in them [19].

The present description considers the flows and forces at the local level, such as two entities on both sides of a cellular membrane (see **Table 1**). This description is known as mesoscopic (at the micron scale) and is governed by the paradigm of mesoscopic systems, characterized by the presence of fluctuations formally described by the theory of Brownian motion in systems under electromechanical equilibrium [20].

Assuming that equilibrium thermodynamics conditions prevail around the constrictions, such as cellular

**Table 1. Physiological processes are specified as flows produced by forces.**

Generalized Flows ( $J_j$ )	Forces ( $X_j$ )
Diffusive passive	$\Delta\mu = \mu_1 - \mu_2$
Diffusive active	Coupling forces
Volumetric movement of fluids	$\Delta P = P_1 - P_2$
Ion transport	$\Delta\varphi = \varphi_1 - \varphi_2$
Advance of chemical reaction	Chemical affinity

membranes, then the principle of regression of fluctuations is valid and the system is stable and behaves according to the Le Chatelier-Braun principle [21].

Equilibrium thermodynamics prescribes the law of entropy growth when generalized flows [22] occur through a membrane from locality 1 to locality 2.

$$d\bar{S} = d\bar{S}_1 + d\bar{S}_2 \geq 0 \quad (1)$$

The differential expression for specific entropy is given by:

$$d\bar{S}_1 = \frac{1}{T} du + \frac{P}{T} dv - \sum_{j=1}^c \frac{\mu^j}{T} dn^j \quad (2)$$

In (2)  $u$ ,  $v$  and  $n^j$  are the internal energy, volume and number of particles per unit of mass, respectively, associated to a locality with  $c$  different species. Considering the presence of two localities separated by a membrane, the change of total specific entropy is given by the following equation:

$$d\bar{S} = \left( \frac{1}{T_1} - \frac{1}{T_2} \right) du_1 + \left( \frac{P_1}{T_1} - \frac{P_2}{T_2} \right) dv_1 - \sum_{j=1}^c \left( \frac{\mu_1^j}{T_1} - \frac{\mu_2^j}{T_2} \right) dn_1^j \quad (3)$$

where the laws of conservation of energy, conservation of volume and conservation of mass have been applied.

$$du = du_1 + du_2 = 0 \quad (4)$$

$$dv = dv_1 + dv_2 = 0 \quad (5)$$

$$dn = dn_1 + dn_2 = 0 \quad (6)$$

Equalities (4-6) indicate that the system is operating under conditions of isolation ( $\Delta U = 0$ , where  $U$  is the total internal energy).

According to classical thermodynamics, the contribution to the variation of entropy of each of the terms in (3) must be positive, as indicated by the Second Law of Thermodynamics.

$$d\bar{S}_1 = \left( \frac{1}{T_1} - \frac{1}{T_2} \right) du_1 > 0 \quad (7)$$

$$d\bar{S}_1 = \left( \frac{P_1}{T_1} - \frac{P_2}{T_2} \right) dv_1 > 0 \quad (8)$$

$$d\bar{S}_1 = \sum_{j=1}^c \left( \frac{\mu_1^j}{T_1} - \frac{\mu_2^j}{T_2} \right) dn_1^j > 0 \quad (9)$$

The validity of conditions (7-9) requires no additional or external actions influencing the flows or forces described. Therefore, the effects expressed in these equations are considered independent (system regarded as isolated).

In **Table 1**, the generalized flows and the thermodynamic forces are given explicitly.

It is important to point out that the present thermodynamic description is valid at the cellular [23] or mesoscopic [24,25] level, as well as at the macroscopic level. **Figure 1** shows the differences in scale of both levels in a biological system. The cellular or mesoscopic level represents the locality; this is where the life support processes occur, such as osmosis [26], blood oxygenation, cellular nutrition, ATP production, and gas exchange in the lung alveoli. The scale of the macroscopic level is where the geometric properties of size and shape are located, particularly the frontier or surface surrounding the volume of the body system.

## 2.1. Definition of Negentropy

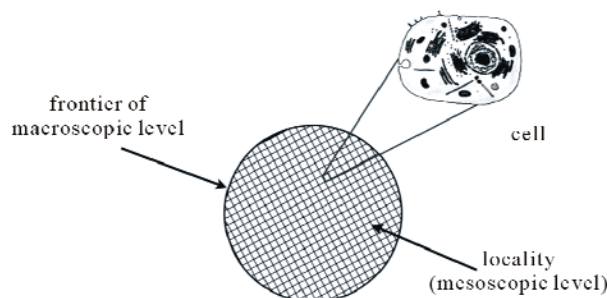
One characteristic of biological systems is the restitution of the initial-operation state after completing a flow process. This is represented in a state diagram as  $\oint d\bar{S} = 0$ , indicating that the value of entropy of each locality is that of the initial-operation state. To specify, we could say that the system operates in two stages: in the first from the initial point ( $i$ ) to the final point ( $f$ ) the entropy of the system increases (see **Figure 2**), its production is attributed to the dissipated heat in (7), the work done in (8) and the electrochemical balance in (9).

Entropy production in the internal processes (physiological) related to the equations stated above is originated by the presence of flows, which occur spontaneously [27]. The heat flow occurs from higher to lower temperature, the work is done by the localities of higher pressure toward the localities of lower pressure, and the flows of charge and mass occur in the direction that electrochemical potential decreases.

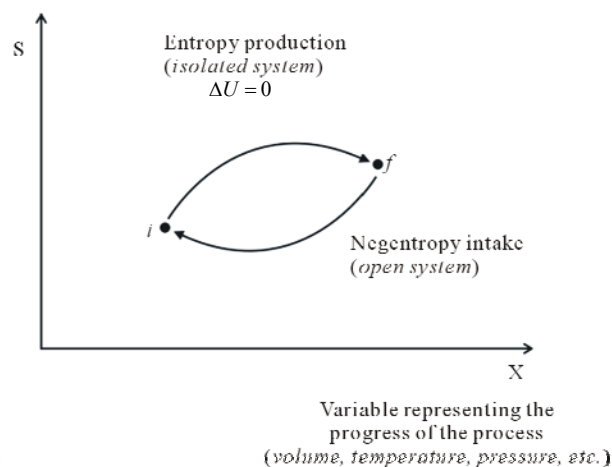
Since the system is isolated, the surroundings do not contribute to the increase in entropy; then the entropy growth both inside the system and on the surroundings is positive [28]. Consequently, for the first stage the following expression is valid:

$$\Delta S > 0 \quad (10)$$

In the second stage, from point ( $f$ ) to point ( $i$ ), this entropy increase is compensated by either doing work or taking energy from the surroundings. Under these conditions, the operation is that of an open system. In other words, in the second stage the system is not isolated, as it was considered in the first stage, but rather it is in contact with the surroundings and introduces work and energy from a source in thermodynamic contact. Considering both the system and its surroundings, for the restitution of the initial-operation state the following expression must be satisfied:



**Figure 1.** Biological system at the macroscopic level composed of organizations of cells in the mesoscopic level. The frontier separating the external and internal environments is shown.



**Figure 2.** Operation cycle of a physiological process. The diagram shows the total entropy of a system versus the progress of an independent variable. The process starts at point ( $i$ ) of the diagram (initial-operation state) and ends at point ( $f$ ), in this first stage it operates as an isolated system. In the second stage, from ( $f$ ) to ( $i$ ), it operates as open.

$$\Delta U = T\Delta S + W = 0 \quad (11)$$

Then,

$$\Delta S = -\frac{W}{T} \quad (12)$$

Establishing that work is being done on the system,  $W > 0$ , and therefore in the second stage:

$$\Delta S < 0 \quad (13)$$

Entropy decreases and cancels the increase of the first stage, as shown in **Figure 2**, which illustrates that the entropy of the system has not changed after the cycle.

The change in entropy produced in the second stage is defined as negentropy ( $H$ ).

$$H \equiv -\Delta S = \frac{W}{T} \quad (14)$$

Then, it is said that there has been an intake of negen-

ropy to the system [29].

On the other hand, a structure growth could have occurred in the system, which can also be described by (10) and (14) establishing two stages, as mentioned above. Then, the first stage features the transformation of food proteins and the ligands produced in the cell, where entropy increases. In the second stage, the structuring of the produced components involves work ( $W$ ). Therefore, there are two types of negentropy intake: one occurs in the common physiological processes ( $H_1$ ) in the irreversible flows, and the other in structure growth ( $H_2$ ). Thus, the total negentropy intake will be:

$$H = H_1 + H_2 \tag{15}$$

### 2.2. Dissipative Structures

From the macroscopic point of view, the biological system behaves essentially as a dissipative structure, but the heterogeneity of its internal structure differentiates it from the physicochemical systems capable of becoming dissipative structures. For example, a metallic rod connected to two electric poles, kept under isothermal conditions, dissipates to the surroundings an amount of energy defined by the product of the voltage applied and the intensity of the electrical current. At this level, the internal structure of the metal has a microscopic arrangement at angstrom-level, much smaller than the scale of the mesoscopic structure. Another characteristic that separates the dissipative structures of the biological systems from those of the physicochemical systems [30] is the ability to grow with time and reproduce itself without losing this characteristic. For example, the dissipative structures of Marangoni and Bénard [31,32] operate without these attributes. However, the biological dissipative structures [33] can be described by physicochemical methods, as discussed below.

The cellular formulation for entropy production at the local level is established according to a balance equation:

$$\rho \frac{d\bar{S}}{dt} = \sigma_s - \nabla \cdot \mathbf{J}_s \tag{16}$$

Equation (16) establishes that the gain or loss of entropy per unit volume is equal to the entropy produced minus the net entropy flow through the surfaces of the localities. Here,  $\sigma_s = \sum_j J_j \times X_j$  is the entropy production given by the sum of the tensor products of flows ( $J_j$ ) and forces ( $X_j$ ) present in the localities. The second term of (16) is the divergence of the flow of entropy that corresponds to its net flow through the cellular surface.

Alternatively, considering the macroscopic formulation of the biological system at the global level, by integration of (16) we find the following expression for the

production and flow of entropy:

$$\frac{dS_T}{dt} = \frac{d^i S}{dt} + \frac{d^e S}{dt} \tag{17}$$

where,

$$\frac{dS_T}{dt} = \frac{d}{dt} \int_V \rho \bar{S} dv \tag{18}$$

In (18)  $V$  is the volume of the biological system.

$$\frac{d^e S}{dt} = -\oint_{\Sigma} \mathbf{J}_s \cdot \mathbf{e} d\Sigma \tag{19}$$

where  $\mathbf{e}$  is a unit vector pointing in the direction of the normal of every point of the frontier, indicated by the surface  $\Sigma$ .

$$\frac{d^i S}{dt} = \int_V \sigma_s dv \tag{20}$$

Considering entropy production for a biological dissipative structure in the global formulation, from **Table 2** we have that:

$$\frac{d^i S}{dt} \leq -\frac{d^e S}{dt} \tag{21}$$

Equation (21) is the mathematical expression of the negentropy principle in the ontogenic scale of a prototype. It indicates the requirement for negentropic growth: that the entropy produced in the system by the internal

**Table 2. Some cases where Equations 17-20 are applied according to the type of system considered.**

Type of system	Conditions	Relations of $\bar{S}$ (cellular formulation)	Relations of entropy $S$ (global formulation)
Thermodynamic system	Isolated (strict validity of the second law of thermodynamics)	$\nabla \cdot \mathbf{J}_s = 0$ $\rho \frac{d\bar{S}}{dt} = \sigma_s \geq 0$ $\sigma_s = 0$ reversible process	$\frac{d^e S}{dt} = 0$ $\frac{dS_T}{dt} = \frac{d^i S}{dt} \geq 0$
Physicochemical dissipative structure	Open system with elimination of produced entropy	$\rho \frac{d\bar{S}}{dt} = 0$ $\sigma_s = \nabla \cdot \mathbf{J}_s \geq 0$ $\sigma_s = 0$ reversible process	$\frac{d^i S}{dt} = \frac{d^e S}{dt}$
Biological dissipative structure	Open system with elimination of entropy and structure growth	$\rho \frac{d\bar{S}}{dt} \leq 0$ $\sigma_s \leq \nabla \cdot \mathbf{J}_s$	$\frac{d^i S}{dt} \leq -\frac{d^e S}{dt}$

processes and that generated by the growth of the prototype are eliminated through the frontiers [34]. The need to eliminate the entropy produced in the internal environment of biological systems denotes a principle of survival.

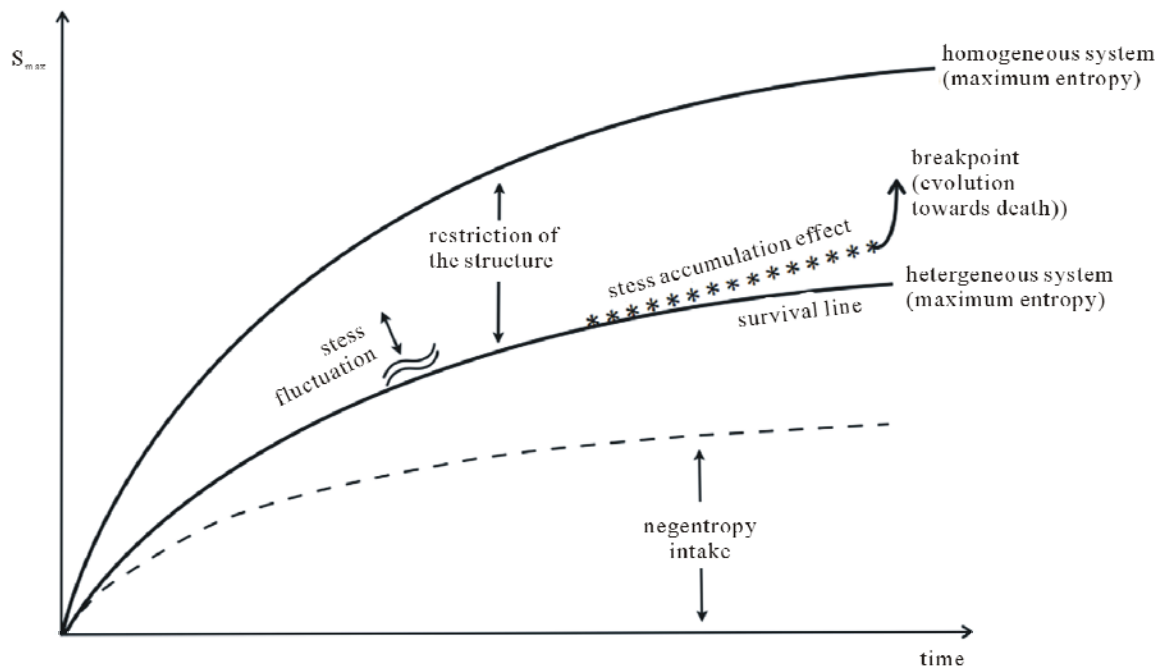
Describing **Figure 3**, the biological system distances itself from the homogeneous or uniform system, thus behaving as a heterogeneous system (survival line). For this to occur, entropy production of the biological systems must be eliminated through the intake of negentropy (energy and work to maintain the structure). Living matter evades [35] decay to the homogeneity since organisms evidently feed on negative entropy to restore the initial-operation state. The difficulties produced by internal and external environments are manifested by a change from the survival line to the line of maximum entropy of the homogeneous system, where stress indicates the appearance of survival risk. The stress fluctuations [36] represent the difficult situations experienced by a biological system, these are reflected on the survival line as perturbations either to the structure or to the physiological functions, and as such are followed by the regression of fluctuations as established by the Le Chatelier-Braun principle of stability applied to biological structures. This principle states that upon a perturbation, systems react against it to return to the initial-operation state. In a broader sense, the same thing occurs when there is dam-

age to the structure, showing the capacity of biological systems to self-regenerate [37]. The accumulation of stress indicates the presence of the process of aging [38], manifesting an increase in vulnerability to external perturbation (senescence [39,40]), which will result in the breakpoint and ultimately in death when there are no conditions to return the system towards its initial-operation state. The cumulative effect of stress preceding the breakpoint (see asterisk-line in **Figure 3**) shows a deterioration of the physiological functions present in aging.

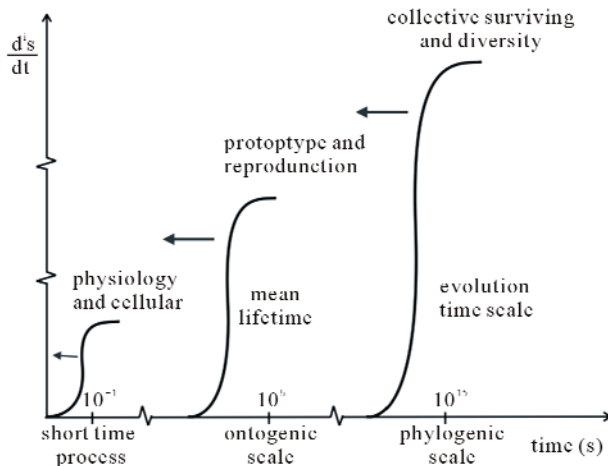
### 3. The Principle of Evolution: The Negentropy

The problem of explaining the evolution of species [41,42] raises the question about the mechanism of adaptation of living organisms to the environment [43]. This section is dedicated to establishing the thermodynamic description of adaptation, showing that evolution can be described as a kinetic phenomenon.

To describe evolution it is necessary to change the descriptive scale from the prototype or ontogenic scale to the collective or phylogenic [10] scale. **Figure 4** shows the levels of entropy production, pointing out the qualitative changes present in each scale. For the phylogenic processes entropy production is associated to a collective, thus the evolutive processes are established at this time scale.



**Figure 3.** The line of maximum of entropy versus time is shown for a homogeneous system (where all the molecules of an organism form a liquid-like mixture); and for a heterogeneous system, organized with internal constrictions (organs and flesh). The dotted line represents the difference between the maximums of entropy of the homogeneous and heterogeneous systems. This difference is equal to the negentropy required to maintain constant the acquired structure and avoid death (survival line). Note that the structure remains constant until the breakpoint.



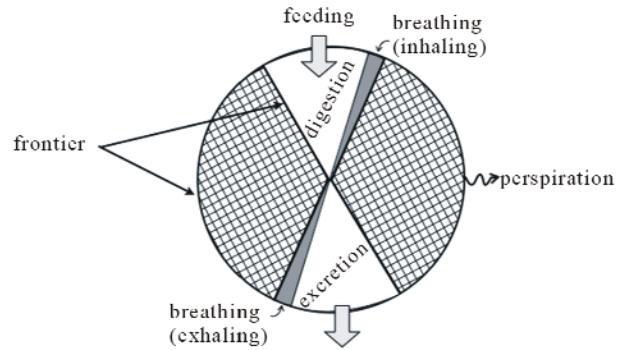
**Figure 4.** The different scales of time and entropy production in different systems, from the mesoscopic or cellular scale to the phylogenetic scale.

Thermodynamically, the evolution of living matter is described by postulating the validity of the negentropy principle [44], which establishes that the evolution of biological systems occurs in the direction [45] that the structure [46] becomes more complex. That is, the phylogenetic changes occur in the direction that the negentropy of the structure increases.

However, this postulate represents the sufficient condition, since it only shows the need to evolve by gaining structuring; moreover, the adaptation must be established simultaneously, when the system has adjusted to the environment in a stable condition.

The negentropy principle can be associated with the inherent difficulty that the growth of the system escalates in size [47] and shape [48-50], and particularly it is found that entropy production increases with volume [51,52,3] ( $V$ ), as shown by the expression for internal entropy production ( $d^i S/dt$ ) according to (20). In contrast, the elimination of the entropy of the system ( $d^e S/dt$ ) depends on the area of the frontier ( $\Sigma$ ), as seen in (19). Finally, the evolutionary structuring of the system does not occur in accordance with the volume growth of the species, but rather a balance between size and shape must be maintained for an efficient elimination of produced entropy. Then, it is clear that growth is governed by thermodynamics. Particularly, the rate of entropy elimination with increasing body mass obeys the power law (with 0.75 instead of 1). **Figure 5** shows how evolution has made more efficient the negentropy intake and entropy elimination without increasing the surface of the system [53].

One possible formulation of the necessary condition for survival is the adaptation of species to the environment, so as to minimize entropy production [54,55]. This can be established by the condition that the system operates

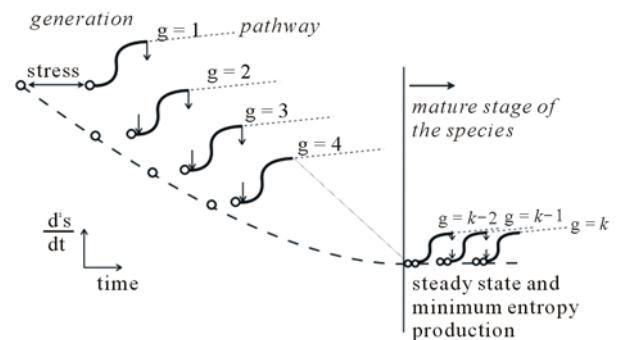


**Figure 5.** How evolution has made more efficient the negentropy intake and entropy elimination without increasing the surface of the system.

under stationary conditions. According to the requirements of thermodynamics, for the fulfillment of this principle it is necessary that, at least for a given period of time, the action of a species be specifically coupled to its ecological surroundings [56-62] in a way that its relation with the environment does not change during this period of time. With this, efficiency is achieved in both energy consumption and entropy elimination: the metabolism reaches maximum efficiency.

In the evolution of the species two parallel and independent events occur, as illustrated in **Figure 6**. These processes are the growth of the organic structure and the adaptation to the environment.

The evolution pathway [65] is guided by natural selection through the active mechanisms of heritage between generations in  $k$  steps [66-68]. In **Figure 6**, the arrows indicate the step from one generation to the next. This process leads to an increase in the demographic survival capacities [17]. It has been established that the evolutive process implies many generations and many events of



**Figure 6.** The negentropy principle in terms of an evolution pathway. The adaptation process is established in  $k$  steps, where  $k \gg 1$  to produce a stationary state between the prototypes of a species and the environment. The dashed line with white circles shows the separation between the species and the environment that produced the stress [63,64]; for the  $k$  generation the stress becomes zero.

combination and recombination of DNA between members of a large group. Then, the groups that failed to evolve in  $k$  steps, in accordance with the negentropy principle, have disappeared from the environment. In this sense, natural selection relates the two aspects: structure growth and the course of adaptation.

Regarding the sufficient condition of the negentropy principle, the evolution appears to be continuous. However, from the molecular point of view [69], it is a sequence of jumps occurring stochastically.

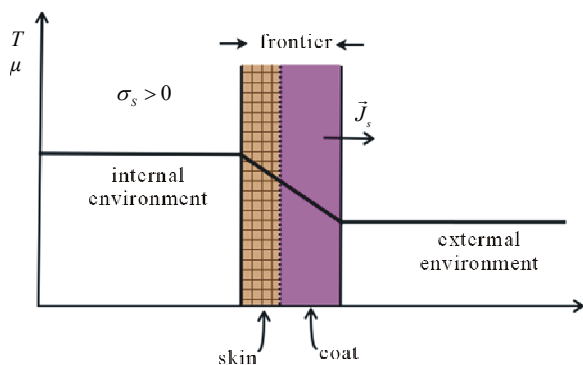
Concerning the formulation of the necessary condition of the negentropy principle, it has been established in two ways: firstly by using the principle of minimum entropy of linear non-equilibrium thermodynamics; and secondly by the self-organization of dissipative structures far from equilibrium. This last point will be discussed in the next section.

In relation to the principle of minimum entropy of non-equilibrium thermodynamics, it shows the requirements for the transport coefficients to be constant and the flow-force relations to be linear. The first requirement is fulfilled by the condition that during a long enough period of time the physiological capabilities acquired do not change significantly. On the other hand, the linearity is satisfied by the requirement that evolution has minimized the gradients under which life operates.

This is evidenced by two facts of the operation of physiological processes: first that they occur near electro-mechanical equilibrium; and second that they occur in nearly isothermal conditions in the internal environment of the system without taking into account the variations of the external environment, since they are controlled at the frontier (composed of the skin and its coat), as shown in Figure 7.

#### 4. Parallel Formulations

The negentropy principle formulated in the previous



**Figure 7. Production of entropy occurs internally and the entropy flow occurs at the frontier. In average, the stationary state condition prevails internally.**

section describes the evolution of life as a dissipative structure regulated by entropy production, its elimination from the system [70], and the adaptation to the environment. Parallel to this formulation, other alternatives presenting basic relations with thermodynamics have been established, such as information theory [71,72], the energetic formulation of biological structures, and the theory of self-organization of complex systems far from equilibrium. These are not contrasting formulations but rather complementary aspects, since they highlight the kinetic descriptions that thermodynamics does not specify within its own context, which are important aspects to explain the evolution of species. They are described below.

#### 4.1. Information Theory

According to information theory, entropy is defined by the following summation:

$$S = \sum_{j=1}^{\Omega} p_j \ln(p_j) \quad (22)$$

where  $j$  indicates the number of each element involved in the information set representing the system, with the probability of occurrence  $p_j$ . The factor  $\Omega$  is the total number of elements or complexions [8,9] in the set. The difficulty of applying this theory to biological systems lays in having to fully describe the details of the system within a numbered information set [73,74], since generally  $\Omega$  is very large. The information is a quantity related to a physical state [75].

A similar difficulty is found in statistical physics when defining entropy, which is overcome by using an algorithm that counts the number of microstates that are accessible to the system, thanks to the simplifying hypothesis that all the elements in the representative set have an equal probability [76]. In that case, if  $p_j = 1/\Omega$  then  $S = \ln \Omega$  (note that the entropy is a nondimensional quantity) [77].

For biological systems all probabilities are not necessarily equal, in fact they could even change with time since these systems operate irreversibly. It is thanks to modeling that the information contents of a biological system have been described, providing an insight to the characteristics of the evolution of life [78].

Recent advances in this direction highlight the achievements using evolutionary models that combine mutations and mechanisms of speciation [79,80]. Some bibliographic sources have referred to the feedback between the prototype and the environment as cybernetic [81] aspect of evolutionary mechanisms.

Significant progresses have occurred in the analysis of biological entities of small dimensions, as is the case of DNA [82-85] and other cell components, down to the

description of the cell itself [23,86].

Information theory gives a partial quantitative evaluation of the degree of organization [87], preserving the meaning of entropy according to statistical physics [88]. In fact, the increase of  $S$  corresponds to a loss of uncertainty; the approach dealt here indicates the lack of information. The same occurs with thermodynamic theory, where irreversibility, counted as  $\Delta S$ , is also associated with the degradation of the useful energy to restore the initial-operation state after spontaneous processes occur, which can be interpreted as a loss of information. Along these lines, based on information theory, the interpretation of entropy-increase is linked to the increase of disorganization for biological systems. Therefore, the negentropy principle is reflected as an increase in the enabled organization and system functions, indicating the presence of greater organization.

Consequently, evolution is directed (teleonomy [13]) in the direction that organization increases. In this sense, the adaptation to an environment requires an increase in information and a greater efficiency in handling it (that is the meaning of the negentropy [89]).

However, the connection between the concepts of entropy in information theory and thermodynamics is lacking. To achieve a quantitative comparison between these concepts, it is necessary to relate the probabilities used as measures of certainty with the thermodynamic variables of internal energy and the parameters that specify the constriction of the system. What stands out successfully in the theory of evolution is the relationship between organization and negentropy [90,7].

## 4.2. Energy Intensiveness Hypothesis

The intensiveness of energy consumption of a species can provide an evolutionary pattern as selection criteria in the evolution of species [91,92]. This relates to biological evolution by considering the interactions between species of the same environment, particularly the ability to find, consume and guard resources as the dominant aspect of such evolution. According to this hypothesis it is the capacity to process energy (escalation), which has been a requirement given the critical situations that some species have faced [93]. Rigorously speaking, the negentropy principle is not contradicted, since the processing of energy and its conversion to work, as well as the capacity to discard part of the energy, is the way to conceive a biotic machine [23] that can operate under conditions of irreversibility, thus satisfying this principle.

The relation between the energy intensiveness approach and negentropic growth becomes clear from the fact that biological systems obtain energy from the exterior, such as the sun, and store the available energy inside their struc-

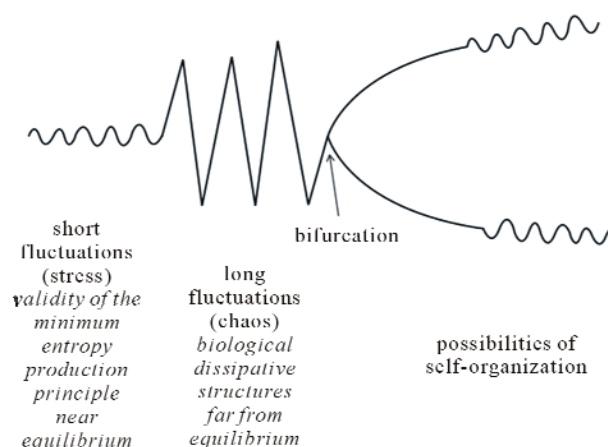
ture as negentropy [94]. From this point of view, biodiversity multiplies modes of energy consumption [95], and life evolution manifests itself by increased complexity [96], energy-gathering metabolic systems [97], teleonomic [13] character, as well as its abundance and diversity.

## 4.3. Self-Organization of Dissipative Structures

According to the nonlinear hydrodynamic stability theory [98-101] and the description of coupled chemical reactions by chemical kinetics [102-104], dissipative structures as open systems outside equilibrium are capable of self-organization and forming structural patterns [105,106] depending on the boundary conditions imposed on the system [107].

The hypothesis that the same occurs for biological systems with a higher level of complexity has helped to establish new theoretical developments to explain both the origin of life as well as the diversity of species. Referred to as chaos theory [108,109], it describes dissipative structures capable of transforming themselves through a mechanism of time-space symmetry breaking. The new structures emerge in a point called bifurcation, after critical fluctuations, where several branches or possibilities of pattern formation appear (see **Figure 8**). Natural selection could choose one of the branches influenced by the environment (adaptation requirement) or simply any possibility of change could present itself (probabilistic requirement for diversity).

The continuous transition towards a specific branch is possible, called "transitional bifurcation" [110,111]. This is also a result of self-organization at the edge of chaos [112]. In addition, some systems may show self-organization of the first or second kind depending on boundary



**Figure 8.** The possibilities of evolution of a system near equilibrium affected by an environmental crisis, it goes through long fluctuations and a bifurcation is produced to reach a new evolutionary branch to overcome the need for adaptation.



and initial conditions [113], they can also exhibit the development of complex hierarchical structures [114,115].

So far, the basic postulation of negentropic growth that negentropy intake is the cause for structure growth is still valid. However, kinetic formulations have sought to replace the minimum dissipation principle for a broader one that explains not only adaptation but also the causes of evolution.

## 5. Discussion

The thermodynamic description of the vital processes and their evolution is quantitative for the physiological processes in the mesoscopic scale, the global scale for a prototype, but qualitative in the phylogenetic scale of the species. In the mesoscopic scale an endless row of physiological processes occur that in the ontogenic or global scale appear as a continuum. Then, it makes sense to talk about the entropy associated with a heterogeneous biological system with its maximum compatible with the internal constraints, which are represented by the internal energy barriers established in the organization of the system. This entropy is lower than that which the same molecules would have if they were arranged homogeneously in a liquid-like mixture. The difference between both amounts is the negentropy associated to the organic structure; it is interpreted as the amount of work or heat energy required to restore the initial-operation state. At the same time, to maintain the organic structure invariant, the entropy produced in the physiological processes when they reproduce the irreversible thermodynamic flows must be eliminated to avoid producing stress and risking life. This is how survival and proximity to death (breakpoint) are defined.

On these bases, the thermodynamic image of life is that of a system that develops a cycle, with entropy production on one part and elimination on the other closing the cycle. Emphasizing the process of elimination, organic systems are regarded as dissipative structures highly organized both mesoscopically and globally. The previous image is centered on the ontogenic scale. Regarding the phylogenetic, the time scale widens to contain biological changes in a time period much longer than the duration of a generation of prototypes of a species. In the preceding thermodynamic terms, the negentropy principle is established with two requirements: an increase in organic structuring over time, and the establishment of a stationary state of high metabolic efficiency (minimum production of wasted energy). The determining factor of the negentropy principle is that one cannot be achieved without the other (necessary and sufficient conditions). The second requirement is set in a state of minimum entropy production in relation to a stationary one, thus guar-

anteeing the property of the regression of fluctuations, ensuring the survival of the species.

The negentropy principle has been considered adequate for describing the general aspects of living matter and its evolution. At present, this principle is established as a biological law due to its general validity.

The mechanisms proposed in the linear non-equilibrium thermodynamic description of adaptation to an environment through the establishment of a minimum dissipation stationary state are a good proposal. So much so, that attempts have been made to extend their validity to the stationary case far from equilibrium, creating a new insight to search for a nonlinear theory for biological systems.

Currently, there are several ideas that treat the evolution of life and they postulate structural growth as the motor of evolution. However, the limitations to growth have been scarcely foreseen except for the criticism to Cope's rule due to the advantages in volume growth. In this direction, the restrictions due to the surface increase of biological bodies are a topic that could be discussed in the future. The energy intensiveness hypothesis is similar regarding the capacity to process energy from the habitat. Nevertheless, it is not possible to generate or consume energy without wasting some to be removed as excess entropy, but it remains the key to achieve efficiency and even equally important, the survival of the species. The most appropriate critical view is thus established from the thermodynamic point of view, where the two aspects are included in the negentropy principle.

In contrast, information theory, using Brillouin's definition of entropy, gives a new interpretation to thermodynamic entropy with its own methodology to measure it for small biological organisms, both at the microscopic and mesoscopic scales. The achievements show the descriptive capabilities of the theory. It is expected to achieve a more complete description of the principle of entropy balance on the phylogenetic scale with the developments in the techniques of advanced Monte Carlo [116], to verify the negentropy principle using information theory.

The kinetic theory of chaos provides several possibilities of results that describe the change of stable dissipative structures far from equilibrium. Two things are implicit: that evolution is continuous since the boundary conditions provide the information of mutations, and that the choice of one of the many predictions could be determined by natural selection. The image of evolution is that the adaptation process is a branch of a solution of a set of differential equations. This is interesting, since it shows a new insight from the kinetic point of view, which thermodynamics cannot describe. This is a plausible idea and contributions in this direction will be welcome.

Finally, it has been suggested to consider the social and cultural products of men, both social (work division and language) and intellectual in sciences and arts, as part of the characteristics of animal evolution guided by the principle of negentropic growth. In this sense, the evolutionary properties are transferred to those products in terms of the increase of organizational and hierarchical levels [117] and differentiation [118], highlighting the abilities to transfer information and knowledge [119].

## 6. Conclusion

In the present work the nature of biological systems was described from a thermodynamic point of view. Two aspects of living matter have been identified. The first refers to mesoscopic aspects, which describe thermodynamically the physiological processes at the level of a cell or local scale, where entropy production is generated by the presence of irreversible flows. The second relates to the macroscopic aspects in the global scale, where the elimination of entropy through the surface of the bodies occurs, thus operating as open systems. At this level, the organization of a biological system is identified by the number of constrictions; which are equivalent to entropy reducers. The total provides the negentropy of the system.

Regarding the division of the time scale, two are identified: the ontogenic or the evolution of the prototype, and the phylogenic or the evolution of the species. In the ontogenic description there is a difficulty to restore the initial-operation state at the presence of stress; therefore a regression of fluctuations is required for maintaining the structure. The difficulty arises when stress accumulates, since the entropy produced by physiological processes is not being eliminated from the system and there is no negentropy intake, then the open system has been blocked and is operating like a closed system, which could result in death. In the phylogenic description, the need for adaptation is established in the principle of minimum dissipation and maximum metabolic efficiency. Both evolutionary aspects are included in the negentropy principle.

Moreover, the negentropy principle links two aspects: the necessity of adaptation to prevent the collective death; and the probabilistic aspect where mutations occur randomly or induced by the need of survival, enhancing the possibility of adaptation.

Regarding the validity of the negentropy principle, in particular with the assumption of minimum energy dissipation, several efforts have been made to go beyond linear equilibrium thermodynamics and improve its formulation. Encouraging results have been obtained, like those found in information theory, the energy intensiveness hypothesis, and the nonlinear stability theory of dissipative structures far from equilibrium. In all these cases,

the description of biological systems and their evolution is a task that is far from being finished.

## 7. Acknowledgements

The authors acknowledge the financial support provided by DGPA-UNAM (Project IN112109).

## 8. References

- [1] D. Dix, "Toward a Definition of Life: Semantic and Thermodynamic Considerations," *Journal of Theoretical Biology*, Vol. 102, No. 2, 1983, pp. 337-340. doi:10.1016/0022-5193(83)90371-5
- [2] J. S. Wicken, "Entropy and Evolution: Ground Rules for Discourse," *Systematic Zoology*, Vol. 35, No. 1, 1986, pp. 22-36. doi:10.2307/2413288
- [3] D. W. McShea, "Possible Largest-Scale Trends in Organismal Evolution: Eight 'Live Hypotheses'," *Annual Review of Ecology and Systematics*, Vol. 29, 1998, pp. 293-318. doi:10.1146/annurev.ecolsys.29.1.293
- [4] J. Kestin, "A Course in Thermodynamics," 2nd Edition, McGraw-Hill, New York, 1979.
- [5] E. Schrödinger, "What is Life? Mind and Matter," Cambridge University Press, Cambridge, 1944.
- [6] L. Demetrius, "Directionality Principles in Thermodynamics and Evolution," *Proceeding of the National Academy of Sciences of the USA*, Vol. 94, 1997, pp. 3491-3498. doi:10.1073/pnas.94.8.3491
- [7] H. B. Hollinger and M. J. Zenzen, "An Interpretation of Macroscopic Irreversibility within the Newtonian Framework," *Philosophy of Science*, Vol. 49, No. 3, 1982, pp. 309-354. doi:10.1086/289065
- [8] L. Brillouin, "Maxwell's Demon Cannot Operate: Information and Entropy. I," *Journal of Applied Physics*, Vol. 22, No. 3, 1951, pp. 334-337. doi:10.1063/1.1699951
- [9] L. Brillouin, "Physical Entropy and Information. II," *Journal of Applied Physics*, Vol. 22, No. 3, 1951, pp. 338-343. doi:10.1063/1.1699952
- [10] M. Ruse, "Monad to Man: The Concept of Progress in Evolutionary Biology," Harvard University Press, Massachusetts, 1996.
- [11] I. Prigogine and T. M. Wiame, "Biologie et Thermodynamique del Phénomènes Irréversibles," *Experientia (Basle)*, Vol. 2, 1946, pp. 451-453.
- [12] F. Crick, "Life Itself: Its Origin and Nature," Simon and Schuster, New York, 1981.
- [13] J. Monod, "Chance and Necessity," Random, New York, 1972.
- [14] M. Rossignol, L. Rossignol, R. A. A. Oldeman and S. Bensine-Tizroutine, "Struggle of Life or the Natural History of Stress and Adaptation," Treemail, The Netherlands, 1998.
- [15] B. McDowell, "An Examination of the Ecosystems Perspective in Consideration of New Theories in Biology

- and Thermodynamics,” *Journal of Sociology and Social Welfare*, Vol. 21, No. 2, 1994, pp. 49-68.
- [16] J. G. Miller, “Living Systems: Basic Concepts,” *Behavioral Science*, Vol. 10, No. 3, 1965, pp. 193-237. doi:10.1002/bs.3830100302
- [17] M. T. Hannan and J. Freeman, “The Population Ecology of Organizations,” *The American Journal of Sociology*, Vol. 82, No. 5, 1977, pp. 929-964. doi:10.1086/226424
- [18] H. B. Callen, “Thermodynamics and an Introduction to Thermostatistics,” 2nd Edition, John Wiley & Sons, New York, 1960.
- [19] A. Katchalsky and P. F. Curran, “Nonequilibrium Thermodynamics in Biophysics,” Harvard University Press, Massachusetts, 1981.
- [20] A. B. Pippard, “Elements of Classical Thermodynamics,” Cambridge University Press, Cambridge, 1957.
- [21] L. D. Landau and E. M. Lifshitz, “Statistical Physics,” 3rd Edition, (Part I by E. M. Lifshitz and L. P. Pitaevskii), Pergamon Press, Oxford, 1980.
- [22] G. Lebon, D. Jou and J. Casas-Vázquez “Understanding non-equilibrium Thermodynamics. Foundations, Applications, Frontiers”, Springer-Verlag, Berlin, 2008. doi:10.1007/978-3-540-74252-4
- [23] E. B. Jacob, Y. Shapira and A. I. Tauber “Seeking the Foundations: From Schrödinger’s Negative Entropy to Latent Information,” *Physica A*, Vol. 359, 2006, pp. 495-524. doi:10.1016/j.physa.2005.05.096
- [24] J. M. Rubi, “The Non-Equilibrium Thermodynamics Approach to the Dynamics of Mesoscopic Systems,” *Journal of Non-Equilibrium Thermodynamics*, Vol. 29, No. 4, 2004, pp. 315-325. doi:10.1515/JNETDY.2004.058
- [25] D. Reguera, J. M. Rubí and J. M. Vilar, “The Mesoscopic Dynamics of Thermodynamic Systems,” *Journal of Physical Chemistry B*, Vol. 109, No. 46, 2005, pp. 21502-21515. doi:10.1021/jp052904i
- [26] L. F. del Castillo, “El Fenómeno Mágico de la Ósmosis,” Colección Ciencia para Todos, Vol. 16, Fondo de Cultura Económica, México, 1996.
- [27] M. W. Zemansky and R. H. Dittman, “Heat and Thermodynamics: An Intermediate Textbook,” 6th Edition, McGraw-Hill, New York, 1981.
- [28] D. ter Haar and H. Wergeland, “Elements of Thermodynamics,” Addison-Wesley Publishing Company, Massachusetts, 1966.
- [29] L. Brillouin, “The Negentropy Principle of Information,” *Journal of Applied Physics*, Vol. 24, No. 9, 1953, pp. 1152-1163. doi:10.1063/1.1721463
- [30] V. M. Zhukovsky, “Thermodynamics of Environment,” *Journal of Mining and Metallurgy B*, Vol. 36, No. 1-2, 2000, pp. 93-102.
- [31] R. Swenson and M. T. Turvey, “Thermodynamic Reason for Perception-Action Cycles,” *Ecological Psychology*, Vol. 3, No. 4, 1991, pp. 317-348. doi:10.1207/s15326969eco0304\_2
- [32] M. G. Velarde and C. Normand, “Convection,” *Scientific American*, Vol. 243, No. 1, 1980, pp. 93-108.
- [33] C. M. Visser and R. M. Kellogg, “Biorganic Chemistry and the Origin of Life,” *Journal of Molecular Evolution*, Vol. 11, No. 2, 1978, pp. 163-169. doi:10.1007/BF01733891
- [34] H. F. Blum, “Time’s Arrow and Evolution,” 3rd Edition, Princeton University Press, Princeton, 1968.
- [35] G. Stent, “That was the Molecular Biology that was,” *Science*, Vol. 160, No. 3826, 1968, pp. 390-395. doi:10.1126/science.160.3826.390
- [36] W. Arthur, “Mechanisms of Morphological Evolution: A Combined Genetic, Developmental and Ecological Approach,” John Wiley & Sons, Chichester, 1984.
- [37] B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts and P. Walter, “Universal Mechanisms of Animal Development,” *Molecular Biology of the Cell*, 4th Edition, Garland Science, New York, 2002.
- [38] W. M. Bortz II, “Aging as Entropy,” *Experimental Gerontology*, Vol. 21, No. 4-5, 1986, pp. 321-328. doi:10.1016/0531-5565(86)90039-2
- [39] W. Arthur, “Theory of the Evolution of Development,” John Wiley & Sons, New York, 1988.
- [40] O. Toussaint, P. Dumont, J. F. Dierick, T. Pascal, C. Fripiat, F. Chainiaux, F. Sluse, F. Eliaers and J. Remacle, “Stress-Induced Premature Senescence. Essence of Life, Evolution, Stress, and Aging,” *Annals of the New York Academy of Sciences*, Vol. 908, 2000, pp. 85-98. doi:10.1111/j.1749-6632.2000.tb06638.x
- [41] C. Darwin, “On the Origin of Species,” John Murray, London, 1859.
- [42] D. J. Depew and B. H. Weber, “Darwinism Evolving Systems Dynamics and the Genealogy of Natural Selection,” The MIT Press, Cambridge, 1996.
- [43] J. Wu and W. Gao, “Spatial Patterns of Species Richness: A Hierarchical Perspective,” *Chinese Biodiversity*, Vol. 3, 1995, pp. 12-21.
- [44] R. E. Ulanowicz and B. M. Hannon, “Life and the Production of Entropy,” *Proceedings of the Royal Society of London B*, Vol. 232, No. 1267, 1987, pp. 181-192. doi:10.1098/rspb.1987.0067
- [45] M. Ziehe and L. Demetrius, “Directionality Theory: an Empirical Study of an Entropic Principle in Life-History Evolution,” *Proceedings of the Royal Society B*, Vol. 272, No. 1568, 2005, pp. 1185-1194. doi:10.1098/rspb.2004.3032
- [46] I. Prigogine, “Time, Structure and Fluctuations,” *Science*, Vol. 201, No. 4358, 1978, pp. 777-785. doi:10.1126/science.201.4358.777
- [47] D. W. Hone and M. J. Benton, “The Evolution of Large Size: How does Cope’s Rule Work?” *Trends in Ecology & Evolution*, Vol. 20, No. 1, 2005, pp. 4-6. doi:10.1016/j.tree.2004.10.012
- [48] J. G. Kingsolver and D. W. Pfennig, “Individual-Level Selection as a Cause of Cope’s Rule of Phyletic Size Increase,” *Evolution*, Vol. 58, No. 7, 2004, pp. 1608-1612. doi:10.1111/j.0014-3820.2004.tb01740.x
- [49] B. van Valkenburgh, X. Wang and J. Damuth, “Cope’s Rule, Hypercarnivory, and Extinction in north American Canids,” *Science*, Vol. 306, No. 5693, 2004, pp. 101-104.

- doi:10.1126/science.1102417
- [50] J. A. Finarelli, "Testing Hypotheses of the Evolution of Encephalization in the Canidae (Carnivora, Mammalia)," *Paleobiology*, Vol. 34, No. 1, 2008, pp. 35-45. doi:10.1666/07030.1
- [51] J. T. Bonner, "The Evolution of Complexity by Means of Natural Selection," Princeton University Press, New Jersey, 1988.
- [52] M. T. Carrano, "Body-Size Evolution in the Dinosauria," In: M. T. Carrano, R. W. Blob, T. J. Gaudin and J. R. Wible, Eds., *Amniote Paleobiology: Perspectives on the Evolution of Mammals, Birds, and Reptiles*, University of Chicago Press, Chicago, 2006, pp. 225-268.
- [53] D. Jou, J. E. Llebot and C. G. Perez, "Física para Ciencias de la Vida," 2nd Edition, McGraw Hill Interamericana, Madrid, 2008.
- [54] I. Prigogine, "Introduction to the Thermodynamics of Irreversible Processes," Wiley & Sons, New York, 1955.
- [55] S. R. de Groot, "Thermodynamics of Irreversible Processes," North-Holland Publishing Company, Amsterdam, 1966.
- [56] F. J. Ayala, "The Concept of Biological Progress," In: F. J. Ayala and T. Dobzhansky, Eds., *Studies in the Philosophy of Biology: Reductionism and Related Problems*, Macmillan, New York, 1974, pp. 339-354.
- [57] D. C. Fisher, "Progress in Organismal Design," In: D. M. Raup and D. Jablonski, Eds., *Patterns and Processes in the History of Life*, Springer, Berlin, 1986, pp. 99-117.
- [58] J. S. Huxley, "Evolution: The Modern Synthesis," Harper, New York, 1942.
- [59] J. W. Valentine, "Patterns of Taxonomic and Ecological Structure of the Shelf Benthos during Phanerozoic Time," *Palaeontology*, Vol. 12, 1969, pp. 684-709.
- [60] G. G. Simpson, "The Meaning of Evolution," Yale University Press, New Haven, 1967.
- [61] D. M. Raup, "Testing the Fossil Record for Evolutionary Progress," In: M. Nitecki, Ed., *Evolutionary Progress*, Chicago University Press, Chicago, 1988, pp. 293-317.
- [62] F. J. Ayala, "Can 'Progress' be Defined as a Biological Concept?" In: M. Nitecki, Ed., *Evolutionary Progress*, Chicago University Press, Chicago, 1988, pp. 75-96.
- [63] H. Selye, "A Syndrome Produced by Diverse noxious Agents," *Nature*, Vol. 138, 1936, p. 32. doi:10.1038/138032a0
- [64] H. Selye, "The General Adaptation Syndrome and the Diseases of Adaptation," *Journal of Clinical Endocrinology*, Vol. 6, No. 2, 1946, pp. 117-230. doi:10.1210/jcem-6-2-117
- [65] R. S. Boardman and A. H. Cheetham, "Degrees of Colony Dominance in Stenolaemate and Gymnolaemate Bryozoa," In: R. S. Boardman, A. H. Cheetham and W. A. Oliver, Eds., *Animal Colonies: Development and Function through Time*, Dowden, Hutchinson & Ross, Stroudsburg, 1973.
- [66] S. J. Gould, "Wonderful Life," Norton, New York, 1989.
- [67] P. D. Gingerich, "Quantification and Comparison of Evolutionary Rates," *American Journal of Science*, Vol. 293, 1993, pp. 453-478. doi:10.2475/ajs.293.A.453
- [68] W. Scharloo, "Canalization: Genetic and Developmental Aspects," *Annual Review of Ecology and Systematics*, Vol. 22, 1991, pp. 65-93. doi:10.1146/annurev.es.22.110191.000433
- [69] R. Lewin, "Patterns in Evolution: The New Molecular View," W. H. Freeman & Company, New York, 1999.
- [70] J. S. Wicken, "Thermodynamics and the Conceptual Structure of Evolutionary Theory," *Journal of Theoretical Biology*, Vol. 117, No. 3, 1985, pp. 363-383. doi:10.1016/S0022-5193(85)80149-1
- [71] C. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, Vol. 27, 1948, pp. 379-423, 623-656.
- [72] E. T. Jaynes, "Information Theory and Statistical Mechanics," In: K. Ford, Ed., *Statistical Physics*, Benjamin, New York, 1963, pp. 181-218.
- [73] G. Chaitin, "On the Length of Programs for Computing Finite Binary Sequences," *Journal of the Association for Computing Machinery*, Vol. 13, 1966, pp. 547-569.
- [74] G. Chaitin, "Randomness and Mathematical Proof," *Scientific American*, Vol. 232, No. 5, 1975, pp. 47-52. doi:10.1038/scientificamerican0575-47
- [75] L. Brillouin, "Science and Information Theory," 2nd Edition, Academic Press, New York, 1962.
- [76] J. Kestin and J. R. Dorfman, "Course in Statistical Thermodynamics," Academic Press, New York, 1971.
- [77] F. Reif, "Fundamentals of Statistical and Thermal Physics," McGraw-Hill, Singapore, 1965.
- [78] D. R. Brooks, P. H. Leblond and D. D. Cumming, "Information and Entropy in a Simple Evolution Model," *Journal of Theoretical Biology*, Vol. 109, No. 1, 1984, pp. 77-93. doi:10.1016/S0022-5193(84)80112-5
- [79] D. R. Brooks and E. O. Wiley, "Evolution as an Entropic Phenomenon," In: J. W. Pollard, Ed., *Evolutionary Theory: Paths to the Future*, John Wiley and Sons, London, 1984, pp. 141-171.
- [80] J. Campbell, "Grammatical Man: Information, Entropy, Language, and Life," Simon & Schuster, New York, 1982.
- [81] N. Wiener, "Cybernetics: Or Control and Communication in the Animal and the Machine," MIT Press, Massachusetts, 1948.
- [82] J. S. Wicken, "Entropy, Information, and Nonequilibrium Evolution," *Systematic Zoology*, Vol. 32, No. 4, 1983, pp. 438-443. doi:10.2307/2413170
- [83] L. Kari and L. F. Landweber, "Biocomputing in Ciliates," In: M. Amos, Ed., *Cellular Computing*, Oxford University Press, Oxford, 2003.
- [84] R. D. Knight, L. F. Landweber and M. Yarus, "How Mitochondria Redefine the Code," *Journal of Molecular Evolution*, Vol. 53, No. 4-5, 2001, pp. 299-313. doi:10.1007/s002390010220
- [85] G. Burger, I. Plante, K. M. Lonergan and M. W. Gray, "The Mitochondrial DNA of the Amoeboid Protozoon, *Acanthamoeba Castellani*: Complete Sequence, Gene

- Content and Genome Organization,” *Journal of Molecular Biology*, Vol. 245, No. 5, 1995, pp. 522-537. doi:10.1006/jmbi.1994.0043
- [86] C. H. Waddington, “New Patterns in Genetics and Development,” Columbia University Press, New York, 1966.
- [87] C. J. Smith, “Problems with Entropy in Biology,” *Bio-systems*, Vol. 7, No. 2, 1975, pp. 259-265. doi:10.1016/0303-2647(75)90033-7
- [88] N. H. Gregersen, “From Complexity to Life: on the Emergence of Life and Meaning,” Oxford University Press, New York, 2003.
- [89] L. Brillouin, “Thermodynamics and Information Theory,” *American Scientist*, Vol. 38, 1950, pp. 595-599.
- [90] P. A. Corning and S. J. Kline, “Thermodynamics, Information and Life. Revisited, Part I: ‘To Be or Entropy,’” *Systems Research and Behavioral Science*, Vol. 15, 1998, pp. 273-295. doi:10.1002/(SICI)1099-1743(199807/08)15:4<273::AID-SRES200>3.0.CO;2-B
- [91] G. J. Vermeij, “Evolution and Escalation,” Princeton University Press, New Jersey, 1987.
- [92] G. J. Vermeij, “The Evolutionary Interaction among Species: Selection, Escalation, and Coevolution,” *Annual Review of Ecology and Systematics*, Vol. 25, 1994, pp. 219-236. doi:10.1146/annurev.es.25.110194.001251
- [93] G. J. Vermeij, “Economics, Volcanoes, and Phanerozoic Revolutions,” *Paleobiology*, Vol. 21, No. 2, 1995, pp. 125-152.
- [94] M. Tribus and E. C. McIrvine, “Energy and Information,” *Scientific American*, Vol. 224, 1971, pp. 179-188. doi:10.1038/scientificamerican0971-179
- [95] S. N. Salthe, “The Natural Philosophy of Work,” *Entropy*, Vol. 9, No. 2, 2007, pp. 83-99. doi:10.3390/e9020083
- [96] E. Mayr, “Toward a New Philosophy of Biology,” Harvard University Press, Massachusetts, 1988.
- [97] A. Pross, “The Driving Force for Life’s Emergence: Kinetic and Thermodynamic Considerations,” *Journal of Theoretical Biology*, Vol. 220, No. 3, 2003, pp. 393-406. doi:10.1006/jtbi.2003.3178
- [98] S. Chandrasekhar, “Hydrodynamic and Hydromagnetic Stability,” Clarendon, Oxford, 1961.
- [99] D. D. Joseph, “Stability of Fluid Motions,” Springer, Berlin, 1976.
- [100] A. Movchan, “The Direct Method of Lyapounov in Stability Problems of Elastic Systems,” *Journal of Applied Mathematics and Mechanics*, Vol. 23, No. 3, 1959, pp. 483-693. doi:10.1016/0021-8928(59)90161-3
- [101] A. J. Pritchard, “A Study of the Classical Problem of Hydrodynamic Stability,” *IMA Journal of Applied Mathematics*, Vol. 4, No. 1, 1968, pp. 78-93. doi:10.1093/imamat/4.1.78
- [102] G. Nicoli and I. Prigogine, “Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order through Fluctuations,” Wiley-Interscience, New York, 1977.
- [103] P. Glandsdorff and I. Prigogine, “Structure, Stabilité et Fluctuations,” Masson, Paris, 1971.
- [104] D. Kondepudi, R. J. Kaufman and N. Singh, “Chiral Symmetry-Breaking in Sodium-Chlorate Crystallization,” *Science*, Vol. 250, No. 4983, 1990, pp. 975-976. doi:10.1126/science.250.4983.975
- [105] V. Castets, E. Dalos, J. Boissonade and P. de Kepper, “Experimental Evidence of Sustained Standing Turing-Type Nonequilibrium Chemical Patterns,” *Physical Review Letters*, Vol. 64, No. 24, 1990, pp. 2953-2956. doi:10.1103/PhysRevLett.64.2953
- [106] Q. Ouyang and H. L. Swinney, “Transition from a Uniform State to Hexagonal and Striped Turing Patterns,” *Nature*, Vol. 352, No. 6336, 1991, pp. 610-612. doi:10.1038/352610a0
- [107] A. M. Turing, “The Chemical Basis of Morphogenesis,” *Philosophical Transactions of the Royal Society of London. Series B - Biological Sciences*, Vol. 237, No. 641, 1952, pp. 37-72. doi:10.1098/rstb.1952.0012
- [108] M. Tabor, “Chaos and Integrability in nonlinear Dynamics: An Introduction,” Wiley-Interscience, USA, 1989.
- [109] P. Davies, “The New Physics: A Synthesis,” In: P. Davies, Ed., *The New Physics*, Cambridge University Press, Cambridge, 1989.
- [110] J. Swift and P. C. Hohenberg, “Hydrodynamic Fluctuations at the Convective Instability,” *Physical Review A*, Vol. 15, No. 1, 1977, pp. 319-328. doi:10.1103/PhysRevA.15.319
- [111] M. C. Cross and P. C. Hohenberg, “Pattern Formation Outside of Equilibrium,” *Reviews of Modern Physics*, Vol. 65, No. 3, 1993, pp. 851-1112. doi:10.1103/RevModPhys.65.851
- [112] K. Ito and Y. P. Gunji, “Self-Organization of Living Systems towards Criticality at the Edge of Chaos,” *Biosystems*, Vol. 33, No. 1, 1994, pp. 17-24. doi:10.1016/0303-2647(94)90057-4
- [113] E. Bodenschatz, W. Pesch and G. Ahlers, “Recent Developments in Rayleigh-Bénard Convection,” *Annual Review of Fluid Mechanics*, Vol. 32, No. 1, 2000, pp. 709-778. doi:10.1146/annurev.fluid.32.1.709
- [114] P. L. Engle, “Conjectures Concerning Complexity and Hierarchy,” *Far from Equilibrium*, Laurel Highlands Media, Greensburg, 2002.
- [115] J. Walleczek, “Self-Organized Biological Dynamics and Nonlinear Control: Toward Understanding Complexity, Chaos and Emergent Function in Living Systems,” Cambridge University Press, Cambridge, 2000.
- [116] R. Luzzi, A. R. Vasconcelos and J. G. Ramos, “Predictive Statistical Mechanics: A Nonequilibrium Ensemble Formulation,” Kluwer Academia Publishers, Dordrecht, 2002.
- [117] R. A. Eve, S. Horsfall and M. E. Lee, “Chaos, Complexity, and Sociology: Myths, Models, and Theories,” Sage Publications, London, 1997.
- [118] R. Boyd and P. J. Richerson, “Culture and the Evolutionary Process,” University of Chicago Press, London, 1988.
- [119] L. L. Cavalli-Sforza and M. W. Feldman, “Cultural Transmission and Evolution: A Quantitative Approach,” Princeton University Press, New Jersey, 1981.