

# From external to internal measurement: a form theory approach to evolution

Eugenio Andrade \*

*Departamento de Biología, Universidad Nacional de Colombia, Santa Fe de Bogota, D.C., Colombia*

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## Abstract

The point of view of external observers has led to an explanation of life based on digitally encoded information. In contrast, the existence of natural internal observers, or agents that belong to the same scale of the observed objects, explains the appearance of *form* centered approaches. The main controversies in thermodynamics and evolution are due to the changes of perspective, so as to speak, if measurement is considered to be external or internal. Equilibrium theories developed for closed systems under ideal conditions are analogous to external measurements. On the other hand, morphogenetic perspectives as far from equilibrium thermodynamics applicable to open systems allow to imagine self-organizing agents that perform local measurements. Chaitin's algorithmic approach would help to elucidate the relation between digitally encoded information and active *forms*, because *forms* and shapes are responsible for specific pattern recognition and play a major role in the process of finding the proper measuring standard. The predominance of *form* over digital records is illustrated by studying the mapping between genetic descriptions and functional shapes, originally suggested for RNA, by Schuster. Therefore, interactions between living entities are seen as reciprocal measurement processes that bring about couplings (shortened descriptions and local decreases of entropy) that are paid by partial record erasure (increase of entropy). To conclude, this approach centered on the inner dynamics or form is appropriate for understanding how Lamarckism and the modern neutral theory of evolution can be integrated for expanding the neoDarwinian perspective. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

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## 1. Introduction

The evolution of living systems has been traditionally explained in terms of the interplay be-

tween external and internal forces, as quoted from Haeckel:

In the formation of crystal individuals, two different counter-acting formative tendencies come into operation. The inner constructive force, or *inner formative tendency*, which corresponds to the Heredity of organisms, in the case

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\* Corresponding author.

*E-mail address:* eandrade@ciencias.ciencias.unal.edu.co (E. Andrade).

of the crystal is the direct result of its material constitution or of its chemical composition. [...] The external constructive force, or the *external formative tendency*, may be called Adaptation in crystals as well as in organisms [...]. Consequently, the *form* of every single crystal, like the form of every single organism, is the result of the interaction of two opposing factors — the *inner formative tendency*, which is determined by the chemical constitution of the matter itself, and the *external formative tendency*, which is dependent upon the influence of surrounding matter

(Haeckel, 1868).

I agree with several recent proposals that favor a shift of perspective to place a major emphasis on internal forces. The external forces will not be totally dismissed, but will, however, be better understood within a hierarchical approach. This paper will present the interplay between internal and external forces as a semiotic activity that involves measurement processes. Within this framework, the discussions on the concept of *form* and digital, analogic conversions are revisited.

## 2. From external to internal measurement in thermodynamics

It is often argued that the use of thermodynamics in biology has a long history that is rich in confusion (Morowitz, 1992). It is my tenet that this confusion arises as a consequence of the simultaneous use of concepts developed from opposite standpoints: externalism and internalism.

Externalism is exemplified in classical approaches developed in the 19th century. In these theories, systems are studied within stable boundary conditions that are obtained by isolating the systems so that the descriptive parameters remain under the observer's control. Thus, systems are described by an external observer, who performs measurements and gathers data, making possible the production of a logically consistent description. In this way objectivity is attained. Clausius's entropy approach deals only with phenomena at this macroscopic level, while Boltz-

mann's development reconciles the macroscopic description with molecular mechanics. However, any prediction of future cases becomes possible only when the individual behavior of every molecule is subsumed into the global statistical equilibrium parameters that are kept constant. In this external approach the irreversible increase of entropy brings forth homogeneity, symmetry and destruction of *form* in the same extension as the available energy diminishes.

The limitations of this approach were raised by James C. Maxwell, who proposed a thought experiment in order to illustrate that the behavior and properties of large quantities of molecules is different than the behavior of small quantities of matter. There is a very deep and real distinction between the properties of individual molecules and the properties of observable systems. In order to make this point clear, he introduced an observer or an intelligent being endowed with finite and very acute faculties that provided it with the ability to discriminate fast from slow moving molecules so that by operating a valve, this agent could produce a thermal non-equilibrium state (Daub, 1970; Heimann, 1970).

While physicists asserted that Maxwell's demons cannot operate in closed systems, and therefore, are unable to perform selective work, in agreement with the second law of thermodynamics (Brillouin, 1951), neoDarwinians subscribed to natural selection as the fundamental explanation of evolutionary processes. The apparent contradiction between these two perspectives resides in the fact that Darwinians considered selection as an external pressure, while the activity of a Maxwellian demon is more akin to an internal selective action. Notwithstanding, in all instances the idea of selection suggests that in living matter takes place what Maxwell's demon can not do in equilibrium systems.

In the last few decades, Prigogine has advanced a morphogenetic perspective compatible with an internalist view point, wherein microscopic dynamics that take place in open, far from equilibrium systems is considered to act as a source of increasing organization. This approach has paved the way for the introduction of an observer into the system. In this case, boundary conditions are

focal and transient, so that measurement is always in the process of being completed. As a consequence, the principle of selection must be seen as a process of concrete and immediate choices made by real organisms at a local scale (Fig. 1).

Brooks and Wiley (1986) contribution clearly shows how the contradiction between evolution and entropy or rather between negentropy accumulation in living systems and entropy increase, boils down to a question of the location of the observer. It can be deduced from his internalist perspective that evolution is fueled by entropy. In a recent analysis by Zurek (1990), the notion of physical entropy is referred to an information gathering and using system. In all these internalist approaches the irreversible increase in dissipated entropy brings forth heterogeneity, rupture of symmetry and a diversity of *forms*, as entropy is dissipated to the environment. In this manner, internalism rightly addresses the issues relative to *form* and organization that were traditionally raised by the so-called ‘vitalists’ viewpoint.

External and internal perspectives are complementary, in the sense that, the descriptions they produce are incompatible when made simulta-

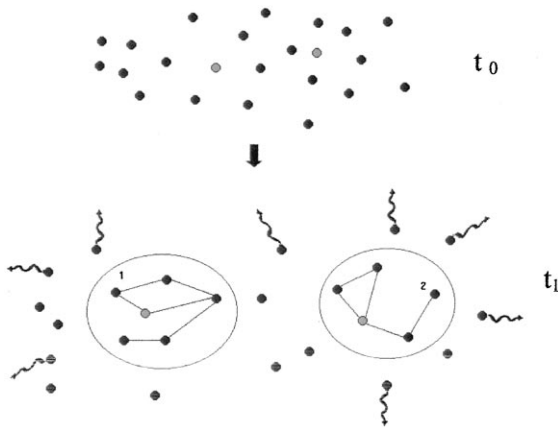


Fig. 1. The action of internal measurement brings forth a radius of non-random interactions and structural closure while a perturbation is transmitted to the nearest environment. Only local records that deal with connected units are created, paid by increases in uncertainty about the environment beyond their influence. A higher level of organization performing a sort of external measurement can partially resolve the uncertainty by stabilizing compromises between the newly created structures.

neously. However, if we consider that evolution has proceeded from the simplest to the more complex forms, then priority should be given to the internalist approach, for it considers living entities within their nature as units of experience that measure and create records at a local scale. Only when higher levels of organization appeared, did an external measurement analogous to the imposition of boundary conditions to these lower levels develop; however, actions that take place within the same scale or level of organization, are the inner measurement.

This suggests that a phenomenon that we can consider as an external measurement does take place in nature but not in the manner of the idealized mechanical and equilibrium approaches of classical science. Instead, a newly emergent higher level overlooks many microstates and variants that are not needed for the specification of this hierarchical level. Therefore, microstates that are disregarded and pass by undetected by this external measurement are equivalent to the so-called ‘neutral’ variants. Of course, the external measurement contributes with restrictions, but there are no natural systems that can physically exert such a deterministic control. There are two main reasons for this.

1. A structural complexity, though it may be large, has a limit. This limit confers a restricted capacity for discrimination and detection. This discriminating capacity, algorithmic potential, coding ability and record storage capacity is necessarily limited, finite and incomplete.
2. The acquisition of information requires a prior work-action of measuring and recording. This action is costly and has to be paid for by entropy dissipation that is responsible for random fluctuations that prevent the full conservation of records. It is, therefore, unavoidable that some information is lost.

Matsuno (1989) has claimed that the limit of speed light explains the impossibility of obtaining global and synchronous descriptions, but within the realm of living organisms one could consider such descriptions almost instantaneous. Ho and Popp (1993) discussed the possibility of quantum coherence in living systems. They suggested that

organisms emit light at a steady rate from a few photons per cell per day to several hundred photons per organism per second, and concluded that this emission was responsible for coherence in living systems.

### 3. Epistemological status of form

Life and *form* are two intimately associated terms such that one can hardly imagine one without the other. Biology has shifted from the externalist morphologic centered paradigm to the more internalist information paradigm. Nonetheless, the study of digitally encoded information in the DNA opened some avenues that inevitably lead us back to the morphologic perspective. However, this time we are not limited to organismic body patterns but to the patterns of organization that shape every level in the organized hierarchy, and therefore, we may state that the active agency that might explain the recording of information as DNA resides in *form*. I suggest that the present change of perspective from digitally encoded information, back to *form*, will also support an internalist standpoint.

In Plato's terms, *forms* are a priori, they are immutable and eternal. *Forms* are ideas that explain the intelligible world because they remain unchanged in contrast to the sensible world of variation and constant change. These intelligible and unchanging entities are ideas 'eidos' that represent objective, real and universal states that have no concern whatsoever for individual, concrete and sensible entities. *Forms* confer intelligibility that marginalizes the concrete and sensible world as experienced by every single individual. As I will discuss below, if *forms* had epistemological priority and real existence separated from matter, it would leave unsolved the problem of how to achieve logical consistency without discarding the concrete and sensible world experienced by individuals.

In a similar manner, Aristotle's 'logos' is equated with *form* and intelligibility, which is why we speak of formal reasoning or mathematical formalism. Nonetheless, 'matter' and *form* are two metaphysical principles inseparable of each

other in what is termed 'substance'. For Aristotle, matter can not be reduced to formless atoms acted upon by external forces, 'matter-form' is instead a principle of activity and intelligibility better expressed in the notion of 'substance' (Aristotle, 1998). *Form* has priority in as much as its properties are intrinsic to matter. That is, the priority of *form* and the *formal cause* over the other Aristotelian causes has to do with the fact that it operates from within, and so becomes the principle or cause of movement (Jaeger, 1946). Today, one might explain Aristotle's thought by stating that intelligibility of a process must be sought in the internal dynamics associated with *forms*.

In terms of Thompson (1961) the *form* of any portion of matter (living or dead), and the sensible changes of *form*, that is, its movements and its growth, may in all cases be described as due to the action of forces. The *form* of an object is the result of a composite 'diagram of forces', and therefore, from the *form* we can deduce the forces that are acting or have acted upon it. Although, force is a term as subjective and symbolic as *form*, forces are the causes by which these *forms* and changes of *form* are brought about. This constitutes the best attempt so far, to reduce *form* to forces while keeping the autonomy of the *form*. Thompson's attempt to eliminate intrinsic *formal* causes by working only with extrinsic efficient ones, resulted in an affirmation of the autonomy of *form*. The point that was missed, however, is that forces are not just mechanical interactions but are the directionality imposed on the flow of physical energy as a consequence of semiotic process of measurement.

This latter insight is latent in Whitehead's philosophy of organism. For him, substance (actual entities) suffers changing relationships, and therefore, only *form* is permanent and immortal. Organism or living entities are individual units of experience and can be regarded from either internal or external perspectives. The former (microscopic) is concerned with the formal constitution of a concrete and actual occasion, considered as a process of realizing an individual unit of experience, and the latter (macroscopic) is concerned with what is given in the actual world, which both

limits and provides opportunity for the actual occasion. His remarkable insight is that ‘actuality’ is a decision amid ‘potentiality’. The real internal constitution of an actual entity progressively constitutes a decision conditioning the creativity that transcends that actuality. Conversely, where there is no decision involving exclusion, there is no givenness, for example in Platonic *forms*, but in respect to each actual entity there is givenness of such forms. The determinate definiteness of each actuality involves an action of selection of these *forms*. Therefore, form involves actual determination or identity (Whitehead, 1969).

Thus, the formal constitution of an actual entity would be a process analogous to measurement or to a transition from indetermination (potentiality) towards terminal determination (actuality). Consequently, these theories of life incorporate thermodynamics or the study of the flow of energy and its transformation in alternative *forms*. This becomes the basis for understanding the transmission of simple physical feelings from one living entity to another.

When we deal with the question of how *form* emerges and is conserved along a defined lineage of descent, Buffon’s answer still provides an interesting insight (in Canguilhem, Buffon, 1976; Jacob, 1982). *Forms* (a three-dimensional arrangement of component parts) have something to do with shapes (external contour of organisms) that are produced by casting on molds, in this case an ‘inner mold’ constituted by ‘the folding of a massive surface’. Even in the 1930s, biochemistry was not totally alien to such ideas, and was not unusual to find in the literature references to molecules that shape each other as likely carriers of instructive information (Olby, 1994). The real breakthrough of the molecular biology revolution in the 1950s was the concept that the organisms could be reduced to digitally encoded one-dimensional descriptions. After this, DNA became the carrier of *form* or the informative molecule by excellence. Yet, it has never been made clear how *forms* and three-dimensional shapes get encoded in one-dimensional records.

Following Schrödinger (1983) form (structure, organization) and not ‘substance’ (material content) is the fundamental concept, because it deter-

mines identity. Likewise, *form* as examined by Rene Thom is an archetype that has an epistemological status higher than force. If shapes, conversely, are emergent with regard to components, then paradoxically, the now more basic components should have possessed *form* to have been able to interact in the first place. This is not to advocate for a Platonic view since the prior character of some type of *forms* does not imply that they are to remain eternal and separate from matter, but rather the opposite, it is the unleashing of an evolutionary process.

For interactions to be established two conditions are required; (1) openness, and (2) affinity or the non-random preference of one entity for another as selected from among others. The problem is that in order to knit together a whole network of interactions in the physical world, some basic *forms* inherent to elementary particles must have preexisted in order to make possible further recognitions and increments in complexity.

I state that priority should be given to form for its nature explains the appearance of digitally encoded semiotic records. *Form*, is one of those concepts in which Peirce’s three categories can not be easily differentiated. *Form*, as stubborn fact, has the qualitative aspect of firstness, the functional, determinate and relatedness traits proper of secondness and, as a source of coordinating activity and intelligibility is also an expression of thirdness<sup>1</sup>.

I conceive *form* as the process that is responsible for the establishment, transfer and conservation of a specific set of non-random interactions. Thence, *form* is responsible for the emergence of functions that materialize in a specific spatio-temporal arrangement of parts, of whatever nature, that are required to maintain a coherent performance. This perspective favors the current shift of outlook, as noted by Matsuno (1995), that considers that the emerging systems characteris-

<sup>1</sup> The fact that ‘form’ has some attributes of firstness does not mean that it is eternal, unchangeable and separate form matter. It is rather, a succession of a series of *form*. This paper is closer to Aristotle (Phys. II,7 in Jaeger, 1946) in his remark that *form* is seen as a cause responsible for inner dynamics and movement, which is a point I tried to rescue.

tics are the outcome of inner measuring processes. Furthermore, it is understood that organisms are as real, as fundamental, and as irreducible as the molecules out of which they are made. Form is, therefore, understood as a relational order among components that matters more than the material composition (Bateson, 1979). *Form* and information are not a priori properties, for they arise as a consequence of selection, but paradoxically in order to initiate the process of selection some *forms* must have existed to start with.

Thus, *form* is to be understood as a principle of activity that organizes (dynamic geometry) the world as a result of dynamic interactions. This concept is in open contrast to the Newtonian view where absolute space-time is filled with passive geometricized entities. The concept of organic *forms* also opens the way to hierarchical reasoning, since the interactions of a defined set of *forms* gives birth to higher order *forms*.

#### 4. Living entities are systems of representation

For representation to take place, both a comparative process, where differences can be detected (measurement), and a translation process, of coding and recording are necessary. Translation by codification implies that the difference is incorporated into a circuit with an appropriate network of processes that permits such a change of codification. In a similar manner, coded versions that make use of certain type of symbols and belong, so to speak, to a defined language, may transfer that data to another codal version by using another language that employs different symbols.

Systems of representation provide the living entity with the capacity to pursue its own interests or subjective aims. This is a unique strategy that provides that organism with the possibility of handling, manipulating, contrasting, validating and integrating or eliminating the irrelevant elements of its external world, and therefore, to use the terms of Bateson, “to select the difference that makes difference” (Bateson, 1979). Their representations, therefore, become, an expression of feeling, experiencing, measuring and interacting,

in accordance with their inner structure or self-reference. In this way, the organisms suppress the confusion of the vast ‘multiplicity of things’ and shape their own experienced world.

For instance, prokaryotes are subject to high rates of lateral genetic transfers; (Kidwell, 1993; Syvanen, 1994; Ravi et al., 1999), so that a bacteria like *Escherichia coli* bears a considerable amount of foreign DNA. This fact demonstrates that identity does not depend on the genetic record alone, but derives from the coherence of experience felt as a unity. The genetic record only restricts the type of measurement devices that can be utilized.

The tendency of the active *forms* to link with their selected counterparts and the actions of the higher level hierarchical systems to integrate different elements into an autonomous organization that functions as a cohesive set of interests, can be understood as an attempt to attain some degree of consistency. Complete consistency is never achieved, because of the unpredictable disturbances created in the interactions that result in couplings. The logical inconsistency intrinsic to each level is the consequence of their inner dynamics. It is, however, partially resolved from without by virtue of the boundary conditions and restrictions imposed by the higher level of organization.

All living entities are ‘subjects’ with active interests and prospects. Different living entities belong to varying degrees of organization, in as much as they are subjects of representation, that manage to promote their interests, regardless of whether they are considered as a community or simple isolated units. A collective validation of representation systems goes on all the time. For instance, Margulis and Sagan (1995) stated that eukaryotic cells are nothing but a community of prokaryotes, thus, there is no ontological identity that can be resolved by decomposition into parts, for individuality is relative to the limit of discrimination imposed by the observer. The point is, regardless of what component sub-units a living entity can be dissected into, there is a coordinating activity responsible for experience felt as a unity.

## 5. Measurement and analogic digital conversion

I propose that the establishment of links or couplings between living entities acting as observers is the result of a process of measurement and recording. I start by persuading, as stated by Hoffmeyer and Emmeche (1991), that the records have a dual nature (digital and analogic). The structural features that are responsible for the coupling between living entities are analogous to compressed descriptions. An encoded compressed description is relatively free from external influences, but is susceptible to internal influences that are directed or canalized by the intention of the observer agent, which is to obtain a coherent performance. Although these couplings appear to be ‘selected’, in as much as they improve the relation between energy, spent and success.

Experience shows that an appreciable number of descriptions can be significantly shortened, by slightly modifying them in the interaction with the observer. It is well known, however, since Chaitin’s work, that a random series of symbols (0, 1) cannot be compressed (Chaitin, 1969), but it is less known that after a few directed variations, the degree of compression increases in the region where those directed variations took place. The subjective goals of the observers, their inner drive to interact, make them active agents responsible for adjustments that permit the discovery or actualization of previously hidden patterns. Reciprocal fit is not provided by a type of ‘pre-established harmony’ but is instead developed within an interactive process where the observer’s intention to ‘find a match’ plays a major role. The observer’s intentions are driven by the tendency to grasp available energy, while enabling both the conservation and transfer of energy that might result in perturbation of observers’ inner patterns or measuring devices. Thus, only by including the transient character of both the action of measurement and the created records, the internal observers’ dynamics could be modeled in terms of Chaitin complexity approach. Directed transformations due to the active agency performed by the observer must be paid for by dissipating entropy that might affect some existing records.

There are always sectors that remain both uncompressed and compressed. The former will remain so, as long as this sector does not provoke an observer who can direct the compression, and the latter will remain so, only as long as selective activity goes on or is perceived by any living entity. As energy flows, there is a tendency to compress information in the records paid for by entropy increases. These entropy increases become manifest as dissipating perturbations and/or partial erasing of records that appear in a variety of forms, from single base perturbation, to the deletion of larger fragments and the accumulation of mutations. This partial record erasure is the only way to relieve the structural constraints of the evolving systems, as exemplified within the events of the Cambrian explosion.

The creation of new links does not always involve the loosening of former ones, since any transmission of perturbation is most likely to affect uncoupled motifs, for they represent a majority. That is, as suggested, that non-coding DNA regions play a passive role in buffering against mutations (Vinogradov, 1998). The more intensive the ability to take advantage of random fluctuations, or the satisfaction of the subjective goals, the higher the transmitted perturbation. In other words, the more pressure that is exerted upon a solid mold, the higher the perturbation and unexpected fractures that affects the mold. Similarly, let us remember that each level of organization exists within a defined threshold of energy barriers and that if the work executed is not sufficient to drive the system out of its stability well, the perturbed system will remain stable and will not degrade into component subsystems. Conversely, to move upward in the organized hierarchy requires selective work, however, as complexity increases the system will also develop types of algorithmic rules that may be used to compress the previous uncompressed domains. Therefore, semiotics becomes operative as a physical dynamics that is restricted only by thermodynamic considerations and by the presence of actually existing *forms*.

In order to develop Chaitin’s algorithmic complexity in Peircian terms, a two level hierarchy is required, to distinguish between a random un-

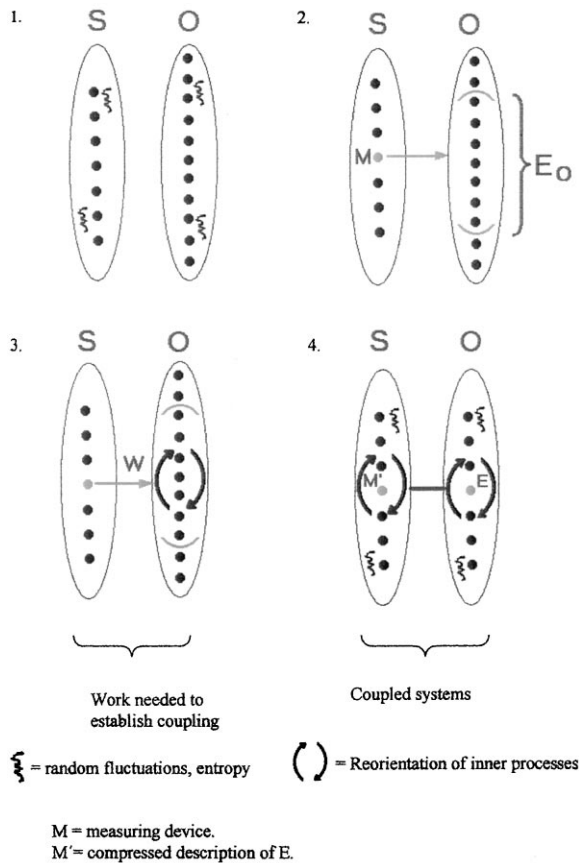


Fig. 2. Work needed to establish a coupling. (1) Uncoupled systems. (2) System (S) bears a measuring device (M) that might recognize some elements ( $E_o$ ) in system (O). (3) System (S) performs a work in order to establish a coupling. (4) Coupling established between systems S and O as a consequence of the direct interaction between M and E. This coupling is paid by random fluctuations in S and O.

compressible series that has been provided a priori to the system, and a random series that appear after execution of a compressing algorithm performed by the higher level system. Therefore, (1) firstness corresponds to random uncompressed a priori sectors, some of which have the potential of being compressed. A priori random series are relative to the observer's formal systems complexity. Then (2) secondness is represented within the actually compressed sectors or the existing definite and tangible forms. These regions appear as random from a non-hierarchical ontology, but they stand for ordered and coupled entities as per-

ceived from the higher level. Thus, secondness is the inter-phase where inner randomness and external restrictions meet. We may note that maximal compression cannot be attained because of the ensuing susceptibility to higher risks by mutations. (3) Thirdness is equivalent to the organizing and *formative causes*, which can be understood as the tendency to find regularities and patterns or to elaborate a compressed description<sup>2</sup>.

In the evolution of binary series, one might find the following cases:

1. (Uncompressible)  $t_0 \rightarrow$  (Uncompressible)  $t_1$ : a series remains uncompressible regardless of the formal system used to study it.
2. (Uncompressible)  $t_0 \rightarrow$  (Compressible)  $t_1$ : an uncompressed series becomes compressible when either it is studied with a more complex formal system, or it has been modified so the previous less complex formal system can account for it.
3. (Compressible)  $t_1 \rightarrow$  (Compressed)  $t_2$ : a compressible series of symbols becomes a compressed description after execution of the appropriate algorithm.

Let us assume a series of digits, (O) that makes up part of the possible external world that might be experienced by a living entity trying to make its living in a subregion of the said world. Let (S) be that living entity. S employs M as a measuring or discriminating device and is seeking a match in order to catch the available energy, but this goal cannot be achieved gratuitously. S has to perform some work in order to succeed in such an endeavor. In the Fig. 2, the line stand for coupling and the arrow represent the 'work' executed by (S) upon (O). M recognizes a set of elements that become a shortened description incorporated into S as M'. This coupling action disrupts the matrix where fitting is being attained and this disruption, as entropy increase, pays off the cost of coupling. This disruption explains the permanence of uncompressed and redundant subregions, described

<sup>2</sup> Compression of symbol series is a truly semiotic activity in as much as it requires the identification of regularity patterns that permit such compression as a result of an active agency explained as thirdness. But, compression of digitally encoded information results in shape



in evolutionary theory as random neutral variations (Fig. 2).

Compressions elucidate the intelligibility that was hidden in the former uncompressed state. The basic assumption of science is that the universe is ordered and comprehensible. In a similar vein, it can be said that this order within the universe is compatible with the processes of life for at least one world, our earth, exists in which life has emerged.

Therefore, the world must have a property analogous to algorithmic compressibility for life to exist. We may conclude that life forms are adapted for the discovery of suitable compressions. And also, that living forms possess embodied algorithmic compressions. The point, however, is that suitable compressions are only those that fit a defined shape. Shapes permit the recovery and storage of compressed descriptions. Digital descriptions are compressed within their actions as they collapse or materialize in functional shapes.

In the classical Maxwell's demon thought experiment, 'Information Gathering and Using Systems' measure and compute positions and velocities of particles, however, these actions constitute only the mathematically formalized aspect of the demon's activity. For instance, sense organs work with images and analogic pattern recognition, nonetheless they both are required for the classical demon to perform his job. As increasing organization goes on, what has hitherto been unmeasurable becomes measurable. Thus, the demon must evolve measuring devices, which can be represented in any structural feature that might serve to this purpose, though its agency is always experienced as a unity. Therefore, the analogy between living entities and Maxwell's demons deals only with the mathematically formalized aspect of what a living form can feel and experience.

The transition from analogic (holistic three-dimensional pattern recognition) to digital coding (linear) entails a loss of information. This is equivalent to the passage from an image (perception) to a statement (cognition). Enzyme-substrate recognition is holistic; however, in spite of its dependence on highly specific sequence domains,

it does not completely eliminate the non-relevant information in terms of sequence specificity, because this type of information is required as structural support of the active site. However, shortening of descriptions take place in the transition from analogic to digital (Dretske, 1987), since context dependent information can be dispensed with. The adequate shape that is encoded in a compressed description, is all that is required for the activity of a living system, namely, the establishment of interactions that permit the continuation of the measuring and recording process.

On the other hand, the mapping of digital semiotic descriptions into analog semantic versions (shapes), shows that shapes maximize the amount of information contained in the space of sequences, and that the relation between these two sets is not the bijective.

This point can be illustrated by looking at the mapping of sequence space into shape space elaborated by Schuster (1997) for RNA molecules of 100-nucleotide length. Billions of linear sequences can satisfy one shape. But what is really striking is that any random subregion of the sequence space might encode all possible forms and shapes ( $7 \times 10^{23}$ ). While the space of possible forms is nearly complete in the real world of molecules, the space of existing sequences is astronomically little and restricted in relation to the space of all possible sequences. This latter assessment assumes that we are dealing with sequence spaces that all throughout evolution keep their dimensionality constant, so to speak, the molecular variants are searched within the same restriction length. In real evolution, the search of molecular variants takes place not only by testing variants but also by the increasing length, so to say that sequence space has also increased in dimensionality. Nonetheless, in all the instances the number of functional shapes is always lagging far behind the number of possible linear sequences. At the level of primary sequences, biosphere seems to have explored only a minute astronomical fraction of the total possible sequences, whereas the space of all possible shapes is almost complete. If evolution is concerned only with the expansion of the realm of actually existing sequences, it has hardly begun its task, conversely, if its aim is to produce all the

possible functional shapes, it has long been near to completion of that task, since chordate appeared. The point is, that what matters for life is not just the random sorting of sequences but the finding of functional and active shapes, and there are prime possibilities of obtaining them at the molecular level. Moreover, it is the filling of the shape-space what drives evolution to higher levels of organization even if the exploration of sequence space is confined to a minute region. For example, molecular diversity in high level organisms endows them with a universal molecular tool kit of an estimated magnitude of  $10^8$  for any enzymatic reaction or antigen recognition (Kauffman, 1993). Any potential substrate or antigen will be recognized (Perelson, 1988; Segel and Perelson, 1988). If the evolution of functional forms is close to saturation, the vast majority of molecular variants is neutral and corresponds to the already existing shapes. Therefore, function can be assimilated to a degenerate set of numerous linear series of symbols.

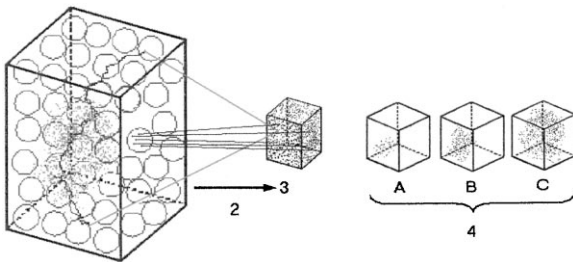


Fig. 3. (1) 'Borges Library of Babel', or world of all semiotic digitally encoded genetic descriptions, better known as sequence space. Actually existing genetic descriptions represented as a tiny cloud of scattered points. (2) Translation and complex dynamical folding; a one way process as stated in the Central Dogma; (3) world of all possible shapes that provides the context of meaning or semantics; (4) world of actually existing functional shapes. (A), Prokaryote; (B), invertebrate; (C), chordate. Throughout evolution this space has been filled to almost reach the size of (3). When (3) is mapped into (1), it seems that encoded semiotic descriptions are randomly assigned, unless the architecture of synonymous paths is known. From (1) one could not predict (3), since this is a NP problem for proteins. The reverse operation which is to identify the particular DNA sequence that produce a determinate protein shape violates the central dogma of molecular biology, though a very large set of degenerate possible synonymous sequences can be defined as a neutral path as shown in the picture.

I find the earlier previous conclusion as a very telling argument that supports the prevalence of forms over digital records. It is the reciprocal fit between local shapes that is responsible for non-random interactions between molecules. As explained by Root-Berstein and Dillon (1997), this type of complementary interaction, drives evolution in a non-random way towards higher degrees of organization.

Thus, we are dealing with a mapping of many (sequences) to one (shape), which shows a characteristic of degeneracy given by the existence of neutral paths. However, this mapping also exhibits a holographic correspondence where each minuscule part of the world of semiotic genetic descriptions holds within it the makings of the entire whole world of forms (Fig. 3).

The mapping of living cells, words or proteins and their corresponding genetic descriptions, for a given determinate length, is expected to show that the number of linear sequences that satisfy one form is much larger than it is for RNA. The following data are only tentative estimations based on length restriction of 100 nucleotides for RNA and 100 aminoacids for proteins Schuster (1997), Kauffman (1993), Perelson (1988) and Segel and Perelson (1988): Magnitude Prot. seq. space =  $20^{100} = 10^{130} \gg$  magnitude RNA seq. space =  $4^{100} = 10^{60}$ . Magnitude Prot. shape space<sup>3</sup> =  $10^8 \ll$  magnitude RNA shape space ( $7 \times 10^{23}$ ). Ratio, magnitude seq. sp.: magnitude shape sp. (proteins) =  $10^{122}$ . Ratio, magnitude seq. sp.: magnitude shape sp. (RNA) =  $1.4 \times 10^{36}$ . Thus,  $10^{122} \gg 1.4 \times 10^{36}$ .

These last figures are in agreement with the fact that the probability that a mutation is neutral for protein genes is as high as 70% (Tiana et al., 1998), in accordance with the existence of neutral networks that traverse sequence space (Blastolla et al., 1999).

<sup>3</sup> This figure  $10^8$  refers to the basic fundamental protein shapes that can account for basic catalytic functions, nonetheless this figure can be made 1000-fold higher, if one takes into consideration more specific adapted forms that are obtained after few mutational steps from the original basic forms. Anyhow, the figure of  $10^{11}$  still holds as an argument in favor of this discussion.

The central dogma of molecular biology obscures these complex relationships, for it is only concerned with a one-way, unidirectional, one to one mapping. Therefore, it is possible to conclude that all the possible digitally encoded worlds, bizarre as they may be, have a potential meaning, but most of them remain meaningless unless their corresponding shape is selected. Linear monotonous versions that do not fold in stable shapes, and cannot be selected since selection operates within a defined semantic context given by the network of interacting forms or a higher order form. Thus, one is bound to conclude, that what matters for life is not the random sorting of sequences, but the finding of functional and active shapes and there are all odds to obtain them!

## 6. Enzymes as agents of inner measurement or Maxwell demons

As mentioned above, measurement is equivalent to the imposition of boundary conditions or restrictions so the observer's uncertainty about the states of the immediate environment decreases. This local exploration by an observer entity leads to a non-random reciprocal interaction between *forms* (Fig. 1).

It was only with the discovery of self-organization that the selecting and measuring activity of the enzymes began to be recognized as anticipated by Monod (1970). More recent developments include the work of Otsuka and Nuzawa (1998) on RNA self-reproducing systems.

However, the interaction between the observer and observed systems must result in the production of a record or specific link that is paid for by an increase of dissipated entropy in the form of fluctuations that affect randomly some regions beyond the system. These interactions correspond to what can be described, for they become part of the experienced world, while the perturbations must be considered as a source of uncertainty that might even affect some earlier encoded records. Measurement and coding are intimately associated. Measurement sets on an irreversible chain of transformations, in as much as records are created within that action of measurement. Once, a record

is created, selection acting from within, operate in a canalized way as the measuring device increases its discriminating capacity. As Zurek (1990) has pointed out, measurement can only be performed in far from equilibrium states, and it pays! But, the record produced is nothing less than the measuring agent, itself, as an ongoing process of self-organization.

Internal measurement is the only logical formalized way to describe the nature of interactions that are established by living entities themselves and not forcedly imposed on from without. But if measurement requires recognition of patterns as a whole, similar to the compatibility of surfaces that envelop three-dimensional organic bodies, then some primitive forms must have existed prior to self-organization.

As Pattee (1993) has proposed, there are little doubts that enzymes act as measuring agents and that individual molecules are the simplest, control mechanism of the cell. The essential function of the enzyme is to establish a measurement-control coupling, that is, a statistical rule that relates substrate recognition to specific catalytic control. For the enzyme, this coupling is strictly local, both spatially and temporally. The enzyme, functions dynamically as a complex rate controlling molecule and its semiotic genetic description contains only enough symbolic information to construct the linear sequence of amino acid residues. Furthermore, 'the enzyme must bind a substrate before it catalyzes a reaction, and this substrate recognition is a form of measurement. It is the complex constraints in the dynamic folding process that result in coherent template fit or the enzyme's recognition of the substrate that explains its catalytic rate control. The computation of protein folding dynamics and enzymes' behavior is beyond the present computational power. Biological controls do not depend on measurement of simple observables but utilize complex pattern recognition based on coherent dynamic interactions, as in folding template fit, catalysis, self assembly, and network controls. Enzyme activity is responsible for the continuing stability of the whole system. In terms of Matsuno (1995) "if internal descriptive agents stop acting the whole descriptive enterprise would come to collapse".

Furthermore, enzymatic activity is generative (Matsuno, 1995), so, it is a causative agent of developmental process that is triggered as internal measurement is carried out in the egg.

The fact that enzymes are genetically encoded does not obscure the capacity for generation of variation that is inherent to internal measurement, yet genetic encoding became necessary to prevent the production of unfitted enzymes by *de novo* synthesis. DNA encoding became the preferred way to avoid the damaging effect of enzymatic inner measurement, and one might investigate the origin of DNA mutations, errors or fluctuations, as a consequence of the dissipation or record erasure produced by the replicating enzymes that perform such a highly specific task.

### 7. Selection as either external or internal action

The classical Darwinian principle of natural selection is congruent with mechanistic approaches where living entities are either preserved or eliminated according to external pressures. In contrast, from an internalist evolutionary stand point, external pressures cannot be accepted *a priori*, but rather as an emergent phenomenon that originates in contingent particular events that take place at micro-scale level.

The diverse circumstances of this level posit a challenge that living entities overcome by establishing the adequate interactions. Their activities as observers that measure and record, allow them to solve the challenge through their own choices. Organisms actively transform their niches, furthermore, they create and select them. This creative act, in which they manifest their initiative, is clearly an action of internal measurement for, it depends upon the manner in which their external world is classified and discriminated. Thus, selective pressures exerted from, without *a posteriori*, are a consequence of their previous inner choices (Cadena, 1994). In so creating their niches, organisms define the structural changes that will be directed towards a better adaptation of these very same niches. When the newly created niche selects the best variants that are adapted, the selection is considered as an external measurement. Nonethe-

less, this action is wholly dependent upon the earlier changes of relationships between organisms and some elements of their then external world. Thus, changes that came about by internal processes are the ones that impose directionality and orientation to organisms upon the inner structural modifications. This is a true emergence, which corresponds to the coupling of inner processes with external elements. An internalist perspective in evolution will permit to recuperate the Lamarckian tenet and its emphasis on the intentionality or 'internal striving' of organisms. Whereas Lamarck could only speak of fluids as conveyors of that inner activity, today equilibrium thermodynamics can bring us closer to the nature of what he was trying to present. At the present time, there is a massive accumulation of molecular data that depicts a dynamic picture of the internal genetic constitution and sets up a number of necessary interlocking processes for gene expression. For instances, mechanisms as Dover (1986) molecular drive can partially account for canalized and directed evolution. In the case of bacteria and most microorganisms a permanent feedback with the environment can result in direct genic rearrangements and mutations that actively facilitate the breakdown and metabolic uptake of chemically synthesized substances. On the other hand, it is accepted that most mutations are neutral and randomly produced. Redundancy seems to be an uneconomical process unless a broader scope is taken, since it is in these neutral variations, which are considered as entropy bound to structure, where we may find a hidden potential for evolution. This notion of evolutionary potential cannot be easily dismissed as shown by Grassé (1977) and Wesson (1991). Entropy or randomness provides an immense well of novelty, where new functions arise as the molecular shape-space approaches saturation. Neutrality, as a source of useful novelty, was first illustrated by Ohno (1970), with the classical example of gene duplication. However gene duplication can also be interpreted as a coupling that expands the experienced world by the system's own inner dynamics.

Among the causes that explain the acceptance of the concept of selection as an external invisible hand we find the following.

1. The lack of knowledge about the internal structure of the organisms (both at the molecular and cellular level). This prejudice is no longer tenable as discussed above.
2. The development of statistical and probabilistic analysis that always has an equilibrium state as a point of reference. This prejudice is also untenable, since far from equilibrium thermodynamics shows that the most probable state is no longer the most disordered one, so rendering useless a probabilistic analysis where random fluctuations build up resulting in an intense generative process.
3. Shannon information theory, in which a particular structure is measured in terms of the number of alternative binary choices made by an external observer. Shannon's approach is misleading, for it confuses the number of binary choices needed to identify a system from an external observer, with the number of alternative choices required to produce it from an internal process. All probabilistic quantitative assumptions are insufficient for what matters is the function and meaning that are responsible for the coherent fulfillment of organisms' actions.
4. Selection was seen as the best clear explanation of how nature opposes entropic decay (Kauffman, 1993). The problem is that when entropy was perceived as an inexorable negative and destructive fate, selection came to be understood as an external operation, functioning as an a priori metaphysical concept called in to recuperate order and to free us from the horror of randomness and formlessness. In this earlier manner, selection had very little to do with any actual physical processes. In contrast, far from equilibrium self-organizing perspectives provide a new approach where entropy is also seen as playing a vital formative and creative role that explains how selection is developed from within. Physically describable selective processes are internalist and operate at the micro scale and yield the actual forms, but when it is presented as an external activity it obscures all the processes and real choices behind it.

In the interface between hierarchical levels, internal and external measuring processes collapse in an unpredictable manner. Some internal variants are integrated into a broader world of interactions, where inner creative statements are stabilized and retained in the form of couplings, some others might disappear, and most of them pass undetected transferring evolutionary potential to the next generation.

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### References

- Aristotle, 1998. *Metafísica*. Translated by Francisco Larroyo, XII ed. Porrúa, México.
- Bateson, G., 1979. *Mind and Nature. A necessary Unity*. Bantam Books.
- Blastolla, U., Roman, E., Vendruscolo, M., 1999. Neutral evolution of model proteins: diffusion in sequence space and overdispersion. *J. Theor. Biol.* 200, 49–64.
- Brillouin, L., 1951. Maxwell's demon cannot operate: information and entropy I. *J. Appl. Phys.* 22, 334–337.
- Brooks, D., Wiley, E.O., 1986. *Evolution as entropy*. In: *Towards a Unified Theory of Biology*. The University of Chicago Press, Chicago.
- Buffon, G.L.L., 1976. *Histoire des Animaux*. In: Canguilhem, G. *El Conocimiento de la Vida*, Anagrama, p. 63.
- Cadena, L.A., 1994. Ni holismo ni reduccionismo: azar y necesidad. *Colección Memorias No.1 Academia Colombiana de Ciencias Exactas, Físicas y Naturales*, pp. 99–100.
- Chaitin, G.J., 1969. On the length of programs for computing finite binary sequences: statistical considerations. *J. Assoc. Comput. Mach.* 16, 145–159.
- Daub, E.E., 1970. Maxwell's demon. *Stud. Hist. Phil. Sci.* 1, 213–227.
- Dover, G.A., 1986. Molecular drive of multigene families: how biological novelties arise, spread and are assimilated. *Trends Genet.* 2 (6), 159–165.
- Dretske, F.I., 1987. *Conocimiento e Información*. Salvat, Barcelona.
- Grassé, P.P., 1977. *Evolución de lo Viviente*. Hermann Blume.
- Haeckel, E., 1868. *The History of Creation*. Kegan Paul Trench, London, pp. 336–337.
- Heimann, P.M., 1970. Molecular forces, statistical representation and Maxwell demon. *Stud. Hist. Phil. Sci.* 1, 189–211.

- Ho, M.-W., Popp, A.-A., 1993. Biological organization, coherence, and light emission from living organisms. In: Stein, W.D., Varela, F.J. (Eds.), *Thinking About Biology*, SFI Studies in the Sciences of Complexity, Lecture Note. Addison-Wesley, Reading, MA, pp. 183–213.
- Hoffmeyer, J., Emmeche, C., 1991. Code-duality and the semiotics of nature. In: Anderson, M., Merrel, F. (Eds.), *On Semiotics of Modeling*. Mouton de Gruyter, New York, pp. 117–166.
- Jacob, F., 1982. *The logic of life. A History of Heredity*. Translated by B.E. Spillmann. Pantheon Books, New York, pp. 79–80.
- Jaeger, W., 1946. *Aristotles*. Translated by José Gaos. Fondo de Cultura Económica. Mexico.
- Kauffman, S., 1993. *The Origins of Order*. Oxford University Press, Oxford.
- Kidwell, M.G., 1993. Lateral transfer in natural populations of eukaryotes. *Annu. Rev. Genet.* 27, 235–256.
- Margulis, L., Sagan, D., 1995. *Microcosmos*. Tusquets. Summit, New York.
- Matsuno, K., 1989. *Protobiology: Physical Basis of Biology*. CRC Press, Boca Raton, FL.
- Matsuno, K., 1995. Competence of natural languages for describing the physical origin of life. *International Seminar on Evolutionary Systems*, Vienna, 8–12, March.
- Monod, J., 1970. *El Azar y la Necesidad*. Orbis, Barcelona. p. 13.
- Morowitz, H.J., 1992. *Beginnings of Cellular Life: Metabolism Recapitulates Biogenesis*. Yale University Press, Yale, p. 69.
- Ohno, S., 1970. *Evolution by Gene Duplication*. Springer, Berlin.
- Olby, R., 1994. *The Path to the Double Helix*. Dover Publications, New York.
- Otsuka, J., Nuzawa, Y., 1998. Sel-reproducing system can behave as Maxwell's demon: theoretical illustration under prebiotic conditions. *J. Theor. Biol.* 194, 205–221.
- Pattee, H.H., 1993. The limitations of formal models of measurement, control, and cognition. *Appl. Math. Comput.* 56, 111–130.
- Perelson, A.S., 1988. Toward a realistic model of the immune system. In: Perelson, A.S. (Ed.), *Theoretical Immunology II: Santa Fe Institute Studies in the Sciences of Complexity*. Addison-Wesley, Reading, MA.
- Ravi, J., Rivera, M.C., Lake, J., 1999. Horizontal gene transfer among genomes: the complexity hypothesis. *Proc. Natl. Acad. Sci. USA* 96, 3801–3806.
- Root-Berstein, R.S., Dillon, P.F., 1997. Molecular complementarity I: the complementarity theory of the origin and evolution of life. *J. Theor. Biol.* 188, 447–479.
- Schrödinger, E., 1983. *Mente y Materia*. Tusquets, Barcelona.
- Schuster, P., 1997. Extended molecular evolutionary biology: artificial life bridging the gap between chemistry and biology. In: Christopher, L. (Ed.), *Artificial Life*, pp. 48–56.
- Segel, L.A., Perelson, A.S., 1988. Computations in shape space: a new approach to immune network theory. In: Perelson, A.S. (Ed.), *Theoretical Immunology II: Santa Fe Institute Studies in the Sciences of Complexity*. Addison-Wesley, Reading, MA.
- Syvänen, M., 1994. Horizontal gen transfer: evidence and possible consequences. *Annu. Rev. Genet.* 28, 237–261.
- Tiana, G., Broglia, R.A., Roman, H.E., Vigezzi, E., Shakhnovich, E.I., 1998. Folding and misfolding of designed proteinlike chains with mutations. *J. Chem. Phys.* 108, 757–761.
- Thompson, D'Arcy, 1961. In: Bonner, J.T. (Ed.), *On Growth and Form*. Cambridge University Press, Cambridge.
- Wesson, R., 1991. *Beyond Natural Selection*. The MIT Press, Cambridge, MA.
- Vinogradov, A.E., 1998. Buffering: a passive-homestasis role for redundant DNA. *J. Theor. Biol.* 193, 197–199.
- Whitehead, A.N., 1969. *Process and Reality*. The Macmillan Company, Toronto, pp. 151–297–372.
- Zurek, W.H., 1990. Algorithmic information content, church-turing thesis, physical entropy, and Maxwell's demon. In: Zurek, W.H. (Ed.), *Complexity, Entropy, and the Physics of Information*, SFI Studies in the Sciences of Complexity, vol. III. Addison-Wesley, Reading, MA, pp. 73–89.