

ON MAXWELL'S DEMONS AND THE ORIGIN OF EVOLUTIONARY VARIATIONS: AN INTERNALIST PERSPECTIVE

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Received 7-I-2003

ABSTRACT

This paper defends an internalist perspective of selection based on the hypothesis that considers living evolutionary units as Maxwell's demons (MD) or Zurek's Information Gathering and Using Systems (IGUS). Individuals are considered as IGUS that extract work by means of measuring and recording processes. Interactions or measurements convert uncertainty about the environment (Shannon's information, H) into internalized information in the form of a compressed record (Chaitin's algorithmic complexity, K). The requirements of the model and the limitations inherent to its formalization are discussed. This approach offers an alternative view to the causes of evolutionary variations which goes beyond the classical Lamarckian-Darwinian controversy. I argue that random variations only apply near-to-equilibrium at the time organisms have attained structural closure, and that a speed up of mutation rates that facilitates the production of directed variations occurs far-from-equilibrium due to organisms' openness to the surrounding conditions. However, real organisms are located somewhere between the above two cases and thus, operate at an intermediate stage where there is a maximum efficiency of H/K conversion. In consequence, IGUS keep their autonomy and evolving capacity by compromising between external circumstances and inner constraints. This compromise is made possible by closure regulation. Likewise, this model explains why nature has favored the selection of agents capable of selectively recording a partial description of their environment.

Key Words: Evolutionary variations, Maxwell's demons (MD), Information Gathering and Using Systems (IGUS), analog information, digital information, entropy.

1. INTRODUCTION

This paper explores an internalist contribution to evolution inspired by Maxwell's demon (MD) thought experiment. Zurek (1989a,b, 1990) conceives MD as Information Gathering and Using Systems (IGUS) and suggests its applicability to the study of Complex Adaptive Systems such as living entities. I show that this analogy provides a heuristic framework that allows discussion of the merging of external and internal dynamics that account for the origin of evolutionary variations, and helps to



Acta Biotheoretica 52: 17–40, 2004.

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understand the reciprocity between the nature of the organism and the nature of the conditions. This model affirms the existence of analog information with its corresponding ecological and epigenetic inheritance systems and digital information that corresponds to genetic inheritance system.

Three thermodynamic regimes help in understanding the action of the IGUS as an evolving living entity: 1. Far-from-equilibrium (Openness): Shannon's information from the IGUS viewpoint (H) prevails and variations directed to external circumstances may take place. 2. Near-to-equilibrium (Closure): IGUS genetic encoded information (K) prevails and random variations take place. 3. Real organisms are located somewhere between the above two cases and thus, operate at an intermediate stage where there is a maximum efficiency of H/K conversion that confers IGUS autonomy.

The contents of Darwinian evolutionary theory were greatly influenced by free market economic theories (Green, 1981: 7), as manifested in the analogy of the survival of the fittest and the view of natural selection as an external regulator between organisms and environment. Thus, Darwinism was cast into a Newtonian frame via political economy (Depew and Weber, 1995: Ch. 5). In contrast, in the late eighteenth century natural philosophers attempted to base the science of the living on non-Newtonian concepts, as illustrated in Lamarck's theory in which the action of the expansive caloric fluid (heat) played the essential role as the excitatory cause of life (Burkhardt, 1995: Ch. 6). Lamarck considered life as a process of heat disengagement coordinated by a material center, thus, the internalization of the fluids manifested as an *inner power* or a tendency to attain increasing organization (Burkhardt, 1995: Ch. 6). This intellectual endeavor that would have anticipated today's thermodynamic approaches to evolutionary biology was abandoned and misinterpreted, as Darwinians preferred Newtonian based analogies. Furthermore Boltzmann's statistical approach to the study of inanimate matter as a population of molecules, paved the way to Fisher's incorporation of statistical thermodynamics into population genetics (Depew and Weber, 1995: Ch.10). However, Fisher had to incorporate selection *ad hoc*, since it was absent in Boltzmann's approach. Fisher's contribution became the rational foundation of Neodarwinism. Selection was, then, considered as an external force that provokes a population shift in a gradient of fitness towards a state of equilibrium. In this way selection became the causal explanation of an equilibrium distribution, because it leads to statistically predictable outcomes so long as the parameters that permit recovery of the normal distribution remain invariant. Boltzmann developed a statistical mechanical analysis for molecules and like Darwin accepted the irreversibility of natural process irrespective of the final state, molecular disorder for Boltzmann, emergence of new forms for Darwin.

Fisher's reconciliation between thermodynamics and evolutionary theory reinforced the mechanistic view of the organism as passively selected by an external force (natural selection) that was meant to bring order into an otherwise chaotic world dominated by random variations. Thus, the classical view that dissociates variation and selection was justified. In opposition to the classical externalist view this approach considers evolution as a process of individuals interacting with their surroundings (including other individuals) resulting in variations that oscillate between directedness and randomness according to the thermodynamic regime and degree of structural closure that the organisms happen to be in.

An internalist approach was latent in Maxwell's thought experiment in which a demon was acting from within as a living inner observer¹. Maxwell saw a radical difference between the behavior of massive matter at the macroscopic scale, that is explained in statistical terms, and the behavior at the molecular level where small amounts of matter are considered (Heimann, 1970). He made explicit the problem of applying statistical analysis to populations (macroscopic scale), when decisions are to be made over individual entities (microscopic scale). Statistics supply a quantitative tool to describe populations against an equilibrium background that neglects individual characteristics that could be relevant in the evolutionary processes in case these individual characteristics were amplified. In contrast, from a far-from-equilibrium standpoint, free energy² plays a vital formative and creative role that explains how selection can be exerted from within. Physically describable selective processes are internal and operate at the micro scale and yield the actual forms, but when they are

¹“One of the best established facts in thermodynamics is that it is impossible in a system enclosed in an envelope which permits neither change of volume nor passage of heat, and in which both the temperature and the pressure are everywhere the same, to produce any inequality of temperature or of pressure without expenditure of work. This is the second law of thermodynamics, and it is undoubtedly true as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being, whose attributes are still as essentially finite as our own, would be able to do what is at present impossible to us. For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform, though the mean velocity of any great number of them, arbitrarily selected, is almost exactly uniform. Now let us suppose that such a vessel is divided into two portions, *A* and *B*, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes the hole, so as to allow only the swifter molecules to pass from *A* to *B*, and only the slower ones to pass from *B* to *A*. He will thus, without expenditure of work, raise the temperature of *B* and lower that of *A*, in contradiction with the second law of thermodynamics”, Maxwell 1871, quoted by Leff and Rex (1990: 4).

²Far-from-equilibrium, the lower the entropy the higher the free energy that can be used by an evolving dissipating system. Entropy defines the thermodynamic behavior of a system in terms of the relationships of three parameters, pressure (*P*), volume (*V*) and temperature (*T*) that conforms to $S = \Delta PV/T$. Then, *S* will spontaneously increase as an indication of irreversible dissipation of useful energy. According to Boltzmann this thermodynamic behavior can be explained in terms of the movement of large numbers of particles, for the movement of particles absorbs energy, thus, reducing the useful free energy in a system. At equilibrium, the system will be maximally distributed among all possible configurations or microstates. Thus, the thermodynamic behavior of the system is the macroscopic manifestation of probabilistic phenomena. Furthermore, any system of particles can be viewed as an *ensemble* existing in *phase space* and the expected thermodynamic behavior would be the occupying of increasing amounts of the phase space through time.

presented as an external activity, the individual interactions that produced the statistical shift are neglected.

Along these lines, I propose extrapolating Maxwell's approach including an inner observer in the description, as a way of overcoming the limitations of equilibrium thermodynamics for isolated systems, that I summarize as follows:

1. The influence of statistical and probabilistic approaches that requires an equilibrium state as a background assumption. This prejudice goes against the fact that far-from-equilibrium the most probable state is not the most disordered one; then, probabilistic analysis becomes useless at the time local fluctuations build up abruptly so producing a macroscopic change.

2. The influence of Shannon's information theory. According to Shannon the information content of a given structure can be measured as the number of alternative binary choices made by an external observer. Shannon's approach can be misleading when researchers confuse the number of binary choices needed to identify a system with the number of alternative choices required to produce it in an endogenous natural process.

3. The search for a universal law that offsets the second law. Natural selection was thought of as an external force that brings forth order against entropic destructive fate. In this externalist account selection is unrelated with any actual physical processes.

The major reason why the MD metaphor has not been incorporated into evolutionary thought was that it was meant to act in a thermodynamically closed compartment where its operations were physically forbidden. Brillouin (1951) pointed out that for thermodynamically closed systems, entropy reduction and work extraction by the actions of a hypothetical agent within it, are physically impossible. The rejection of MD as a heuristic model was in conformity with the lack of a physical model of open thermodynamical systems that enables one to figure out the operations of a natural intelligence, and in addition these models were victims of a prejudice against vitalistically inspired theories. MD was associated with vitalism (Césarman, 1974: 53) because it was imagined as a ghost-like entity that by its own will and intelligence manipulates matter in order to direct the flows of energy, and therefore its physical existence was discarded³. However, MD heuristics were never completely forgotten. For example Monod (1970: 53-65) and Jacob (1982: 279, 285) claimed that enzymes are material realizations of MD. Furthermore, a recent model of MD proposed by Zurek (1989a,b, 1990), yet to be developed, shows that for open far-from-equilibrium systems the demons' activities in the form of an IGUS do not violate the second law. In this paper I show how an internalist view that includes selection as a truly internal and constitutive force could be incorporated into evolutionary thought providing an account of evolutionary variations.

³“He is an intelligent being endowed with free-will and fine enough tactile and perceptive organization to give him the faculty of observing and influencing individual molecules of matter. ... He is a being with no preternatural qualities and differs from living animals only in extreme smallness and agility.... He cannot create or annul energy; but just as a living animal does, he can store up limited quantities of energy, and reproduce them at will”, Thompson (1879).

2. ZUREK'S IGUS AS A MODEL OF NATURAL INNER OBSERVER

An inner observer is defined as any kind of physical entity that is interested in extractable work. Due to the externalist outlook that associates observation with the elaboration of objective descriptions, the inner activity of a natural system cannot be easily seen as an act of observation from within. To observe from within is not to stand apart from an object but conversely, it means to extract work, to participate, to interact, to contact and to facilitate the flow of energy⁴. In order to expel any discomfort that the notion of cognition may suggest, I propose that cognition, as a property of a material system that behaves as an IGUS, must be error prone, finite, partial and uncompleted, but good enough to preserve the performance and identity of the evolving system.

An IGUS was originally conceived as a computing machine that can extract work taking into account the balance of entropy production as a result of data processing. In order to estimate the amount of free energy that can be converted into useful work, Zurek defined "physical entropy" (S). Thus, a MD can be imagined as a self-referential "information gathering and using system" (IGUS) that probes its surroundings by performing a series of measurements and processing the results in order to optimize the amount of useful work. As the number of measurements proceeds, its uncertainty about the environment decreases and the gained information increases the size of the digital record (see Figure 1).

Zurek's physical entropy (S) is equal by definition to the sum of two independent quantities: Missing information (H)⁵ plus Chaitin's algorithmic complexity (K) of the string that records the known data. Therefore, for any state of the system $S = H + K$. It is

⁴The puzzle about where to draw a dividing line between what is subjective and objective is illustrated by the inner observer metaphor. This internalist perspective emerges against two extreme positions, the exclusive human external and objective observer and the complete absence of any differentiated observer. The heuristics of an inner observer helps to understand the inseparability of subjective and objective reality, because it asserts the existence of organizing "centers" as seats of sensitivity that act as participants (subjective reality) in a permanent coevolutionary unfolding with their environment (objective reality). Then, the inner observer shapes its environment while it is being imprinted by it.

⁵Missing information or ignorance remnant in the observer is measured as Shannon's information or entropy (H). It is defined as the observer's uncertainty relative to the number of possible messages that can be emitted by a given source. It is a statistical, probabilistic notion that is always referred to as the total number of elements of a set, or collection of microstates that are compatible with a macro state, it is given by $H = \log_2 P$ for P events with equal probability and $H = -\sum p_k \log_2 p_k$ for k elements with different probability and equal to p_k . $H_d = -\sum p_{k/d} \log_2 p_{k/d}$, stands for the information about actual microstates that are still missing, in spite of the availability of data (d). Let $p_{k/d}$ stand for the conditional probability of the state s_k given d . Measurements change the conditional probability $p_{k/d}$ of the microstates; and as a result H_d decreases.

assumed that an IGUS acts as the converting agent of missing information into known randomness (K) of the record⁶.

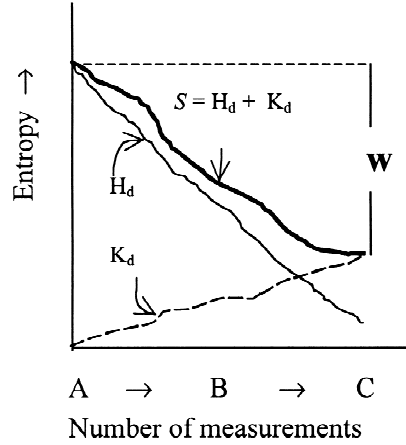


Figure 1. Zurek's physical entropy $S = H + K$ variations against the number of measurements performed by an IGUS in a far-from-equilibrium environment. The bold curve represents the variation of S . The faint curve represents variations of H with the number of measurements. The dotted curve represents the variation of K with the number of measurements. W stands for the amount of work that can be extracted by the IGUS. From left to right A , B and C stand for one cycle of an evolutionary process. Stage A: Early evolution/ openness/directed variations/ prevalence of H . Stage B: Intermediate stage of evolution/partial closure/ maximum conversion from H to K . Stage C: Stabilizing evolution/closure/random variations/dominance of K .

Measurement decreases the ignorance about surroundings, but increments the size (algorithmic randomness) of the record that encodes the obtained information. The model explains how the amount of energy that can be used by the IGUS is dependent on the algorithmic complexity of the record, since the more compressed the record (the lower K), the higher the amount of work (W) that can be extracted. The difference between ΔH and ΔK determines the net gain of work. Far-from-equilibrium, ΔH is greater than ΔK , and a quantity of net work can be extracted, by contrast in equilibrium ΔH would be equal to ΔK and no net work can be extracted. The net work (ΔW) obtained at temperature T by the IGUS is determined by the sum: $\Delta W = \Delta W^+ + \Delta W^-$. Where ΔW^+ is the work gained due to the change of H , given by $\Delta W^+ = T(H_f - H_i)$. ΔW^- is the cost of the observer's memory updating that replaces the outdated record r_i about the initial state, with the record r_f that describes its knowledge about the final state, given by $\Delta W^- = T(K_f - K_i) = T([r_f^*] - [r_i^*])$.

⁶Minimal programs are the smallest programs capable of generating a particular series in the output tape of computer C ; the size of these programs are measured in bits and its value correspond to the algorithmic randomness or algorithmic complexity of the series (Chaitin, 1975). In accordance with this, Zurek (1990) defined algorithmic information content (the algorithmic randomness or algorithmic complexity) of a binary sequence s , as the size of the minimal program S^*_u , which computes sequence s on the universal computer U ; $K_{u(s)} \equiv [S^*_u]$. The introduction of universal computer reduces, but does not eliminate, the thermodynamic importance of subjectivity. The size of the minimal program in bits is denoted by $[r^*]$.

Zurek (1989a,b) showed that $\Delta W^- = K_{iff} = r_{iff}^* = [r_i^*] - [r_j^*]$. Let r_{iff}^* be the size of the minimal program that computes r_i given r_j^* . Energy extraction becomes possible only through compression of the record (r) that is dependent on efficient encoding, or the IGUS' ability to comprehend its experienced world in term of regularities. But the maximal efficiency in energy extraction can only be attained by the IGUS when r_{iff} is the minimal program r_{iff}^* , that can only be accomplished when n , the finite number of steps used to find r^* , tends to ∞ in conformity with the halting theorem of computation. To conclude, the conditions that permit the measuring and recording operations of an IGUS are according to Zurek: 1. Openness. 2. Far-from-equilibrium. 3. Memory. Zurek (1989b, 1990) asserts that the second law cannot be violated because the missing information sets the limits for the extraction of work.

3. EXTRAPOLATING THE IGUS MODEL FROM THERMODYNAMICS TO EVOLUTIONARY THEORY

Zurek, (1989a,b, 1990) argued that IGUS is an adequate model of Complex Adaptive Systems (CAS). In this paper I stress the idea of organisms as IGUS. Nonetheless, a number of authors have proposed that molecular systems such as enzymes can also be understood as MD (Pattee, 1993; Otsuka and Nuzawa, 1998). In the same vein evolutionary ecologists have endeavored to situate natural selection within a broader context provided by the thermodynamics of self-organizing systems where the ecological energy flow plays a paradigmatic role (Johnson, 1992). Ecological systems might prove to behave like IGUS so long as they are shown to internalize the relevant information for processing energy and matter. Adami *et al.* (2000) accept that evolution can be explained as random measurements on the environment, executed by MD that according to him are not real agents. This situation, that would take place in thermodynamic equilibrium, forbids the very actions of the IGUS and if possible would not pay in terms of energy extraction. Consequently, Adami *et al.* (2000) recur to classical Darwinian selection that operates as a filter allowing only informative measurements (those increasing the ability for an organism to survive) to be preserved. But, this argument does not explain how the IGUS can operate and manage to internalize relevant information from their environment. Conversely, this paper shows that in a far-from-equilibrium regime IGUS measurements are oriented towards the extraction of energy and are canalized by previously recorded outcomes. The only way by which organisms increase their ability to survive is by improving their ability to choose, to measure, to selectively record and update information from the environment. Moreover, I assert that the understanding of living entities as IGUS can become a promising working hypothesis only if the following requisites are taken into consideration:

IGUS possess inner structure

IGUS must have an inner structure and exhibit a number of microstates that can shift from one state to another as a consequence of the interactions established with some external motifs. This organization confers to the IGUS a minimal formal system, a set of syntactic rules that govern interactions and manipulation of external referents and rearrangement of inner structural components, which can eventually be used as measuring devices and compressing algorithms.

IGUS actions are irreversible

Although work extraction by an IGUS would be maximized in reversible processes, this is an ideal situation that does not take place in open far-from-equilibrium systems. Bennett (1984) discussed that in the operation of a MD, the irreversible step is the erasure of the record of one measurement in order to make room for the next. Assuming a Turing Machine represents the IGUS, the second law is not violated for the clearing of the recording tape⁷ corresponds to the entropy increase that pays for its actions. This argument derives from Szilard's machine thought experiment that permits estimation of the amount of work that can be extracted by a MD from 1 bit of information. Szilard imagined a compartment flanked by two pistons containing a single particle with a movable curtain that helps to determine which half of the chamber is occupied. Once the curtain falls, the record that shows which half is occupied lights up. As work is extracted in the form of expansion the record is necessarily erased (Zurek, 1984). For organisms the clearing of recorded information in DNA would reset evolution at every instant making inapplicable this analogy. However, if we consider organisms as open systems the increases of entropy will mostly dissipate outwards leaving only a minimal part to affect the existing record. Notice that point mutations are originated as minimal erasures of the record, and other forms of variations as more or less extensive erasures.

The creation of records always evaluates the restrictions imposed by both the surroundings and the inner structure

Measurement is a source of internal entropy ΔS_i that manifests in the form of new records that increase organism/environment mutual information. MD gathers information about a limited number of microstates from the environment, good enough to act in that very same environment. The dissipation of entropy in open systems but under severe restrictions is the very source of the recording process. If there were no external restrictions acting on the system, neither interactions nor inner restrictions, entropy would dissipate into the environment keeping K at zero value. That is the reason why K becomes a suitable measure of the system's closure.

Gathered information has a cost that is paid for with entropy dissipation

IGUS performs measurements and establishes non-random interactions with other entities (including other IGUS), which are paid for with increments in entropy in the form of random perturbations. Maxwell felt that statistical methods applied only to sensible aggregates of molecules (populations), not to individual molecules that were immutable. He stated that,

“when we pass from the contemplation of our experiments to that of molecules themselves, we leave the world of chance and change, and enter a region where everything is certain and immutable”. (Heimann, 1970).

In fact the opposite is true, Maxwell overlooked the ensuing randomness and indetermination associated with the observation at the molecular level. Any kind of entity that behaves as a MD disturbs the molecular distributions while trying to

⁷The recording tape corresponds to input data that became available as a result of previous measurement operations.

measure and to distinguish them. Moreover, Matsuno (1992) stated that inner measurement could be a source of perturbation when he discussed Heisenberg's indeterminacy principle (HIP)⁸ at the subatomic level. Consequently, the mechanical approach or the computing of position and momentum for every particle once imagined⁹ by Maxwell as being more desirable than the statistical approach was bound to fail.

It is asserted here that inner measurement is based on analog¹⁰ recognition accomplished by entities that belong to the same level of organization. Therefore, a molecular IGUS would let the position and momentum of many particles pass undetected, since its discriminating capacity must be finite. In an open system, only a minor part of dissipated entropy remains bound in the form of a compressed record and most of it, is transmitted elsewhere in the form of random perturbations that can be partially resolved in future transactions between the living system and the environment. It is tempting to generalize the previous argument to other levels of organization, for example Van Valen (1973) suggested that ecological adaptation of one species creates a perturbation in the environment that may result in a challenge for previously adapted species. As explained below, this environmental perturbation will increase H values and consequently decrease organism-environment mutual information content. However, this fact will provoke and induce the IGUS to continue its measurement and recording operations.

IGUS minimizes observed increments of entropy

IGUS as a self-organizing entity does not create a zone with a local decrease of entropy; rather its operations guarantee the lowest possible increments of entropy or H_{obs} as shown by Brooks and Wiley (1986: 40-47). It is shown in Figure 1, that in a non-equilibrium setting an IGUS can extract work (W). The lower K , the greater W , then K follows a tendency of ever-smaller increments driven by IGUS' aim to maximize the extraction of W . Likewise, Figure 2 shows the entropy increases over time from the standpoint of an observer placed in a far-from-equilibrium expanding system. In this particular instance the increases of entropy expressed as algorithmic

⁸Some may feel that it is against standard biological thought to try to base arguments on HIP. Notwithstanding, it is a weak foundation for biology to employ chance arguments as *a priori* explanations that are beyond scientific understanding. HIP would only be one possible way of providing foundations to chance based arguments.

⁹Though Maxwell shares with Boltzmann and Gibbs the authorship of the mechanical statistical approach to thermodynamics, according to Heimann (1970), he believed that a mechanical approach would provide a more truthful, predictable and reliable description.

¹⁰Analog is defined as "direct pattern recognition" of external motifs by some structural motifs of the IGUS. Analog refers to the fact that this recognition is made either by structural complementarity or by similarity and thus, it permits the establishment of non-random interactions (Root-Berstein and Dillon, 1997). Analog information preserves the coherence of the living entity as it interacts with the environment.

complexity of the record (K) (Figure 1), agree with the curve of H_{obs} ¹¹ (Figure 2), for both behave as minimized increases of entropy. Consequently, organization expressed as the difference ($H_{max} - H_{obs}$) always increases as a result of IGUS actions that are responsible for the minimization of observed increments of entropy H_{obs} . As noticed, H_{max} would correspond to the maximum size of the record K_{max} , if the IGUS were permitted to operate at equilibrium.

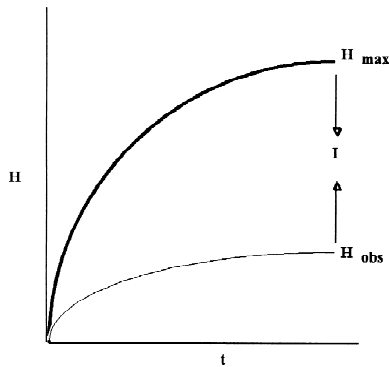


Figure 2. The increase of entropy over time for a physical information system under Brooks and Wiley theory (Brooks and Wiley, 1986). From the perspective of an inner observer (IGUS), the observed increases in entropy (H_{obs}) always lag behind maximum attainable entropy (H_{max}), or the entropy when all constitutive components are randomized. The difference ($H_{max} - H_{obs}$) is a measure of information (I) and always increases as a result of the IGUS actions that are responsible for minimization of observed increments of entropy H_{obs} in a far-from-equilibrium expanding system.

IGUS define an evolutionary pathway

It is possible to trace an IGUS trajectory, from an initial state where Shannon's information prevails ($H = 1, K = 0$) to a final state where digital information prevails (H tends to zero, and K tends to M) as a series of measurements are executed. The values of H from the IGUS viewpoint are a measure of the likelihood that a particular analog recognition among the possible choices offered to the IGUS will be made. The value M stands for the maximum size of the record at a hypothetical point where uncertainty has been reduced enough to facilitate further activity. It is, thus, a model that can be used to describe interactions in terms of reduction of IGUS' uncertainty about the environment and recording of some known microstates.

IGUS convert analog into digital information

The application of Zurek's hybrid entropy to living systems assumes that:

- a) H becomes a measurement of structural openness defined as the likelihood that a new interaction can be established by an observer system (IGUS). In this way, the higher H the higher the structural openness of the IGUS, so that H is an estimate of the degree of IGUS' dependence on the circumstances;
- b) K becomes a measure of structural closure or internalized information, in other words the degree of dependence on the digital (genetic) record.

¹¹ H_{obs} stands for observed entropy or the number of microstates actually present in a defined microstate. H_{max} stands for the maximum attainable entropy of the system or the value obtained in the case where all the components were randomized.

I suggest that as ecological interactions become more predictable, encoded genetic information increases in an evolutionary time-scale. Ecological and genealogical instances are manifestations of the analog-digital code duality (Hoffmeyer and Emmeche, 1991). Ecological interactions, as a movement that goes from the external to the internal realm, take place at an individual (ontogenic) lifetime scale, while recorded information as a movement from the internal to the external manifest themselves in the population at a genealogical time scale. The former is equated with IGUS actions that lead to decreases of H , whereas the latter manifest themselves in the genetic record shared by the population. These movements, as long as they are referred to the IGUS, are precisely what the internalist approach aims to emphasize.

4. IGUS ACTIONS CANNOT BE WHOLLY FORMALIZED

Living beings are material systems that feel and experience their world and have the propensity to interact in response to their subjective aims. This activity can be approached in part as a measuring and recording process. An IGUS expresses the relation between itself and a partially describable external environment in the form of a process that converts H into K . IGUS' subjective aims are not formalizable for they constitute the very source of creative and unpredictable interactions with external referents. Feeling, experience and the capacity to interact have a broader scope than measurement and are *a priori* conditions for it. Nonetheless, to represent interactions as measurements help to formalize what can be, and at the same time, to shed light on the problem of how coding is achieved. Measurements are IGUS' responses to the concrete and immediate challenge of external circumstances and create the possibility of unpredictable functional interactions.

Formalization is understood as the reduction of a phenomenon to a set of syntactic rules by the elimination of self-referents. The conversion of H into K is the core of Zurek's (1989b) proposal and its formalization was discussed for a Boltzmann gas or idealized ensembles of particles modeled in a Turing machine capable of reversible computation. In this case, the conversion of H into K is possible with the precaution that for a small number of microstates, a correction factor related to the length of the program that describes the computer that executes the measurement and recording operation must be added. K (length of the program) stands for objective data, and its value depends on the amount of gathered data and also on the processing and discriminating capacity of the computer. This dependence on the computer capacity shows the self-referentiality of the IGUS. This self-referentiality is more evident when living entities are seen as IGUS, so posing the problem of the formalization of the conversion of H into K . The creation of a new record K proceeds by partial internalization of external referents and reorganization of previous existing records, in accordance with the interactions established with the surroundings. There will always be a number of undefined motifs that can be potentially recorded by the IGUS, and which one is to be incorporated into the digital record cannot be predicted beforehand.

The passage from H to K is contextual and concerns the IGUS (Andrade, 1999, 2000), as a self-referential agent. In addition, IGUS represent a principle of coordination, since the measuring and recording operations cannot continue forever for a decision has to be made about where to stop measurement and recording. The following IGUS actions are necessarily self-referential and therefore unformalizable:

1. The choice of measuring standards. Which structural device is to be used in order to single out external motifs?
2. The extension of measuring, or how far does measurement have to go?
3. In what way does the IGUS condense the internal record?
4. The decision about measurement completion or pragmatic sufficiency of gathered information. When is enough to stop?
5. The interpretation of the records or how are the ensuing actions defined?

5. THE ORIGIN OF EVOLUTIONARY VARIATIONS

In the following discussion, it is assumed that organisms behave like IGUS¹². I shall argue that this approach contributes to merging two seemingly opposite options: 1. Lamarckian: variations of the inner structure are directed to external circumstances (non-random); 2. Darwinian: variations of the inner structure are random and prior to selection by the environment.

Phenotypes as analog information systems can exhibit some adjustments or accommodations in the presence of external stimuli, so to speak that subtle changes of *form* can be understood as analog encoding which can be further used as a condition for digital encoding. The best example of incorporation of external information from the environment by a natural system is *genetic assimilation*. Waddington (1976: 30-34) defined genetic assimilation as the phenomenon by which mutations become fixed in the genome in the context of variation that has already taken place in the presence of external stimuli, so that they will develop the phenotypic feature before the stimulation, in complete absence of the stimuli. In my interpretation, this phenomenon entails that selection has been performed from within by an IGUS that participates in the formation of the adaptations, which are accomplished.

In my view analog information also has an internal component that corresponds to what Maynard Smith (1990) has defined as Epigenetic Inheritance Systems (EIS) that are responsible for the stable transmission of functional states of genes and cell structures. Jablonka *et al.* (1992) identified several EIS that transmit phenotypic stable differences between cells with identical DNA through many cell divisions. According to Jablonka and Lamb (1998), EIS can be influenced by the environment and produce a directed, rapid and reversible adaptive response. In this context, the dichotomy between innate and acquired characteristics proves to be inadequate at phylogenetic

¹²An IGUS is treated as a basic evolving and developing entity; this approach provides an alternative ontology to classical gene reductionism, and offers a frame of interpretation for Developmental Systems Theory (DST). Developmental Systems (DS) can be interpreted as IGUS. A DS is defined as a “mobile set of interacting influences and entities” comprising “all influences on development” at all levels (Oyama, 2000: 72), and involves a whole matrix of resources and interactions that permit reconstruction of the ontogenetic and developmental information in each generation (Griffiths and Gray, 1997). Likewise, my model proposes that the fundamental unit of evolution is neither the individual gene nor the phenotype, but the interacting entity or IGUS that by measuring and recording is responsible for the renewal and updating of the ontogenetic information in each life cycle.

scale, because any phenotypic feature results from an interaction between genetic and environmental factors.

The heredity of adaptations is explained in a more general way by Peirce's notion of *habit*. *Habit* is the higher probability to repeat in the future something that has taken place in the past, or the higher probability to respond in the future, in the same way, as it did in the past in the presence of certain stimuli, (Peirce, CP 1.409). When the stimulus is removed and no longer present, the *habit* tends to affirm itself, thence whenever uniformity increases, *habit* is at work. (Peirce, CP 1.415, 1.416). While *habit* and consciousness¹³ were traditionally considered as themes that could be applied exclusively to describe the working of the mind, nowadays they can be part of the physical explanation. The reconciliation of the working of the mind with the laws of matter is best exemplified in the IGUS metaphor.

All variations become fixed tending in the direction traced by *habit*; IGUS' cognitive activity explains the readiness to retain those *habits* that ratify that direction (functional adaptation) and the side-by-side production of random nor adverse perturbations. The set of equally adaptive variations constitutes the neutral variants. Paradoxically, while evolution tends to go in the direction ratified by *habit*, in fact departs from it. Far-from-equilibrium $\Delta S_e > \Delta S_i$ ¹⁴. While ΔS_e materializes in the form of external random perturbations, ΔS_i affects the inner structure in the form of both neutral and adaptive mutations. The direction ratified by *habit* is directed to the external stimuli and may be considered as an adaptive move; however, since it can only be produced by increasing entropy it constitutes only a minor component of internally dissipated entropy. Therefore, most of ΔS_i must be understood as neutral variations.

The fact that organisms strive to cope with some features of their environment can be expressed as a tendency to increase mutual information content between the organism and the environment $K_{(organism:environment)}$. Adami *et al.* (2000) affirm that an organism's DNA is not only a "book" about the organisms, but it is also a book about the environment it lives in, including the species it co-evolves with. This tendency does not mean that DNA encoding occurs at the level of the individuals exclusively, although it does suggest that individuals make a long-term contribution to the evolutionary process. I add that Waddington's genetic assimilation is nothing more than DNA encoding and selection made by organisms' habitual choices. Analog encoding is equated with reciprocal adjustments that occur in the presence of external

¹³One can understand consciousness as an analog pattern recognition embedded in a feedback loop: stimuli, adjustment, selection, recording, variation, and new stimuli. Consciousness is not exclusive to humans but to any material system that possesses the capacity to create and to internalize a partial record of its environment.

¹⁴According to Prigogine *et al.* (1972), dissipative structures are open thermodynamic systems for which there is a distinction between the inside and the outside. The behavior of such systems can be expressed in terms of entropy changes (ΔS) that are decomposed into two terms, one measuring exchanges between the system and its surroundings (ΔS_e), and the other measuring production by irreversible processes operating in the system (ΔS_i). These systems are thermodynamically allowed so long as the internal component (ΔS_i) is positive or zero, and $\Delta S = \Delta S_e + \Delta S_i > 0$.

stimuli. Since the structural modifications or alternative shapes that can be adopted depend on energy stability landscapes, it is conceivable that similar individuals under the same stimuli tend to react in a similar way and diverge from this tendency attaining alternative thermodynamically stable configurations. Although this phase of adjustment may still be reversible, it is a necessary condition for selection among genomic variants. The selection of mutations that produce the same modification, as the one induced by the stimuli are favored, and in this manner digital encoding becomes irreversible. As Bateson pointed out, Lamarck's mistake was of a logical type amounting to a confusion between individual and population levels (Bateson, 1980: 195-206) that in my view leads to the confusion between analog and digital information.

Lamarckian evolution would be characteristic of systems in their very early stages of evolution, though the evolution of organisms (with highly differentiated somatic tissues) could be put at risk if evolution operated by incorporating characters that are not tested at the population level. Evolution is aimed at stabilizing the digital records since the most primordial levels, for example at prebiotic levels, the passage from RNA to DNA encoding was driven by the tendency to prevent the erasure of the record by obtaining a more chemically stable format since RNA breaks down as it is being used. DNA encoding created a protection in order to prevent extensive breakdown by protein interactions. Furthermore, the evolution of the Weissmann barrier¹⁵ favored the closure of the genetic system and the slowdown of the evolutionary process. The existence of Weissmann's barrier, like the second law of thermodynamics, is reminiscent of the basic irreversibility of living processes. However, neither the existence of Weissmann's barrier nor the second law preclude the action of feedback loops. For example protein synthesis and folding are entropic irreversible processes that have influenced protein evolution and the evolution of the genetic code (Di Giulio, 1998). We have therefore that IGUS account for a circuit of close causality that unfolds like a spiral: Random variation (1) → [Measurement as interaction and recording] + [Cost of measurement = perturbation] → Selection (1) → Canalized variation (2).

To restate the above in terms of Aristotelian causality, it can be asserted that *material* and *formal causes* are represented by IGUS material organization. *Final cause* can be explained as the tendency to optimize energy extraction and reduce energy gradients by compressing the records¹⁶. *Efficient cause* builds up dissipation by entropy that favors the creation of new energy gradients that can be subsequently used up by the IGUS. Therefore, to close the circle *final cause* becomes the lasting begetter of *Efficient cause*.

¹⁵According to Weissmann there is a separation between germinal and somatic cells that prevents the hereditary transmission of acquired characters. This barrier is given by the early segregation of germ line and applies mostly to insects and vertebrates and is not a general condition (Buss, 1987: 1-25).

¹⁶My proposal is to emphasize IGUS's inner goals as the real *final cause* that inevitably lead to the fulfillment of the second law of thermodynamics and assures the permanent renewal of the *efficient cause*.

6. ARE EVOLUTIONARY VARIATIONS DIRECTED OR RANDOM?

The controversy between Lamarckian and Darwinian views of evolution was bequeathed to us, in the form of the directed or random mutation debate. Lamarckians proposed that variations in evolution had to do with the nature of the conditions (external circumstances), whereas Darwinians' emphasis was placed on the nature of the organisms themselves. The Lamarckian perspective was unequivocally associated with the idea of organisms being real agents that strive to cope with external challenges moved by an inner drive or *besoin*. By contrast for Darwinians organisms are not agents, but passive entities whose fate is determined by external forces that counter their propensity to vary at random and to overproduce offspring.

IGUS dissipate entropy and pay for their actions by entropy dissipated into the environment. This is one of the reasons why the environment is not static and also evolves. Not surprisingly variability will tend to be observed in the regions where it was more needed, just lagging behind the present time. Records are necessarily outdated, but they point out and disperse away from past records that registered the direction the process was, going through then. Following the same reasoning in a stable environment records cannot be too far outdated. Organisms try to cope with the environment by incorporating information from it, but this very process induces more environmental variability that results in outdated records. This can be seen as selection inducing canalized variations.

In order to clarify the issue of directed mutations, I quote Darwin:

“I have hitherto sometimes spoken as if variations -so common and multiform with organic beings under domestication, and in a lesser degree with those under nature- were due to chance. This, of course, is a wholly incorrect expression, but it serves to acknowledge plainly our ignorance of the cause of each particular variation. ... But the fact of variations and monstrosities occurring much more frequently under domestication than under nature, and the greater variability of species having wider ranges than of those with restricted ranges, lead to the conclusion that variability is generally related to the conditions of life to which each species has been exposed during several successive generations”. ... “... changed conditions act in two ways, directly on the whole organization or on certain parts alone, and indirectly through the reproductive system. In all cases there are two factors, the nature of the organism, which is the most important of the two, and the nature of the conditions. The direct action of changed conditions leads to definite or indefinite results. In the latter case the organization seems to become plastic, and we have much fluctuating variability. In the former case the nature of the organism is such that it yields readily, when subjected to certain conditions, and all, or nearly all the individuals become modified in the same way. ... “On the other hand innumerable instances are known of species keeping true although living under the most opposite climates. Such considerations incline me to lay less weight on the direct action of the surrounding conditions than on a tendency to vary, due to causes of which we are quite ignorant”, (Darwin, 1872: Chap. V. Underlining is mine in order to call attention to the points being discussed.)

Attempts to explain the causes of variation by the incorporation of thermodynamics, molecular and developmental biology are more within our reach today than in Darwin's time. Darwin believed that variations occur more frequently under domestication than under nature because the changed conditions of artificial selection induced variability that might be in the breeder's interests. According to Jablonka and Lamb (1995: 230-233) domestication induces extensive variability because the imposed conditions induce a severe ecological and behavioral stress. Artificial selection induces the production of new assortments of previously existing alleles, increasing mutation rates, and events of genome reorganization (McClintock, 1984). Likewise, studies in bacteria and unicellular eukaryotes have shown that some genetic changes may not be random, and that in some stressful situations the mutations that occur are adaptive to the environment inducing them (Sniegowski and Lenski, 1995). There is an increasing amount of experimental evidence that can be accounted in favor of the view that stress speeds up variation within an adequate range oriented to specific regions. These are the types of changes that are usually termed as directed. For example, DNA mutases (Taddei *et al.*, 1997; Tang *et al.*, 2000; Johnson *et al.*, 2000), provoke mutations in the regions where variability is needed in order to cope with environmental changes. Radman (1999) suggests that mutases are targeted to genes under selective pressure. For example contingency genes in protozoa code for surface antigens recognized by the host immune system, some of these antigens contain simple repeated sequences (microsatellites), which are preferential sites for polymerase "slippage mistakes" that confer to the contingency genes higher mutation rates than surrounding sequences. In this manner, parasites can keep one step ahead of the immune system. DNA pol. IV mainly produces slippage mutations, thence selection favors a more or less narrow spectrum of variability directed to specific targets.

Changed conditions accelerate evolution because they widen the range of hereditary variations on which selection can act. For Darwin the observed increase in variability was induced by artificial directed selection, at that time he was near to anticipating the closing of the loop: variation → selection → new variation. Darwin's theoretical development started with the suggestion that variations are the product of changed conditions like artificial selection, and later concluded that variations are random with respect to the needs of the organism experiencing them. His first position was influenced by the breeders' experience regarding mixing inheritance, so that in order to prevent loss of the selected characters the same type of variation had to be produced anew oriented to the same challenging conditions. His second position has to do with the prevalence of Malthusian thinking and his commitment to an individualist Newtonian ontology (Depew and Weber, 1995: Ch. 5).

The problem boils down to two opposite standpoints: Lamarckism stresses the directionality of the process given by the tendency of similar individuals to cope with the surrounding conditions in like manner, while Darwinism stresses the dispersion away from this tendency as observed in the population. My point is that the uniqueness of every individual experience is always preserved. Moreover, these two incompatible views may be complementary, if random variations were comprehended, as side effects ensuing from the tendency of similar individuals to cope in a regular manner (not identical because of the unique character of individual experience) with the same stressful stimuli they are exposed to. Therefore, a stressful challenge brings

forth a set of diverse responses, and the dispersion of responses can be so broad that the outcome becomes unrelated to the challenging situation (conditions of life). However, the fact that variations are produced under stress does not undermine the argument of individuals' agency. Despite all the claims of Darwinists, there is an inner tendency to cope with some motifs of the environment with the purpose of extracting work, but the result is not a deliberate adaptation but an unforeseen variation within a permissible range. Ironically as it may sound, Darwin proved to be right for the wrong reasons, while Lamarck proved to be wrong for the right reasons! The point is that there might be degrees of dispersion depending upon the strength of external restrictions and on the degree of structural closure. Furthermore, the IGUS model explains why the uniqueness of individual experience becomes one of the relevant factors that bring novelty into the evolutionary processes. Every individual experiences (measures and records) the world in his own way, leading to divergent records at the population level that characterize the newly emerging lineage.

7. NON-EQUILIBRIUM DIRECTED VERSUS EQUILIBRIUM RANDOM EVOLUTIONARY VARIATIONS

IGUS are material systems that convert analog into digital information while they extract available energy. This model eliminates vitalistic approaches to organisms though it emphasizes the idea of their agency and cognitive activity in opposition to previous models that considered MD as an ideal entity that did not have a material embodiment, and could not participate in any physical process of dissipation. Depending upon the degree of closure the prevalence of either analog or digital information manifests itself in a more noticeable way. Let us consider the curve of physical entropy vs. measurements as proposed by Zurek (1989b, 1990), from left to right: A: Early evolution, B: Midway stage, and C: Stabilizing evolution (See Figure 1). I postulate that evolutionary variations are initially provoked or induced by the environment (left side), and as measurement proceeds, they become neutral and random due to an ever-increasing influence of the nature of the organisms (right side). Let us imagine two extreme idealized situations (cases A and C).

Case A: Early evolution/Far-from-equilibrium/directed variations/prevalence of H.

Living systems shift from one stationary state to another when surrounding conditions change abruptly. If this opening up to the new environment were highly intensive, then uncertainty about the new environment increases and organisms will show a propensity to cope with the new situation. Non-equilibrium is expressed as a tension between IGUS and surroundings due to the lack of congruence between inner and external motifs. Yet, this state represents the potential to establish couplings and corresponds to the highest H value in Zurek's equation where the maximum number of potential choices is presented to the newly evolving system. This uncertainty corresponds to a low mutual information content between organisms and environment, a situation that renders the organisms more dependent on the circumstances. In consequence, a fraction of all possible interactions will tend to be effectively realized leaving a narrow span for neutral variants (minimal dispersion); in other words effective adaptive variations would take place, thus enabling the establishment of interactions with new external referents. During the transition from far-from-

equilibrium towards a new stationary state, some neutral variants become the source of adaptations or new interactions with external referents. From this stage of openness that triggers an evolutionary process, one expects a phase of decreasing potentiality towards specialization, as some couplings are established. H expresses the potential for analog-analog interactions, and it decreases because the more couplings that are established the less the amount of new couplings that can possibly be established. On the left side of Figure 1, one has an evolving IGUS that feels equally attracted by every external object, yet it does not establish differences since all potential couplings are equally likely and remain potential. Measurement comes when distinctions are made forced by the need to match some condition and leaving other choices behind. This reversible coupling happens first as a modification of the analog record induced by the presence of the selected object, but these interactions can lead to an irreversible change when the observer's inner structure is modified in the digital record after some internal processes have been reoriented. Applying Zurek's entropy function at this stage, H must very be high, and K very low. As the process goes on, H will diminish as K increases. When K is still low, the evolution of this system is more dependent upon the nature of the conditions (or the possibility of new interactions) due to its high degree of structural openness.

Case C: Stabilizing evolution/Equilibrium/random variations/ the dominance of K .

Organisms attain structural closure when their own structure and dynamics determine their changes and not what happens in the environment. This situation occurs because the coupling between organisms and environment is stabilized by organisms' internalization of environmental referents. A structurally closed system can be described as being in a near-to-equilibrium or stationary state in which no new interactions with external referents can be established. The inner constitution carries the encoded version of some external referents that enable the IGUS to stabilize in a constant environment, and corresponds to the maximum value of analog and digital shared information content $K_{(analog:digital)}$, or $K_{(organism:environment)}$. Structural closure makes the IGUS more dependent on internalized information and less susceptible to interacting with new external referents.

For stationary states, entropy dissipation to the outside tends to a minimum while internally dissipated entropy reaches its maximum, consequently all random variants would obey the restrictions imposed by the inner structure. However, as stabilization proceeds the dissipation of entropy towards the outside is minimized, and IGUS can only undergo internal increments that manifest themselves in terms of increasing redundancy and cumulative random variations (neutral mutations). Shannon's information (H) has reached a minimum value for the IGUS, and the corresponding ever-smaller increases of K render the system dependent on their own informational load that makes further exchanges of energy with the environment difficult and threatens to degrade the inner structure. At this final stage, genetic mutations are random (unrelated to the surrounding conditions) and depend mostly on the nature of the organism that has become more determinable. This is equivalent to a thermodynamic stationary near-to-equilibrium state, in which all microstates (genetic variations) compatible with the macrostate (phenotype) proliferate. Thence, the distribution of microstates would tend towards the highest dispersion and could be made equivalent to neutral variants in the sense that they do not affect any interactions

with external referents. Structural closure is propitiated when the external environment remains constant, according to Kimura (1983: 104-113) environmental stability favors proliferation of neutral variants. In this stationary state mutual information content between organisms and environment attains maximum value and this phenomenon closes the organisms to the surrounding conditions because the uncertainty about the environment has decreased from the viewpoint of the organisms. The equilibrium end point is attained when the structure of the IGUS decays by destroying the boundaries between inside and outside and returning its material components to the environment, thus giving up the autonomy of the organism.

8. INTERMEDIATE STAGE OF EVOLUTION/TRANSITION FROM FAR-FROM-EQUILIBRIUM TO EQUILIBRIUM/THE CONVERSION FROM H TO K

In real situations, organisms are usually found somewhere between the two cases described above. Real organisms present varying degrees of thermodynamic openness and structural closure, and during their development and evolution¹⁷ they transit from structural openness to closure. This partial closure permits them to regulate their autonomy with regard to the environment. At this stage of evolution IGUS are both open and autonomous, so that the flows from the environment to the organisms, and from the organisms to the environment start to be influenced by what is inside them. This control of inflows and outflows through their own internal states renders them relatively independent of the surroundings; while they close themselves to certain environmental influences, they necessarily open up to others.

As a general rule, one may affirm that their relative openness is proportional to the value of H , since it is a measure of the potential choices presented to the IGUS, and whenever it happens to be in a rapidly changing environment this value tends to increase. On the other hand structural closure exhibits a reverse proportionality to K , since the more information that has been internalized by the organisms in phylogenetic time, the higher their structural closure to the environment. IGUS may elicit the establishment of new couplings, and as they are being established, the structural constituents involved tend to exhibit lower degrees of redundancy. During this period the IGUS's inner constitution shows an increase in the size of the record (K), while Shannon's information has decreased since some external referents have been selected by the IGUS. This stage is poised between maximum uncertainty about the environment and inner structural determination, but nonetheless, shows a tendency to optimize IGUS efficiency in terms of extraction of work. Mutual information content $K_{(IGUS:environment)}$, or $K_{(analog:digital)}$ increases and consequently evolutionary variations reflect a compromise between the nature of the conditions and the nature of the organisms. This capacity to regulate, both the influences from the environment and the dependence on the inner structural constraint, is what constitutes the autonomy of the organisms, and this is, and may well be, the essential difference between living and non-living systems.

¹⁷This approach favors an integrative study of development and evolution as encouraged by proponents of DST like Griffiths and Oyama.

Remarkably, in case (A) living systems are ready to evolve from an initial state entirely dependent on the nature of the conditions to a final state dependent on the nature of the information internalized into the system. The final state corresponds to evolution in a stable environment, where organisms become more dependent on their genealogical history. Conversely, in case (C) systems evolve in conformity with the internalized information (nature of organism) unless sudden environmental changes occur that speed up the evolutionary process by opening them to the new circumstances. In terms of the fractions of dissipated entropy, considering that in stable environments selection pressure relaxes making room for neutral variants, one may expect lower values of entropy dissipated to the outside (ΔS_e) and entropy dissipated internally (ΔS_i) manifest as neutral changes. By contrast after abrupt environmental change, higher values of ΔS_e are expected and ΔS_i manifests as an acceleration of mutation rates that favors the production of directed variants.

9. CONCLUSION

To summarize, the problem regarding the prevalence of the nature of the organisms or the nature of the conditions of life as major factor of evolution, is not an either-or problem. What is at stake is the interplay between organisms and environments that frequently lead to unpredictable outcomes related to the manner organisms manage to regulate their closure. There cannot be a general law that states that the production of evolutionary variations is necessarily unrelated to the needs of the organism, though the final outcome takes the form of a random dispersion away from this tendency. The span of this random dispersion is related to the degree of structural closure. The extensiveness of this random dispersion increases with growing structural closure and evolution in a constant environment. The effects of the varying degrees of openness for a determinate organism are associated with the mutability of the environment, but the mutability of the environment is also influenced by the activity of the organisms, which is dependent on the inherited nature of the organism. To close the circle, organisms are victims of their genealogical history not just because potential information has been canalized (Wiley and Brooks, 1982), but also because there has been an internalization of information from the environment. As evolution has proceeded, organisms have become ever more dependent on their history, or on their internalized encoded information, and less dependent on the environment so long as there are no abrupt environmental changes. Nonetheless, their capacity to regulate these influences is preserved.

The above discussions question the mechanistic idea about the environment that has prevailed in classical evolutionary thought. In the Lamarckian tradition, the environment was seen as a source of external circumstances and contingencies that deviate organisms from the plan of nature that was to be accomplished by organism's inner tendencies (*power of life*). This view shares with the mechanistic approaches the fact that it says nothing about the nature and origin of circumstantial contingencies. Likewise, in the Darwinian tradition the environment became a set of external constraints that act as a filter that retains the fit and eliminates the unfit. The point however is to consider organisms and environment (including other organisms) as real agents (source and receivers of information). The environment does not select organisms, but conversely organisms interact with some external referents that become

their relevant or experienced environment. An internalist viewpoint would stress the initiative of the organisms (Levins and Lewontin 1985: 85-106) in their evolving context and would try to model their reciprocal unfolding. The idea of organisms' inner tendencies to cope with the external circumstances could better be comprehended as the IGUS' aim to internalize some information from the environment in order to reduce their uncertainty. This activity will produce an evolutionary record, which is given by the structure of the organisms that confers some degree of anticipation to the unpredictable mutability of the environment. The whole process becomes cyclical since the tendency to increase mutual information content $K_{(organism:environment)}$, that would improve anticipatory capacity, has a cost that is paid with dissipated entropy into the environment. But dissipated entropy decreases mutual information content $K_{(organism:environment)}$ and lowers anticipatory capacity. This is the reason why there is no need for organisms to remain completely dependent on the environment (open), nor totally independent (closed) by recording every single feature of their experienced world. Hence, it can be deduced from the IGUS model that the completeness of digital recording (or the genetic fixation of every experienced characteristic) is physically impossible. Recording can only be partial, uncompleted and outdated. In the same vein, the optimization of the conversion efficiency of H into K is a tendency that cannot be physically attained.

Considering that organisms can never cope completely with environment uncertainty, nature might have favored a process of survival in which two aspects are considered:

1. The actual information shared by organisms and environment $K_{(organism:environment)}$ must be low because the record carries information of the most stable and archaic characteristics that have evolved in environments that are already degraded. As these characteristics have been incorporated, the environment has eroded and consequently they no longer agree with each other.

2. There must be a tendency to internalize partial information that would enable the organisms to cope with the uncertainty of the new environment. This phenomenon would occur in the case the span of variability were canalized, as in the above examples on DNA mutases; the case of Waddington's genetic assimilation and Jablonka's EIS that favors such irreversible canalization.

The fact that there will always be a selection cost that is paid for in terms of dissipated entropy, explains the permanent room available in the form of unoccupied niche space that the organisms are trying to catch up with¹⁸. If this is so, at different times of an evolutionary process, changes in $K_{(organism:environment)}$ values could be observed. Constant values would mean stability of organism-environment dynamics. If final values were higher than initial values, it would correspond to a period in which recorded information has increased. If final values were lower than initial values, it would correspond to a period of decreasing organisms' recording activity, making more apparent disruptive changes as a loosening of organism-environment coherence by entropy increases.

Future research oriented to the estimation of the structural closure for particular cases that involve different organisms has to be undertaken. For instance, research

¹⁸This phenomenon explains why organisms and environment mutual information content cannot be kept high due to the disturbing effects of dissipated entropy.

must be promoted which is aimed at estimating the range of neutral (genetic) variability for organisms that undergo an adaptive process in changing conditions, and similar estimations for organisms that live in stable environments. These estimations could lead to testable predictions.

This view of evolution as if the evolving system were an IGUS, accounts for the reciprocity between the nature of the organism and the nature of the conditions. In most of the major evolutionary transitions¹⁹ (origin of life, emergence of eukaryotic cells, the Cambrian explosion, etc.), living entities were more dependent on the external conditions, but as the new structures and lineages stabilized, their fate became more dependent on the nature of the inner record or their history. In either case it was a matter of how to regulate organisms' autonomy. Darwin saw the puzzling difficulties of this discussion and after pondering several reasons he made his final choice in favor of the nature of the organisms and random variations. An approach that is supported by the model that considers organisms as IGUS, in their near-to-equilibrium state. Nonetheless, one can never forget that Darwin was only intending to account for the origin of species and left unsolved the problem of the major evolutionary transitions. There are instances, short and rare as it may, that can produce and intensive evolutionary change, it is in these few but highly decisive steps in which canalized variations may have played a prevalent role. In this particular point, Darwin was critical of himself when he wrote:

“In my opinion the greatest error which I have committed has been not allowing sufficient weight to the direct action of the environment, ... independently of natural selection”, Darwin, (1876), letter to Moritz Wagner, Oct.13, quoted by Acot (1997).

However, this last statement applies only for lineages in their very early stages of evolution, or for organisms in far-from-equilibrium evolution that manage to regulate their closure by opening themselves up to some new interactions with the environment.

ACKNOWLEDGEMENTS

I am grateful to the Universidad Nacional de Colombia (Department of Biology) for permanent support and to the anonymous reviewers for helpful suggestions.

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¹⁹In allusion to Maynard-Smith and Szathmary book title “The major transitions in Evolution”, Oxford University Press.

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