Sabelli, H. (1994). Entropy as symmetry: Theory and empirical support. New Systems Thinking and Action for a New Century: Proc. International Systems Society 38th Annual Mtg., B. Brady and L. Peeno (Eds.), Pacific Grove, CA. pp. 1483-1496.

ENTROPY AS SYMMETRY: THEORY AND EMPIRICAL SUPPORT

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Abstract: There is a fundamental contradiction among the three current theories of processes: thermodynamics postulates involution toward resting equilibrium (Clausius) and disorder (Boltzmann); mechanism postulates reversibility and hence the conservation of information; and evolutionary theory describes the emergence of complexity from simpler origins. Process theory provides a framework unifying thermodynamics and evolution, as well as a methodology to study entropy and dimensionality in complex processes. Process thermodynamics postulates the conservation of the asymmetry of action (energy x time) as an asymmetry of structure, and defines the maximization of entropy as a tendency to symmetry, not disorder. The Shannon's entropy and the median dimension of model mathematical distributions and of electrocardiographic data were measured with the recurrence method. In computer-generated time series, it was found that dimensionality decreased and entropy increased with increased order, from random numbers to symmetrically organized distributions. Time series of cardiac intervals showed intermediate values of entropy and dimensionality. These gradients of entropy and dimensionality from disorder to symmetry suggests that entropy maximization creates complexity as partial symmetries (periodic and chaotic attractors, dissipative structures, organisms, etc).

Key words: asymmetry; electropsychocardiography; entropy; evolution; process theory; symmetry; thermodynamics.

The maximization of entropy postulated by the second law of thermodynamics, perhaps the most general law of physics, remains one of the most puzzling issues in contemporary science. There have been at least twenty other different and often mutually exclusive definitions of entropy [6]. Thermodynamic entropy (Gibbs) always increases; statistical entropy (Boltzmann) tends to increase, while informational entropy (Shannon) decreases with the arrival of a message. In Shannon's equation [28], entropy and information are positively related, but many authors consider information as negative entropy. This terminological confusion reflects deep conceptual discrepancies. Contemporary science includes three contradictory models: (1) Mechanics (Newtonian, relativistic, quantic or statistical), postulating static structures and reversible change; time reversibility implies a cosmic symmetry and the conservation of information. (2) Evolutionary theories that postulate a temporal increase in complexity and diversity. (3) Thermodynamics, postulating involution toward resting equilibrium (Clausius) and disorder (Boltzmann). Statistical Mechanics provides a scenario in which mechanism and thermodynamics can coexist by explaining entropy as a probabilistic phenomenon; however, it allows for reversibility (excluded by the second law), it fails to explain why either evolution or irreversibility occur, and it must explain the tendency to maximize entropy as the result of initial conditions, which are both arbitrary and untestable, as there is nothing in the equations of mechanics or of probability to account for it [14].

Figure 1

Two solutions have been offered to the contradiction between evolution and thermodynamics: (a) the expansion of space, both physical [11,17] and genetic [5]; and (b) the hypothesis that entropy increases necessarily only in closed systems (figure 1 A), whereas open systems such as biological organisms [29] and other complex processes [19] may reduce their internal entropy by importing free energy from the environment, and exporting entropy to it (figure 1 B). Here I want to present another potential synthesis, originating with a biologically-based theory of processes [7,20-25] which provides a unifying explanation of cosmological and biological evolution as necessary consequences of thermodynamic processes.

Process thermodynamics: According to process theory: (1) Everything is action, the asymmetric flow of energy in time. (2) Every action is associated with an opposing process, thus generating symmetry; the maximization of entropy represents this tendency toward the generation of symmetry. (3) Processes create structures (partial symmetries) at critical and intermediate values of temperature and dimensionality. Postulating that asymmetry and symmetry are cosmic forms that order all natural processes and structures, process theory provides a reformulation of entropy as symmetry rather than disorder, and of its maximization as a cosmic asymmetry. The tendency of processes to attain a more stable configuration creates symmetry in natural systems. The various forms of partial symmetry attained includes not only more uniform and probable distribution of the system components, but also the formation of complex and asymmetric structures. Entropy thus increases everywhere, and faster in a complex system than in its simpler environment (figure 1 C).

The three laws of process theory: 1. Energetic asymmetry: All is action (where action = energy x time). Thus everything spontaneously changes and exchanges. Everything is a process, i.e., a composite of actions, and hence have two asymmetries, the potential of energy and the unidirectionality of time. Because all processes are forms of the same energy, they change in the same direction, time. Action is a universal asymmetry of nature.

Observing that biomolecules are asymmetric, and postulating a cosmic evolution from fundamental physical entities to biological organisms, Pasteur postulated that asymmetry must also exist in inorganic molecules, in atoms, and in the most fundamental physical entities ("cosmic asymmetry"). Whereas it is still commonly considered that fundamental physical interactions are symmetric ("the conservation of parity") and that time-reversible laws govern microscopic physics, Pasteur's hypothesis has been confirmed by a number of discoveries, beginning with the non-conservation of parity in beta decay [32] and culminating with evolutionary cosmology with a sequence of symmetry breaks starting with the expansion of the universe, a fundamental asymmetry that may explain the emergence of complexity in the road towards entropy [17]. The unified theory of electromagnetism and weak interactions indicates that asymmetry is not limited to nuclear processes; the optical rotation of atoms has been demonstrated empirically [3], and may explain biomolecular asymmetry [16]. String theory postulates that the most elementary components of nature are asymmetric, line-like rather than point-like. In the evolution of the universe, there is a net conversion of energy into matter, and an apparent increase in complexity. Other naturally occurring asymmetries include the asymmetric preponderance of matter over anti-matter; the unidirectionality of causation; the time-asymmetric collapse of the wave function in quantum mechanics; the spontaneous maximization of entropy (second law of thermodynamics); the role of highly asymmetric, non-equilibrium states in the thermodynamics of open processes [19]; the violation of gauge symmetry by superfluids; the lack of time symmetry in magnets [1]; and biological asymmetries, ranging from the ionic asymmetry across plasma membranes, to gross anatomical asymmetries, and social asymmetries [12]. The irreversibility of processes is a thermodynamic asymmetry. Information is a difference or asymmetry of opposites. Energy, information and matter are asymmetries within the symmetric flux of the vacuum state [2] from which energy and matter may arise as random quantum fluctuations [31]. As heat, thought to be a substance by Carnot, turned out to be a motion, so energy-matter, thought to be a substance, may be an asymmetry.

Energy and matter are transformed into each other (Einstein), but, in the evolution of the universe, there has been a net formation of matter from energy. This suggests that energy tends to spontaneously form matter more readily than matter decays to form energy. Since energy is asymmetric flow, and matter is a structure maintained by the equilibrium of opposing forces of attraction and repulsion, this example is paradigmatic of the tendency of asymmetric energy flow to produce more symmetric and more complex structures. However, material structures are only partially symmetric, and in the evolution of matter, life and psyche emerge. Action does not cease, because structures conserve in their organization the asymmetry of the processes that formed them. As the asymmetry of free energy decreases, the complexity of structure increases. We can thus expand the law of the transformation and conservation of energy into a **law of transformation and conservation of asymmetry**.

Prigogine [19] argued that reversible mechanical processes can never explain irreversible phenomena, that irreversibility is true at all levels or at none. He thus proposed to change the microscopic laws of physics, introducing an intrinsic indeterminism. Pasteur's cosmic asymmetry represents an alternative modification of the mechanics of fundamental physical entities, a determined asymmetry. As a result, the universe is a uni-verse, i.e. a unidirectional flow. The second law makes explicit its direction of this as a tendency toward symmetry.

2. Entropy as symmetry: universality of opposition. Every process and every structure includes two opposite components (enantiodromia): attraction and repulsion, union and separation, asymmetry and symmetry, left and right, positive and negative. For instance, every physical force of attraction has a range at which it repels. Gravity itself is counterbalance by the spontaneous expansion of the universe. Every change generates its opposite**, so processes increase their internal symmetry, tending toward attractors and forming structures. Symmetric equilibrium is always partial and local.** Isolated from interactions, processes flow towards stable attractors --a fundamental asymmetry of nature-- but an attractor is a balance or symmetry between opposites, a symmetry. As the term equi-librium (equal forces) indicates, a point attractor is an equality or symmetry of opposite forces. Classic thermodynamics described systems as flowing towards a static point attractor --equilibrium. Periodic attractors, the chaotic attractors, and dissipative structures also represent forms of symmetry, in that they are constructed by the balance of opposite forces, alternating in predominance such as in periodic or aperiodic processes, or counterbalancing each other in structures. A delicate balance of forces erects a cathedral or makes an enzyme. Thus the balance of opposites can maintain ordered structure, accelerate change and enhance complexity, rather than arrest change or erode structure. Point, periodic and chaotic attractors serve to model involutionary, mechanical and evolutionary processes respectively, as three coexisting, complementary and opposite types of change.

The maximization of disorder represents an asymmetric flow toward equilibrium point attractors. Only near equilibrium, closed systems flow toward resting equilibrium [19]. Far from equilibrium, highly asymmetric processes tend to more complex periodic and chaotic attractors. Oscillatory changes, such as Bernard's instability or complex biological rhythms, may be understood in terms of periodic attractors, limit cycles in which opposite states alternate in a repetitive manner. A wide variety of processes, ranging from turbulent hydrodynamic flows and weather [18] to cardiac rhythms [15] and cellular differentiation [30], appear to represent chaotic processes that spontaneously generate novel and complex dissipative structures. Hence, the spontaneous tendency of processes to flow toward attractors cannot be described as a tendency toward disorder, but always represents a tendency toward symmetry. One may thus redefine the second law as a maximization of symmetry resulting from the generation of opposite processes. This reformulation accommodates both processes of aggregation (greater complexity) and degradation (the dissipative production of simplicity). Evolution never achieves the full symmetry of resting equilibrium or disorder. The flow toward symmetry produces multiple types of order, from simplification toward homogeneity and disorder to the formation of complex structures. As free energy decreases and structures are formed, information is both created and destroyed. Energetically-coded information decreases with the maximization of entropy; structural information increases with conversion of energy into matter, the synthesis of heavier atoms from hydrogen in the core of stars, chemical combinations on the surface of the planet, and the origin and evolution of living organisms. All these processes create more complex structures and hence information, although, as energetic processes, they increase entropy. Earlier conceptions of entropy as disorder or uncertainty pictured it as the polar opposite of information, so as one increases the other decreases. In the process formulation, the maximization of entropy (involution) and the production of information (evolution) are two opposite and inseparable aspects of the same process (enantiodromia).

3. Co-creative organization: the generation of complexity: Natural processes spontaneously create material structures, i.e. asymmetric patterns of energy and information in tridimensional space. The formation of matter from energy in the evolution of the universe, the spontaneous formation of condensation structures, the formation of dissipative structures in chaotic attractors, the spontaneous synthesis of inorganic molecules, the generation of living organisms, the evolutionary increase in the number, diversity and complexity of species, the development of varied social cultures, and the psychological processes of individuation--all illustrate the spontaneous creation and destruction of structures through a multiplicity of different processes. Prigogine's model for the spontaneous creation of ordered dissipative structures in chaotic processes far from resting equilibrium may shed some light upon the formation of subatomic and atomic structures from radiation. Although there are obvious differences between dissipative structures and atomic, molecular and astronomical structures, the latter also are dissipative and creative. Stars illustrate the creative and dissipative nature of inorganic structures formed by the asymmetric distribution of matter. In Prigogine's model, the energetic intensity of processes determines their morphogenesis: Near equilibrium, energetic flows converge to a point attractor where opposites neutralize each other. At higher energies, far from equilibrium, flows bifurcate, creating information. The interaction of opposing forces creates fluctuations of repetitive and cyclic nature; bidimensional periodic attractors, rather than equilibrium points, represent the equilibrium state of the system. With even greater energy, fluctuations grow further, with sudden switches from one extreme to the other (catastrophes); powerful oscillations create turbulent states which are relatively stable (tridimensional chaotic or strange attractors), or unstable chemical chaos that forms dissipative structures. Dissipative structures are novel, information-rich, structurally complex, often catalytic and auto-catalytic, thereby increasing the effectiveness of free-energy to produce work. Thus Prigogine explains the spontaneous creation of order out of chaos in chemical processes far from equilibrium.

Within Prigogine's perspective, evolution results from the ability of open systems far from equilibrium to concentrate free energy and export entropy to the environment. The ability of biological processes to import free energy and export entropy has been claimed to explain their existence. The same phenomenon applies also to complex inorganic processes; for instance, the earth, receiving heat from the sun and dissipating it to space, imports free energy and exports entropy [33]. We may also consider an alternative view, namely, that pre-existing complexity increases both the production of new information and the rate of maximization of entropy. This is a consequence of the increase rate of free energy flow density (ergs s^{-1} gm $^{-1}$). This flow density increases with the complexity of processes: 1 for our galaxy, 2 for the sun, 80 for the earth climasphere, 500 for the biosphere, 17,000 for the human body and 150,000 for the brain [11]. Local concentrations of free energy and of informational complexity are associated with each other. One may propose that, free energy flux density and the quality of information are monotonically related. Intense flows of energy create bifurcations, which represent an increase (or decrease) in dimensions, not only a change in form. Evolution is a process of dimensiogenesis. This hypothesis represents a thermodynamic formulation of the fundamental relation between quantity and quality formulated by Hegel and Engels in the most famous law of their dialectic theory of processes.

Process Method: Postulating that everything is a process, process theory leads one to study time series as models for nature. Process theory postulates that all processes include simple components the form of which can be described as numerical orders (0) the disorder of randomness; (1) oneness of temporal asymmetry; (2) twoness of opposition or symmetry; (3) tridimensionality of space. These simpler forms combine to generate spiral components (Fibonacci series 0,1,2,3,5,8...) and to create complex multidimensional components. Here we apply this idea to the study of mathematical time series, and time series of data obtained from complex biological processes, using the time delay method to construct dimensional frameworks from 1 to 500 dimensions.

Empirical study: Based on Eckmann's recurrence method [13] for the investigation of hidden patterns in natural processes, Zbilut and Webber [36] have developed a measure of the entropy of a time series. This provided us with an opportunity to evaluate the thermodynamic hypotheses advanced by process theory by measuring empirically the entropy of time series of data obtained from natural processes, as well as the entropy of time series modelling simple prototypic patterns. To model the simpler patterns of nature, we used the following computer-generated distributions: rectangular pseudo-random numbers for flux of 0 order; (1) normal distribution for unimodality (1); sine wave for opposition (2); ratio between successive numbers of the Fibonacci series (0,1,2,3,5...); Henon's chaotic attractor. As models for complex processes, we studied the time series of cardiac intervals in twenty-four hour recordings of the electrocardiogram obtained from normal controls, schizophrenic and cardiovascular patients as described in a companion article [9]. As an example of complex natural processes, we studied cardiac beat intervals measured in twenty-four hour recordings of electrocardiograms obtained from human subjects, both healthy and with various cardiological and psychiatric illness (as representative of dysfunctions at lower and higher levels of integration). The electrocardiographic data were sampled at the rate of 128 observations per second to determine the R-R intervals. Analyzing these recording with the recurrence method, we have been able to demonstrate significant correlations between cardiac patterns and emotions potentially important in cardiology and psychiatry [8,9,10,26,27]. Data were processed with the recurrence method, using a program that plots and measures recurrences [13]. To study the dimensions of the process, the original time series were embedded in N-dimensional spaces (1 to 500), allowing to reconstruct a constellation of N surrogate variables from a single string of data. Embedding was accomplished by computing Euclidean norms (vectors) from strings of N consecutive points; vectors were compared two at a time for all possible combinations. Whenever the distance between two vectors was less than 0.1%, this was designated as a recurrence. Isolated, apparently randomly scattered recurrences are observed in plots of stochastic (high dimensional) processes. Plots of patterned data reveal line segments parallel to the diagonal, formed by recurrences that are diagonally adjacent, with no intervening white space ("patterned recurrences"); these lines are few or absent in plots of random numbers. To understand the data used to estimate entropy, note that both the % of recurrences and of patterned recurrences (figure 2) increase with the number of embeddings, albeit in different proportions. Recurrences as well as the proportion of patterned recurrences increase slowly for random-like distributions (pseudo-random numbers and Henon's chaotic attractor), and more rapidly for the well ordered distributions (Gaussian bell-shaped curve and sine waves), with cardiac data occupying an intermediate place.

The number of embeddings represents the dimensions of the framework within which the process will be studied. The **median embedding dimension**, the number of embeddings required for 50% of the recurrences to be patterned (embedding fifty, E_{50}) represents the number of dimensions required to describe deterministically half of the component processes, and hence provides as a measure of the distribution of components of various dimensions in a complex process [26]. As shown in figure 4, the E_{50} was low for ordered distributions (Fibonacci spiral, sine wave, and normal distribution) and high for random-like distributions (pseudo-random data and for Henon's chaotic attractor). The process of greater complexity --the cardiac data--, occupied an intermediate place between them. That 10 to 100 embeddings were required for 50% of recurrences to be patterned in cardiac data indicates that complex processes are organized in relatively highly dimensional patterns, rather than describable by low-dimensional attractors (such as thermodynamic or homeostatic equilibrium, or periodic or chaotic attractors) or by probabilistic models of infinite dimensions.

Shannon's entropy was measured with the recurrence method by counting the number of line segments and distributing them over integer bins of a histogram according to their length (which is inversely proportional to the largest positive Lyapunov component [34-37]. Shannon's entropy = $- \Sigma P_i \log_2 (P_i)$ is measured (in bits of information) by taking P_1 as individual bin probabilities of all non-zero bins greater than or equal to the shortest line segment. As measured by the recurrence method (figure 3), values for entropy increased monotonically with the number of embedding dimensions (1 to 500), but varied in an oscillatory fashion for sine waves and for the Henon attractor. At the median embedding dimension, entropy was lowest for random numbers and the normal distribution, intermediate for cardiac data, Henon's attractor and the Fibonacci series, and highest for sinusoidal patterns. This entropy gradient from maximal disorder (randomness) to simple orders (such as the normal distribution --a symmetric distribution around the point attractor of the average--, and the sine wave --a symmetric alternation of opposites-- and the Fibonacci series --which combines cyclicity with convergence), is compatible with the definition of entropy as symmetry. Compared with patterns of similar entropy (Fibonacci series), cardiac data has more dimensions. Compared with series of similar dimensions (normal curve), cardiac data has higher entropy. Taking the randomness (0), the normal curve (1), and the sine wave (2) as basic patterns to construct a scale of order, median dimensionality decreases and entropy increases with numerical order. The data is hence compatible with the hypothesis that processes that maximize entropy create symmetry, order and complexity.

The ratio of patterned recurrences (as % of all recurrences) over recurrences (as % of the total number of possible cases in the N x N matrix) provides a measure of the organization of the time series (**arrangement ratio**). At E_{50}, ratio was lowest for the normal curve, intermediate for random numbers, higher for the sinusoidal distribution, and highest for cardiac data (figure 5); these data suggest that the arrangement ratio measures complexity better than entropy or dimensionality.

<u>Discussion:</u> In summary, the recurrence method allows one to measure the entropy of mathematical models for cosmic forms, and of the forms of actual processes in the cosmos. Measures of entropy and of median dimensional complexity indicate that entropy increases from high dimensional disorder to low dimensional order. Complex biological processes are associated with intermediate degrees of dimensionality and intermediate values of entropy.

Likewise complexity is associated with intermediate temperatures, created as result of the flow of heat towards thermal symmetry. Process theory thus redefines the **second law as a maximization of symmetry resulting from the generation of opposite processes**. Evolution and involution coexist (enantiodromia, the union of opposite processes).

Indeed processes flow towards entropy and create complexity. There is empirical evidence for the spontaneous increase in entropy in all processes in which it has been measured, whether physical or biological, evolutionary or involutionary; there is no demonstration that complex evolving systems decrease their entropy as speculated Schrödinger and Prigogine. Likewise, there is empirical evidence that evolution creates diversity and complexity in biological organisms (Dollo's law) as well as in the universe itself (symmetry breakings in Big Bang cosmology). In the evolution of the universe, energy flow not only produces heat (classic thermodynamics), but it also creates matter (Big Bang cosmology); this illustrates the coexistence of opposite processes (enantiodromia) postulated by process theory. Opposite processes coexist at each point in time, albeit always one predominates. Thus heat flows mainly from hot to cold bodies, but there is a smaller flow in opposite direction, and heat produces work, even if to a lesser degree than heat is transformed into work. The flow between the two poles is asymmetric but bidirectional. As a result, processes are not reversible, but still they never reach a one-sided equilibrium in which only one of the poles remains, while the other disappears.

In the evolution of any process, creative processes that increase complexity necessarily precede those who destroy it -- what rises must fall, but what falls need not rise; this necessary priority of creation over destruction may be sufficient to explain evolution. The production and subsequent destruction (within the limits of the Planck constant) of virtual particles exemplifies this priority of creation over destruction. Actually aleatory processes can also create more permanent forms of order, as illustrated by phenomena of stochastic resonance. The Boltzmannian tendency towards states of greater probability needs not imply that processes tend towards disorder. Complexity can emerge from the spontaneous tendency towards stability: even simple mathematical models and simple physical processes spontaneously flow towards multiple types of attractors, not just towards the static point of equilibrium. In thermodynamic processes, the flow of heat from hot to cold bodies creates intermediate states of warmth that are necessary for the development of greater complexity: in fact, the greatest known form of complexity is associated with a temperature of 37^0. Likewise, when an asymmetric distribution of particles flows towards the more uniform state of mixing, combinations arise, creating more complex structures.

How can we measure complexity? Our data is at variance with the view that entropy and is inversely related with either order, complexity or information. If dimensionality measures some aspect of complexity, then we may conceive evolution as the progressive creation of dimensions by successive bifurcations from a more uniform primordial substance; this view is consistent with the Big Bang theory, according to which physical evolution consisted in a series of symmetry breakings. However cardiac data had intermediate values of dimensionality, much lower than random data or Henon's chaotic attractor. Onne may speculate that the number of dimensions is actually a measure of disorder. As the median embedding dimension was highest for random-like processes (pseudo-random numbers, chaotic attractors) and lowest for simple, well ordered distributions (sine wave and Gaussian curve), with natural processes (cardiac data) having intermediate values, one might speculate that the evolution of complexity results from the generation of intermediate degrees of dimensionality as part of the flow from the heterogeneity of infinitely dimensional randomness to the low dimensionality of uniformity. Evolution and involution would thus be two sides of the same process.

Acknowledgements: We wish to thank Ms. María McCormick for her indispensable support, and J. Zbilut, J. Messer, J. Díez-Martín, K. Walthall, C. Tom, M. Patel, O. Zdanovics, P. Fink, and A. Sugerman for their invaluable collaboration.

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Table 1. Shannon's Entropy [mean ± S.D.] calculated with Zbilut's recurrence method for computer-generated numbers and for cardiac beat intervals (R-R intervals in electrocardiograms) (ECG).

	Median embedding dimension (E$_{50}$)	Entropy at median embedding dimension	Recur-rences at E50	Arran-gement ratio at E50	Entropy at 10 embedding dimensions
0. Random**	215	1.23	3.21	15.606	0.08
1. Normal curve**	24	1.24	8.664	5.743	0.63
2. Sine wave **	10	5.86	1.7	30	5.86
Henon's chaotic attractor***	340	1.60	8.89	5.72	1.10
Cardiac data (normal, awake)*	57.7 ± 3.0	1.91 ± 0.08	0.8 ± 0.002	61.0 ± 2.6	0.62 ± 0.04

Cardiac data: Normal asleep*	37.3 ± 2.6	1.58 ± 0.20	36.8 ± 4.3	34.2 ± 3.5	0.72 ± 0.10
Cardiac data: Schizophrenic awake*	24.7 ± 9.1	1.72 ± 0.30	46.3 ± 31.7	34.1 ± 17.0	0.95 ± 0.18

* 7000 data points, 3 samples per subject, 3 or more subjects per group

** 7000 data point with averages (100) similar to those of cardiac data.

*** 1000 data points/sample.