

SYMMETRY: CULTURE AND SCIENCE

**THE ARROW OF MIND: SYMMETRY-BREAKING,
INFORMATION, AND BIOLOGICAL COMPLEXITY**

James Barham

Address: 404 St Joseph St , Apt. 2, Lancaster, PA 17603, U S.A.

Abstract: *There are two senses in which symmetry-breaking produces information. In the first sense, we human beings interpret spatial symmetry-breaking in a physical system, whether inorganic or organic, as an increase in its information content (where the information is meaningful for us). This provides an information-theoretic measure of complexity, but one which is extrinsic or subjective, because relative to the human observer. In the second sense, temporal symmetry-breaking in a biological system may be interpreted as an increase in its information capacity (where the information is meaningful for the system itself). A dynamical model of the meaning of information is sketched which would provide an intrinsic or objective measure of biological complexity.*

1. INTRODUCTION

Information is one of the most vexed concepts on the contemporary intellectual scene. On the one hand, if we restrict it to its original, syntactic, use as a measure of the carrying capacity of a communications channel (Shannon & Weaver, 1963), then it is mathematically rigorous but hardly relevant to theoretical biology, cognitive science, or epistemology. On the other hand, if we relax our usage so as to encompass its semantic content, or meaning, then the concept of information becomes relevant to wider philosophical and scientific concerns, but only at the price of remaining ill-defined and largely mysterious. It is due to equivocation between these two usages that information has come to assume its aura of a fundamental physical principle on a par with matter and energy. However, as Ho (1993; p. 96) has remarked, “‘information’ is not something separate from energy and organization”; rather, it is a patterned matter or energy structure which acquires meaning by virtue of the role it plays in the organization of functional action (Barham, in press).

The concept of complexity is scarcely less contentious than that of information. On the one hand, information theory has seemed to provide us with various ways of quantifying the complexity of physical objects, including “algorithmic complexity” (defined as the length in bits of the shortest computer program capable of specifying an object) (Chaitin, 1990), “logical depth” (the number of operations, or logical steps, actually executed by such a program) (Bennett, 1988), and other similar measures (Wackerbauer et al., 1994). On the other hand, with respect to the class of physical objects which would appear to be the most complex of all — namely, biological organisms—it has been claimed that the notion of complexity is an anthropomorphic bias lacking objective validity (Gould,

1989; McShea, 1991).

The notion of symmetry-breaking provides a link between the concepts of information and complexity. This is fortunate in two ways. First, symmetry and symmetry-breaking are mathematically rigorous concepts which cannot help but clarify the relatively vague and confused notions of semantic information and complexity. Second, the essence of spatial symmetry-breaking is the creation of discernible differences, or structure, in the world where previously none existed, thus defining a "before" and an "after," and hence throwing light on the time irreversible nature of most real processes (aka, the "arrow of time"). This is useful because the very idea of complexity would seem to contain a directional component, as well; that is, we must assume that the different sorts of things in the world which we call "simple" and "complex" have come into being at different times, with the former preceding the latter. A world in which prokaryotic cells led to eukaryotic cells, on to plasmodial colonies, and ultimately to metazoans, makes intuitive sense to us, whereas a world in which this sequence ran backwards would appear absurd. However, the currently dominant school of thought in evolutionary biology, neo-Darwinism, either dismisses this directional component as subjective (as mentioned above), or else, if it recognizes the phenomenon as real, has only *ad-hoc* explanations to offer (Bonner, 1988). The notion of symmetry-breaking potentially offers a deeper and more unified explanation of this fundamental aspect of the evolutionary process.

In this paper, I will discuss some of the ways in which symmetry-breaking, information, and biological complexity are related to each another. In addition, using conceptual tools borrowed from nonlinear dynamics, I will construct a naturalistic model of semantic information. Finally, I will show how this way of understanding information suggests an objective metric of biological complexity.

2. SYMMETRY-BREAKING AND INFORMATION

On the surface, the link between symmetry-breaking and information would appear to be straightforward and unproblematic. The essence of the notion of symmetry-breaking is the creation of differences, or distinctions, where there were none before. Thus, if a featureless sphere is rotated about an arbitrary axis any number of degrees you like, it is indistinguishable from the unrotated object. As soon as we specify a great circle on the sphere as a benchmark, however, the symmetry is broken; now only a certain subset of rotations (namely, those about the diameter perpendicular to the plane of the great circle) will leave the object invariant. As a concrete example, consider an unfertilized ovum, on the one hand, and a newly-formed zygote, on the other. The former cell is spherically-symmetrical insofar as gross anatomical features are concerned.¹ This means it would be impossible to tell it had been rotated, unless it were marked in some way. At fertilization, however, the diameter formed by the entry point of the sperm cell and the point opposite defines the dorsal-ventral axis around which the process of gastrulation will largely unfold (Gilbert, 1988; pp. 124-25). Following this event, rotations can be discerned by measuring the displacement of this axis. Prior to symmetry-breaking, the

¹Needless to say, the unfertilized ovum is itself highly structured. However, although the future germ layers of the zygote can in fact be predicted from the orientation of the so-called "animal-vegetal" polarity of the ovum, the eventual dorsal-ventral axis of the zygote is not determined until the moment of fertilization (Gilbert, 1988; pp. 124-125). Therefore, the account in the text is an accurate, albeit idealized, description of the gross anatomical symmetry of the embryo

ovum had no discernible gross-anatomical features: the concepts “front” and “back” simply did not apply to it. After symmetry-breaking, the zygote has acquired parts which can then be distinguished by these labels.

Now, information in the Shannonian sense consists precisely in the specification of a particular set of elements out of a probability space consisting of all the permutations of such sets. On this view, then, the information content of an object is just the number of distinguishable parts it contains. Thus, the close connection between syntactic information and symmetry-breaking is readily apparent. On the one hand, spatial symmetry-breaking is the physical process which produces heterogeneity and differentiation in the world. On the other hand, information is a measure of the number of ways in which a region of the world can be subdivided into parts. In short, symmetry-breaking creates information in the Shannonian sense, and the Shannonian information content of an object is a measure of the reduction in its degrees of freedom.

It would appear that here we have penetrated to a deep truth about the nature of things. Thanks to this seemingly intimate link between symmetry and information, it appears possible to proceed directly from cosmogenesis to cognition, thus overleaping the chasm between matter and mind at a single bound. Indeed, it is quite common nowadays to encounter in scholarly writings the notion that information is a fundamental physical concept (e.g., Wicken, 1987), that organic evolution is a computational process (Dennett, 1995), and even that the universe as a whole is a gigantic cosmic computer (Wheeler, 1990). However, despite the conventional wisdom, these ideas are in fact anti-naturalistic; their superficial appeal is due to equivocation between the syntactic and semantic senses of the word “information.”

As we have seen, the notion of information implies an act (the nature of the agent usually being glossed over) of distinguishing one part from another, of specifying one pattern as opposed to other possible patterns, of *preferring* one thing over another. All of this is quite foreign to the traditional mechanistic view of nature. In short, the world cannot be reduced to pure syntax, because the very idea of syntax already presupposes semantics — i.e., a cognitive agent for whom the result of the syntactic operation is meaningful. Therefore, the notion of the cosmic computer implies that mind precedes matter — hence, it comes to imply the existence of a supernatural Hacker who interprets the results of the computations (Rosen, 1991). But if the notion of the cosmic computer is anti-naturalistic, then how can the seemingly close connection between symmetry-breaking and information be understood in a naturalistic way? Shannonian information theory is no help, because it simply ignores the problem of meaning, as Shannon himself was the first to admit (Shannon & Weaver, 1963; p. 31). What is needed, rather, is an objective, naturalistic understanding of the meaning of information on the basis of fundamental physical theory.

3. SYMMETRY-BREAKING AND BIOLOGICAL FUNCTION

The first step toward this goal is to clarify the reason why information cannot be simply equated with structuration due to symmetry-breaking: it is *not* because (as some so-called “postmodern” thinkers pretend) there is no objective structure to the world absent the human knower, or that the human mind somehow imposes its own structures on the external world (Barham, 1995). Rather, it is because the existence of structure is independent of any cognitive agent, whereas the existence of information about that structure depends on the prior existence of a cognitive agent for which the information is mean-

ingful. Information is simply not the sort of thing that can exist in the absence of living things. True, one might speak of a particular structure as having an informational *potential* for a certain kind of organism even if such an organism did not actually exist. But even in that case, the potential would inhere in the structure by virtue of the ability of a possible organism to actualize it, not as a fundamental physical property of the structure *per se*. However you look at it, information is a feature of the world which derives from, and exists only in relation to, living things. With this distinction in mind, then, it becomes clear that our goal is to explain the relationship between the structure of the world and the knowledge of it possessed by organisms, for that is what a physical theory of the meaning of information would amount to.

In the first place, it may be noted that the tendency of matter to arrange itself into one configuration, or structure, rather than another, is a matter of degree. There is clearly a sense in which it is correct to say that inanimate objects — from crystals to planets — have axes of symmetry and thus also have “preferred” orientations in space. The axes of symmetry of the orbiting earth or of a diamond are perfectly real and objective — they owe nothing to human categorization and would be exactly the same if human beings had never existed. In comparison with organisms, of course, this sort of “preference” is very attenuated. The question is, What is it that chiefly distinguishes the higher degree of preference exhibited by living things in comparison with inanimate objects? The answer would appear to be that it is the nature of the symmetry-breaking involved.

In the case of inanimate objects, structuration occurs primarily with respect to the three spatial dimensions. In the case of living things, it occurs above all with respect to time. The dynamical evolution, or motion, of most inanimate objects is remarkably uniform, which is to say that structuration due to symmetry-breaking along the time dimension is of a very low order for this class of objects. For example, the motions of the planets in their orbits may be modeled to a very high degree of approximation by linear equations producing one-to-one, time-symmetric mappings. This fact of celestial mechanics is, of course, what allows us to produce ephemerides that are valid for a period of time on the order of millennia. It is true that the apparent temporal symmetry of the planetary motions is an idealization which breaks down over longer periods of time; nevertheless, in comparison with the dynamics of the living state, temporal symmetry-breaking in the dynamics of most inanimate objects is of a very low order of magnitude. Thus, the “preferences” exhibited by inorganic systems are, for the most part, a matter of spatial rather than temporal structuration.

Matters stand very differently with living things. Here, it is dynamical structure — that is, temporal symmetry-breaking — that is of the essence. As Yates has observed (1993, p. 190-191):

[B]iological order is unlike order in physics or mathematics. Biological order is remarkable not for its degree, but for its specialness. It is a *functional* order that serves to correlate relevant biochemical and physiological events; but it is difficult to formulate mathematically the condition of invariance that must be fulfilled, which can be stated broadly as the need to keep the characteristics of one species constant during all the transformations that give rise to biochemical events during development. In contrast, in the case of a crystal lattice the spatial order is best expressed by the presence of correlations among the positions of equal atoms, and this order is further characterized by a condition of invariance toward the space transformations allowed by the symmetry class of the lattice in question. In functional order the correlations must be formed among the times at which different

events occur.” (emphasis in original)

While inanimate objects may seem to have preferred configurations in space, they are indifferent for the most part to the passage of time; one moment, for them, is much like any other. It seems a matter of indifference to them, so to speak, whether they continue to exist as a whole with a collective identity, or whether their coherence is destroyed and their parts are scattered. Living things, on the other hand, show a distinct preference for continued existence as organized wholes. Indeed, the chief characteristic of the living state is its striving to avoid disintegration. All living things actively resist the inexorable trend towards thermodynamic equilibrium in accordance with the Second Law through the cunning exploitation of physics and chemistry. Perhaps the most fundamental physical principle which life employs to win its temporary victory over the Second Law is symmetry-breaking in time.

In thermodynamically-isolated systems, local energy potentials will be smoothed out as the system relaxes to equilibrium in accordance with the Second Law. In systems thermodynamically open to energy and material flows in which the flux rate is greater than the thermal relaxation time, a steady state will be established away from equilibrium so long as the flow continues. In such nonequilibrium systems, it has been shown (Matsuno, 1989; Morowitz, 1979; Prigogine, 1980; Swenson, 1992) that global, coherent cycling is the expected result, since under these conditions the spontaneous creation of macroscopic structures dissipates energy more rapidly than thermal relaxation can do (hence the name “dissipative structures”). This is the fundamental physical reason why cycles, or oscillations, are discernible in almost all functional activity (Glass & Mackey, 1988; Lloyd & Rossi, 1992; Winfree, 1990). Although all such functional cycles are embedded within densely-nested hierarchical networks of other functions — from individual enzymes to metabolic networks to organ systems — nevertheless, at any given level, each one enjoys a limited degree of coherence and autonomy. This suggests that we might model functional activity in general by means of the notion of a nonlinear oscillator and its associated phase-space attractor. Instead of a one-to-one mapping of initial states onto final states, we have a many-to-one mapping of a large ensemble of possible initial states of the system onto a single final state (the “goal state”). This set of equifinal phase-space trajectories is referred to as the system’s “basin of attraction”; the goal state is its “attractor.” A nonlinear attractor is a mathematical object whose property of equifinality nicely captures the goal-directedness, or teleonomy, that is the essential feature of the dynamical evolution of living things (Delattre, 1986). Once we have taken this step, then the notion of the “success” of a functional action may be identified with the preservation of the dynamical stability of its associated nonlinear oscillator (and hence its continued cycling).

From such a viewpoint, it is clear that, with respect to the dynamical evolution of biofunctions, all times are no longer equal. The activity of each of an organism’s subsystems, or biofunctions, may be viewed as a diachronic structure created by symmetry-breaking along the time dimension in the same way that an ordinary object is a synchronic structure created by symmetry-breaking in three-dimensional space. The temporal symmetry is broken in the sense that the dynamical evolution of a biofunction is no longer invariant under time reversal, since its final state cannot be traced back to a unique initial state.

How is it possible for mere molecules, through “signalling” and “recognition,” to “regulate” and “coordinate” chemical events in time in such a way as to keep the Second Law temporarily at bay in order to make life possible? In spite of the staggering ad-

vances in molecular biology over the past half century, many aspects of this question remain unanswered. However, it does appear that the strong preferences, or goal-directedness, exhibited by living things must be accompanied by a power of discrimination of external conditions in order to be successful. In Section 4, I will sketch a dynamical model of the connection between biological function and cognition. From this model may be derived a physical interpretation of information that is intrinsically meaningful to organisms themselves (Section 5). Finally, in Section 6 I will attempt to show how this interpretation of semantic information can be used as the basis for an objective metric of biological complexity.

4. A DYNAMICAL MODEL OF THE MEANING OF INFORMATION

The resistance to the Second Law which is the chief mark of the living state translates, in physical terms, into a partial autonomy with respect to local energy potentials. More precisely, biological systems are able to vary their rate of energy consumption independently of variations in local gradients thanks to their "on-board" energy supply in the form of ATP and related compounds. This ability allows living things to avoid slavish dependence on their surround and to resist disintegration when external conditions deteriorate by actively seeking out more favorable conditions, either in time (by slowing down their metabolism in order to conserve on-board supplies) or in space (by speeding it up in order to move about). This limited independence of living things from local energy potentials has a crucial corollary: a biofunction must be able to distinguish between those conditions external to itself which will support its continued oscillation, and those which will not. In other words, energy autonomy — and hence life itself — implies a degree of cognition.

How is it possible for a biofunction, conceived of as a nonlinear oscillator, to acquire this ability to distinguish between those external conditions which will support its continued oscillation and those which will not, and to coordinate its functional action accordingly so that its dynamical stability will be preserved? The answer seems to be that living systems achieve limited energy autonomy from local, high-energy potentials by becoming sensitive to nonlocal, low-energy fluxes. As Swenson has put it (1992; pp. 140-141):

...whereas in nonliving systems the dynamics are governed by local field potentials (with dimensions of mass, length, and time, viz, "mass-based" fields), the dynamics of the living are governed by nonlocal potentials linked together through observables with dimensions of length and time (kinematic or information fields).

Thus, the chief difference between an organism and an inorganic nonlinear oscillator (like a hurricane) is the organism's ability to use low-energy fluxes from a distal source in order to detect high-energy potentials before it becomes thermodynamically coupled with them. In order to explain this seemingly mysterious ability, I have proposed (Barham, 1990) that we postulate a fundamental differentiation within all biofunctions between: (1) a high-energy interaction of the oscillator with a set of constraints in its surround (the functional action as a whole); and (2) a low-energy interaction of a subsystem of the oscillator with a second set of constraints which are highly correlated with the first set. Note that this postulated differentiation implies the existence of a component within every biofunction capable of undergoing the low-energy interaction; I have pro-

posed that this subsystem be called the “epistemon.” (In essence, the epistemon is a generalization of the notion of a sense organ.) This conjecture leads naturally to a tetradic model of perception and action, as follows. (See Figure 1)

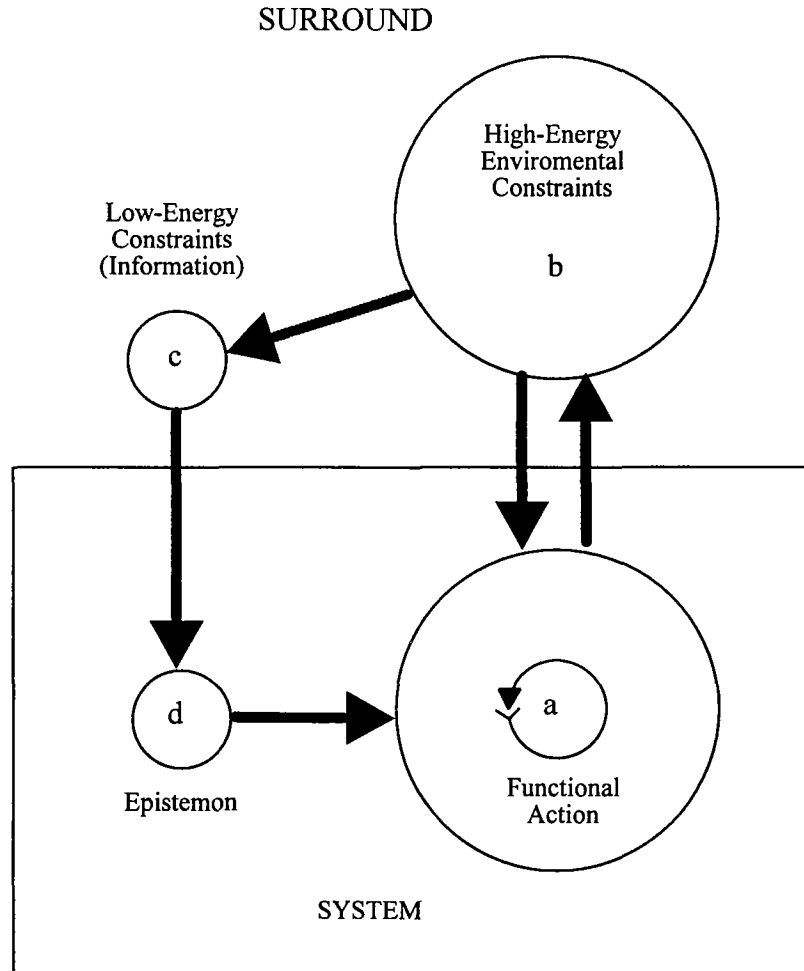


Figure 1: A biological function modeled as a nonlinear oscillator with a low-energy trigger

First, we posit an existing biofunction (a) coupled to its surround in such a way that its functional action is ordinarily successful (i.e., a dynamically-stable nonlinear oscillator). Next, we pick out those high-energy constraints (b) in the surround with which (a) ordinarily interacts. Then, we identify a second set of environmental constraints (c) which

are highly correlated with the first set, but which are lower in energy. Finally, we have the postulated universal subsystem (d) (the epistemon) which is capable of interacting with these low-energy constraints. As a result of the interaction between the low-energy constraints and the epistemon, the latter undergoes a state transition which acts as a *trigger* for the functional action (a), thus completing one perception-action cycle. Now, provided only that the two sets of exogenous constraints — high-energy (b) and low-energy (c) — stand in some causal relation to each other (the precise nature of which will vary from case to case), then the correlation (d)-(a) between the epistemon state transition and the oscillation of the biofunction becomes, in effect, an internal projection of the correlation (b)-(c) between the high- and low-energy constraints. That is, the low-energy constraints act as *semantic information* with respect to the functional action, indicating the presence of those external conditions which successfully support its action.

Another way of putting it is to say that the interaction between the low-energy (or informational) constraints and the epistemon (call it the “epistemic interaction”) *predicts* that the overall functional action, if undertaken now, will be successful (meaning that the dynamical stability of the oscillator will be preserved). In short, *the meaning of information is the prediction of the success of functional action.*

5. INFORMATION: SUBJECTIVE AND OBJECTIVE

At first glance, this conception of information would appear to be inconsistent with the usual Shannonian notion. However, it is easy to see that in fact they are complementary. On the one hand, the low-energy inputs carrying semantic information can be analyzed syntactically (i.e., broken down into “bits”) in the usual way. Of course, even here, syntax remains dependent on semantics, since how the bits are counted will depend on the purpose of the counter, but then that is always true. On the other hand, we can now give a naturalistic account of this dependency of syntax on semantics, as opposed to merely noting it as a brute fact. According to this model, to ascribe a syntactic information content to an object is tantamount to listing the number of different epistemic interactions we can have with that object. For example, if I say that a sheet of paper with some marks on it contains 100 bits of information, what this means is that there are 100 distinct states of the sheet, each of which is capable of interacting with a correlated epistemon in my brain. Thus, we can see the reason why the traditional information-theoretic measures of complexity are inherently subjective. As Grassberger has noted (1989, p. 496): “We really cannot speak of the complexity of a pattern without reference to the observer.” This is because all that the syntactic notion of information content is really measuring is the capacity of the object in question to produce distinct states *in us*.

In applying the theory sketched above reflexively to ourselves in this way, we are stepping outside of the traditional circle of ideas in artificial intelligence, and cognitive science generally, which attempted to explain human cognition in purely syntactic terms on the model of the digital computer. In so doing, we may rely on a growing body of work— which, if it has not yet won widespread mainstream recognition, nevertheless by now constitutes a substantial and respectable rival school of thought — that views brains as nonlinear dynamical systems (Brooks, 1995; Freeman, 1995; Kelso, 1995; Port & van Gelder, 1995; Pribram, 1994; Thelen & Smith, 1994). Freeman’s work, in particular, is congenial to the viewpoint adopted in this paper. For example, he has demonstrated that identifiable chaotic attractors in EEG data, which are generated by coherent oscillations of nerve cell assemblies, can be predictably correlated with individual perceptual cate-

gories. These nerve cell assemblies — or rather, their collective modes of action — are natural candidates for epistemons according to the model of perception and action sketched above.

But even if the syntactic view of information based on Shannonian information theory and the semantic view sketched above based on nonlinear dynamics can be reconciled with one another, nevertheless they remain very different approaches which are useful for different purposes. The syntactic information *content* of an object is extrinsic and subjective in the sense that the information is only meaningful for us, not for the object itself; on the other hand, the semantic information *capacity* of an organism (roughly, the number of epistemic interactions it is capable of entering into) is intrinsic and objective in the sense that the information is meaningful for the organism itself.²

One must be careful about the terms “subjective” and “objective,” here. There is an epistemological sense in which the Shannonian information content of an object is objective: namely, it can be formalized and publicly agreed upon. However, I am using the terms in an ontological sense in order to draw attention to where, in the physical world, the meaning of the information is actually located. In the syntactic, Shannonian case, the meaning is located in the human being, and is extrinsic to the object to which the information content is attributed; therefore, one may say that it is ontologically subjective in the sense that it has no existence independent of the human observer. In the semantic, dynamical case, on the other hand, the meaning of the information is located in the organism itself; it is an intrinsic, objective fact about the world which does not depend in any way on the existence of a human observer. (The fact that the organism in question may also be a human being is irrelevant, since science has long since grown accustomed to viewing the human being in objective terms, ontologically speaking.)

This distinction between the extrinsic, or subjective, and the intrinsic, or objective, senses in which information may exist is of fundamental importance for clarifying a number of difficult scientific and philosophical problems, including that of defining an objective metric of biological complexity. It is to this question that I turn in the next section.

²Some authors (e.g., Brooks & Wiley, 1988) use the term information “capacity” to refer to the probability space against which the actual information “content” of a system is supposed to be measured. For example, the information “content” of an organism might be the number of base pairs present in its genome, while the information “capacity” of the same organism would be the factorial of this number! There are many objections to this way of looking at things. In the first place, this notion of information capacity is subjective and arbitrary, because it is tied directly to the subjective and arbitrary notion of information content (what should count as a “bit” of information? base pairs, or genes? if genes, how do we identify them? do we count proteins, or actual biofunctions? if we try to count biofunctions, how are we going to work backwards to the genes again? and what about introns? etc.) Furthermore, even if an objective measure of information content were possible, what good would it be? Only infinitesimally few of the alternative states in probability space would be functionally viable, and we would still have no way of knowing which were which, therefore, as a theoretical construct, information “capacity” in this sense would be useless. Of course, this just points up the fundamental fallacy of applying extrinsic and subjective information-theoretic measures to organisms as though they were intrinsically and objectively meaningful (see, also, Lewontin, 1993) Unlike the information-theoretic use of the term, my use of information “capacity” describes an objective property of the organism itself. I hope that the other meaning of the term is not yet so entrenched as to foreclose the possibility of diverting it to a more appropriate use.

6. BIOLOGICAL COMPLEXITY AS EPISTEMIC DEPTH

The idea that there exists a natural hierarchical continuum in which all living things have their place — sometimes referred to as the *scala naturae* (“ladder of nature”) — is a very old one (Lovejoy, 1936). Although many specifically European ideological features have been grafted onto this notion over the centuries, particularly during the period of the domination of Christianity, the fundamental insight cannot be attributed to mere cultural conditioning, since similar conceptions have arisen independently in other cultures (e.g., China — see, Tu, 1984). Certainly, when one compares a prokaryotic with a eukaryotic cell, an amoeba with an ant, or an oyster with an octopus, a compelling case can be made for the existence of a vector of increasing complexity over the course of evolutionary history. If that is so, then the *scala naturae* is a striking and important phenomenon which demands scientific explanation.

Nevertheless, as was noted above, many view this intuition as little more than an anthropocentric bias, and certainly it has never been successfully translated into quantitative or operational terms. Therefore, until recently, the whole subject has been scientifically disreputable. At present, it is undergoing renewed scrutiny (Bonner, 1988; Cowan et al., 1994; Nitecki, 1988; Weber et al., 1988; Zurek, 1990). However, most recent authors who have studied the fossil record with a view to quantifying the intuitive notion of an increase in morphological complexity have come to a pessimistic conclusion. For example, Boyajian and Lutz (1992) and McShea (1992, 1993) have shown that the history of repetitive skeletal structures does not support the hypothesis of an overall trend toward increasing complexity. It is true that one occasionally meets with a grudging acknowledgement of the existence of some trend or other in the fossil record — such as Gould et al.’s (1987) study of species diversity (coupled, however, with the earnest denial that the trend in question constitutes evidence of genuine complexification). There is even a minority viewpoint which allows that complexity increase may be real — see, e.g., Valentine et al.’s (1994) study of the increase in the number of cell types in metazoans over time. On the whole, though, the majority opinion within evolutionary biology remains highly skeptical. Most practitioners still feel it is preferable to explain the impression of a natural hierarchy of living things as an artifact of perspective which causes us to attach greater value to organisms which are similar to ourselves.

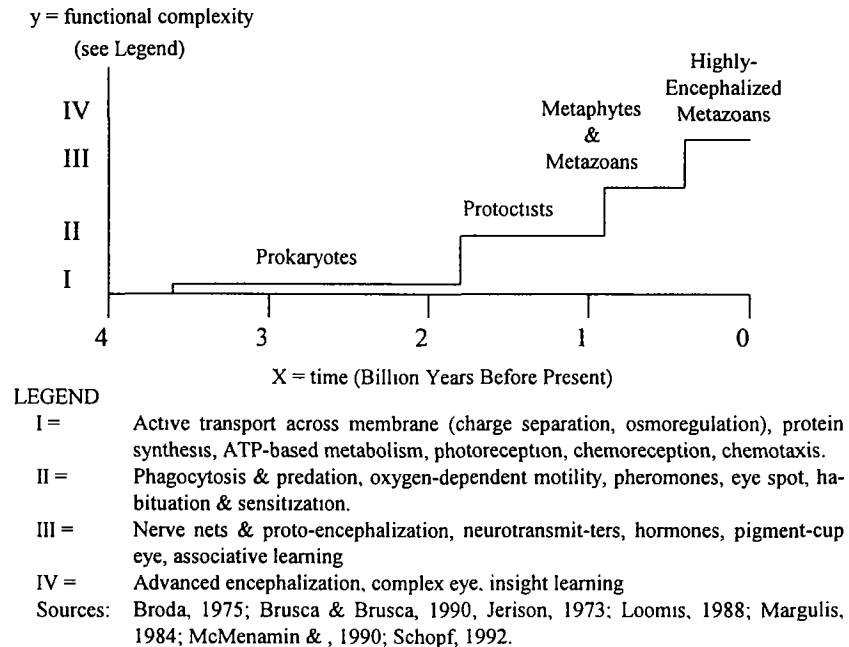


Figure 2: Main stages in the evolution of functional complexity

A glance at Figure 2 ought to be sufficient to convince an unbiased observer that the intuitive idea of the *scala naturae* — that is to say, a time-irreversible vector of increasing biological complexity — is, in fact, objectively valid. The functional repertoire of a highly-encephalized animal (say, the octopus) is built up out of the general metazoan repertoire (e.g., that of the flatworm), which in turn is constructed from the general eukaryotic repertoire (amoeba), which is derived from the prokaryotic repertoire (bacterium) that is shared by all living things. It is tolerably clear that we are dealing here with a natural phenomenon on a par with any other, whose structure is not understood and which therefore deserves a scientific explanation.

How to explain this structure is, of course, another matter. It is clear that none of the various information-theoretic metrics of complexity that have been proposed (e.g., Bennett, 1988; Chaitin, 1990) can help us here, because they measure the extrinsic information *content* of objects; what we want is a way to quantify the intrinsic information *capacity* of organisms. At first glance, Lloyd and Pagels' (1988) "thermodynamic depth" would appear to fill the bill. Whereas Bennett's "logical depth" is the number of steps required to execute the genetic "program" that supposedly produced an organism, the thermodynamic depth of the same organism would be the number of evolutionary steps it took to construct it. This is a step forward because, unlike the information-theoretic notion of a genetic "program," the evolutionary history of an organism in the fossil record gives us an objective quantity that can be estimated independently of human choices or purposes. Furthermore, the concept of thermodynamic depth points to an important aspect of the problem of complexity: namely, the fact that the more intuitively simple creatures must precede the more intuitively complex ones in evolutionary history. Unfortunately, though, what thermodynamic depth is really measuring is not the complexity of

an organism as such, but merely its evolutionary "age." It is an explanation of sorts of how a complex organism got to be the way it is, but it still does not give us an independent way of measuring complexity, apart from the fossil record. Rather, by tacitly assuming the correlation between length of evolutionary history and degree of complexity, the notion of thermodynamic depth begs the crucial question: How do we know that one organism is more or less complex than another, in the first place? What we really need is a thermodynamic (i.e., non-syntactic) approach which focuses, not on phylogeny, but on the individual organism.

The dynamical model of semantic information outlined in Section 4 above provides a way of doing this. If we think of each of the myriad, hierarchically-nested biofunctions within a given organism — enzyme species, metabolic networks, organ systems, nerve cell assemblies, and so forth — as a coherent nonlinear oscillator, then a natural measure of intrinsic biological complexity suggests itself. Namely, the complexity of an organism, on this model, may be measured by the number of different types of epistemic interactions it is capable of undergoing (that is, by the number of different kinds of epistemons it contains). Let us call this value the *epistemic depth* of the organism. Loosely speaking, then, one might say that the epistemic depth of an organism is the sum of the number of distinct biological functions it contains. Since one of the chief means nature employs for creating new biofunctions is the integration of old functions into new emergent wholes, the notion of epistemic depth accords well with the intuitive conception of the *scala naturae* illustrated by Figure 2.

Obviously, it would be out of the question to attempt to assign an actual empirical value to this quantity for a particular organism, because the notion of an epistemon is as yet too abstract to be of much operational value. However, in this respect, the notion of epistemic depth fares no worse than other proposed complexity metrics. Its advantage is that, unlike its information-theoretic rivals, it tackles directly the problem of what we intuitively mean by biological complexity. The basic mistake that most investigators have made is to assume that what mattered was the number of different parts (broken symmetries in space) an organism contained. But surely our intuitive idea of the *scala naturae* is captured better by counting the number of different functions (broken symmetries in time) an organism is capable of performing. Counting biological functions comes much closer to capturing what we intuitively mean by biological complexity because, unlike the counting of parts, it takes into account the information capacity (i.e., intelligence) of an organism. An octopus seems to us more complex than an oyster because it is capable of doing more things, which is equivalent to saying that it knows more things. This explains why those who have focused on cell types — which differ largely according to their function — have come to a different conclusion from those who have studied repetitive structural parts: namely, that a vector of increasing complexity over the course of the evolutionary history of the metazoans really does exist.

The notion of epistemic depth is potentially an even better metric than cell type number, since it may eventually allow us to measure complexity increase from single cells to animals with sophisticated brains on a single scale. By pointing to the fundamentally epistemic aspect of all functional activity, it allows us to characterize the apparent increase in complexity over the course of organic evolution as an increase in information capacity, and to explain this irreversible process as a result of temporal symmetry-breaking analogous to the spatial symmetry-breaking that has occurred over the course of cosmic evolution. In this way, organic evolution may be viewed as a stage in the overall structuration of the universe that is ultimately traceable to the nonequilibrium conditions created by the Big Bang (Frautschi, 1982; Layzer, 1990). One might even go

so far as to say that, with the emergence of life, the cosmological arrow of time assumed the form of a biological "arrow of mind."

REFERENCES

- Barham, J. (1990) A poincaré approach to evolutionary epistemology, *Journal of Social and Biological Structures*, **13**, 193-258.
- Barham, J. (1995) Ni Darwin ni Derrida, *Journal of Social and Evolutionary Systems*, **18**, 277-308.
- Barham, J. (in press) A dynamical model of the meaning of information, *BioSystems*.
- Bennett, C. H. (1988) Dissipation, information, computational complexity and the definition of organization, In: Pines, D., ed., *Emerging Syntheses in Science*, Redwood City CA: Addison-Wesley, pp. 215-233.
- Bonner, J. T. (1988) *The Evolution of Complexity by Means of Natural Selection*, Princeton, NJ: Princeton University Press.
- Boyajian, G. and Lutz, T. (1992) Evolution of biological complexity and its relation to taxonomic longevity in the ammonioidea, *Geology*, **20**, 983-986.
- Broda, E. (1975) *The Evolution of the Bioenergetic Processes*, Oxford: Pergamon.
- Brooks, D. R. and Wiley, E. O. (1988) *Evolution as Entropy: Towards Unified Theory of Biology*, 2nd ed., Chicago: University of Chicago Press.
- Brooks, R. A. (1995) Intelligence without reason, In: Steels, L. and Brooks, R., eds., *The Artificial Life Route to Artificial Intelligence*, Hillsdale NJ: Erlbaum, pp. 25-81.
- Brusca, R. C. and Brusca, G. J. (1990) *Invertebrates*, Sunderland MA: Sinauer.
- Chaitin, G. J. (1990) Algorithmic information theory, In: Chaitin, G. J., *Information, Randomness and Incompleteness. Papers on Algorithmic Information Theory*, 2nd ed., Singapore: World Scientific, pp. 44-58.
- Cowan, G.A., Pines, D., and Meltzer, D., eds. (1994) *Complexity: Metaphors, Models, and Reality*, Reading, MA: Addison-Wesley.
- Delattre, P. (1986) An approach to the notion of finality according to the concepts of qualitative dynamics, In: Diner, S., Fargue, D., and Lochak G., eds., *Dynamical Systems: A Renewal of Mechanism*, Singapore: World Scientific, pp. 149-154.
- Dennett, D. C. (1995) *Darwin's Dangerous Idea. Evolution and the Meanings of Life*, New York: Simon & Schuster.
- Frautschi, S. (1982) Entropy in an expanding universe, *Science*, **217**, 593-599.
- Freeman, W. J. (1995) *Societies of Brains*, Hillsdale NJ: Erlbaum.
- Gilbert, S. F. (1988) *Developmental Biology*, 2nd ed., Sunderland MA: Sinauer.
- Glass, L. and Mackey, M. C. (1988) *From Clocks to Chaos. The Rhythms of Life*, Princeton NJ: Princeton University Press.
- Gould, S. J. (1989) *Wonderful Life*, New York: Norton.
- Gould, S. J., Gilinsky, N. L., and German, R. Z. (1987) Asymmetry of lineages and the direction of evolutionary time, *Science*, **236**, 1437-1441.
- Grassberger, P. (1989) Problems in quantifying self-generated complexity, *Helvetica Physica Acta*, **62**, 489-511.
- Ho, M.-W. (1993) *The Rainbow and the Worm. The Physics of Organisms*, Singapore: World Scientific.
- Jerison, H. J. (1973) *Evolution of the Brain and Intelligence*, New York: Academic Press.
- Kelso, J. A. S. (1995) *Dynamic Patterns: The Self-Organization of Brain and Behavior*, Cambridge MA: Bradford Books/MIT Press.
- Layzer, D. (1990) *Cosmogogenesis: The Growth of Order in the Universe*, New York: Oxford University Press.
- Lewontin, R. C. (1993) *Biology as Ideology: The Doctrine of DNA*, New York: Harper Perennial/HarperCollins.
- Lloyd, D. and Rossi, E. L., eds. (1992) *Ultradian Rhythms in Life Processes*, London: Springer-Verlag.
- Lloyd, S. and Pagels, H. (1988) Complexity as thermodynamic depth, *Annals of Physics*, **188**, 186-213.
- Loomis, W. F. (1988) *Four Billion Years: An Essay on the Evolution of Genes and Organisms*, Sunderland

- MA: Sinauer.
- Lovejoy, A. O. (1936) *The Great Chain of Being*, Cambridge, MA: Harvard University Press.
- Margulis, L. (1984) *Early Life*, Boston: Jones and Bartlett.
- Matsuno, K. (1989) *Protobiology: Physical Basis of Biology*, Boca Raton FL: CRC Press
- McMenamin, M. A. S. and McMenamin, D. L. S. (1990) *The Emergence of Animals: The Cambrian Break-through*, New York: Columbia University Press
- McShea, D. W. (1991) Complexity and evolution: What everybody knows, *Biology and Philosophy*, 6, 303-324.
- McShea, D. W. (1992) A Metric for the study of evolutionary trends in the complexity of serial structures, *Biological Journal of the Linnean Society*, 45, 39-55.
- McShea, D. W. (1993) Evolutionary change in the morphological complexity of the mammalian vertebral column, *Evolution*, 47, 730-740.
- Morowitz, H. J. (1979) *Energy Flow in Biology*, Woodbridge CT: OxBow Press. (Originally published by Academic Press, New York, in 1968.)
- Nitecki, M. H., eds. (1988) *Evolutionary Progress?*, Chicago: University of Chicago Press.
- Port, R. F. and van Gelder, T., eds. (1995) *Mind as Motion. Explorations in the Dynamics of Cognition*, Cambridge MA: Bradford Books/MIT Press.
- Pribram, K. H., ed. (1994) *Origins: Brain and Self Organization*, Hillsdale NJ: Erlbaum.
- Prigogine, I. (1980) *From Being to Becoming*, San Francisco. W. H. Freeman and Company.
- Rosen, R. (1991) *Life Itself. A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*, New York: Columbia University Press
- Schopf, J. W., ed. (1992) *Major Events in the History of Life*, Boston: Jones and Bartlett.
- Shannon, C. E. and Weaver, W. (1963) *The Mathematical Theory of Communication*, Urbana IL: University of Illinois Press (Originally published in 1949.)
- Swenson, R. (1992) Order, evolution, and natural law: Fundamental relations in complex system theory, In: Negoita, C. V., ed., *Cybernetics and Applied Systems*, New York: Marcel Dekker, pp. 125-148.
- Thelen, E. and Smith, L. B. (1994) *A Dynamic Systems Approach to the Development of Cognition and Action*, Cambridge MA: Bradford Books/MIT Press
- Tu W-M (1984) The Continuity of being: Chinese visions of nature, In: Rouner, L.S., ed., *On Nature*, Notre Dame IN: University of Notre Dame Press, pp. 113-129. (Reprinted in: Callicott, J.B. and Ames, R T., eds., *Nature in Asian Traditions of Thought*, Albany, NY: State University of New York Press, 1989, pp 67-78, 298-301.)
- Valentine, J. W., Collins, A. G., and Meyer, C. P. (1994) Morphological complexity increase in metazoans, *Paleobiology*, 20, 131-142.
- Wackerbauer, R., Witt, A., Atmanspacher, H., Kurths, J., and Scheingraber, H. (1994) A comparative classification of complexity measures, *Chaos, Solitons and Fractals*, 4, 133-173.
- Weber, W. H., Depew, D. J., and Smith, D. J., eds. (1988) *Entropy, Information, and Evolution: New Perspectives on Physical and Biological Evolution*, Cambridge MA: Bradford Books/MIT Press
- Wheeler, J. A. (1990) Information, physics, quantum: The search for links, In: Zurek, W. H., ed., *Complexity, Entropy and the Physics of Information*, Redwood City CA: Addison-Wesley, pp. 3-28
- Wicken, J. S. (1987) *Evolution, Thermodynamics, and Information: Extending the Darwinian Paradigm*, New York: Oxford University Press.
- Winfrey, A. T. (1990) *The Geometry of Biological Time*, corrected reprint, Berlin: Springer-Verlag. (Originally published in 1980.)
- Yates, F. E. (1993) Self-organizing systems, In: Boyd, C. A. R. and Noble, D., eds., *The Logic of Life: The Challenge of Integrative Physiology*, Oxford: Oxford University Press, pp. 189-218
- Zurek, W. H., ed. (1990) *Complexity, Entropy and the Physics of Information*, Redwood City, CA: Addison-Wesley.