

Dissipative Structures and the Origins of Life

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1. Introduction

Modern open system thermodynamics, as pioneered by Prigogine, provides a new framework for examining living and associated systems [Ji 1987] [Schorr and Schroeder 1989] [Loye and Eisler 1987]. This paper will show how the behavior of molecules can lead to biological events. Novel hypotheses are proposed that integrate open system, far from equilibrium, physical principles with the many layers of biological complexity. An abstract conceptual development provides a unifying perspective of prebiotic evolution, the origins of the genetic code, and the origins of life itself. An understanding of the nature of health and disease arises as a natural extension of physical phenomena and includes thermodynamic interpretations of the basic living processes of cell division and cell death. The reiteration of underlying physical principles provides new definitions of speciation and individuality. Consideration of man's place in an evolving biosphere is also examined.

1.1 Background

The guiding principle applied to living systems in this paper is that the entropy of the universe must always increase ($dS/dT > 0$) even if an open system within it decreases, albeit to a lesser extent [Prigogine 1980]. While at first glance this statement might appear to be counter-intuitive and in violation of the second law of thermodynamics, it is not.

$$dS/dt = dS_i/dt + dS_e/dt \quad [\text{Prigogine 1980}]$$

dS = total entropy of a system

dS_i = entropy produced by the system (internal)

dS_e = net entropy flowing into the system (exchange)

dS can only be negative if dS_e is sufficiently negative to overcome dS_i , dS_i is always positive.

Creativity, the production of new forms of order (new ideas, information + new physical entities = negative entropy) will occur as long as the entropy of the universe increases to a greater extent than if the entropy of a system within it had not decreased.

2 Sources of Creativity

Paradoxically, new forms of order can be created as a system tends towards equilibrium as well as when a system is pushed away from equilibrium. A collection of molecules at equilibrium will have assumed its most probable distribution and typically, entropy would be maximized. Yet, if the system were not at equilibrium, it would move towards it. In doing so, creative events could occur. For example, if non-equilibrium were in the form of reduced conformational isomers or chemical species compared to what would exist at equilibrium, the move towards equilibrium would require creative events to generate these species [Wicken 1976]. Thus, the creation of order and the destruction of order exist in a time independent balance for any system at equilibrium. Free energy will be at a minimum and/or entropy will be maximized. Intimately linked to both of these processes is the very meaning of time.

Creative events also occur when a system far from equilibrium is pushed beyond a critical point such that a flow dependant phase change occurs and a dissipative structure is formed. The creation of a dissipative structure, and its subsequent maintenance under constant conditions, leaves the system with a time independent entropy value. Entropy, however, is not maximized. Simultaneously, the steady state production of entropy to the universe continues at an enhanced rate for as long as the difference in the generating potential exists and the structure is maintained.

3 Time

Recent work from Prigogine's group provides a resolution to the "time paradox", the problem of an irreversible world that is typically described by physics in which time

is reversible [Prigogine 1997] Time is manifest in the movement of a system towards equilibrium, at which point it is lost. A system at equilibrium has no events that may be used to measure time. Both the equilibrium “steady state” of generation and destruction of chemical species, and the stable, dynamic, steady state that exists far from equilibrium, are characterized by time independent molecular distributions. The meaning of time in the two systems cannot be the same since a continuous degradation of potential due to the presence of an organized system is required only in the latter case. Thus, a dissipative structure requires that a portion of the energy flowing through it be used to maintain the far from equilibrium, stable, steady state, while the entropy of the universe increases at a more rapid rate than would occur if the dissipative structure did not exist. It seems that the degree of organization within either system, equilibrium or dissipative, is timeless. Essentially, time is dependant on a system’s distance from equilibrium. Hence, time is made when a system moves away from equilibrium and time is lost when a system move towards equilibrium. A system may move from equilibrium in a linear (near equilibrium) or nonlinear manner (dissipative structure formation). A dissipative structure existing in a stable steady state may be seen as storing time.

4 Evolution

Biologically speaking, evolution is the process by which species develop from earlier forms of life. More generally, evolution is the gradual development of something into a more complex form. In the following sections, physical processes will be described that result in the increasingly complex forms that become biological species.

4.1 Evolution Phase I: The Generation of Chemical Diversity

Both nonequilibrium (but not dissipative) and equilibrium processes generate chemical diversity by conventional chemical mechanisms that are driven by photodynamic, geothermal and electrical potentials.

4.2 Evolution Phase II: Dissipative Structures First Appear

The chemical diversity created in Phase I is sufficient to add chemical potential as a gradient producing source that, in addition to the energetic sources mentioned above, lead to the formation of dissipative structures.

4.3 Evolution Phase III: Simple Interactions between Dissipative Structures Form

Relationships (source and sink) developed between dissipative structures composed of prebiotic chemical pathways such that they became dependant on each other. The prebiotic precursor pathways are what will evolve into to carbohydrate, lipid, amino acid and nucleic acid pathways. The primordial genetic code need not have been between proteins and nucleic acids, but could have been between prebiotic dissipative

structures that would evolve into the biochemical pathways of carbohydrate, nucleic acid and amino acid synthesis. This line of thought provides an abstract mechanism that allows for the evolution of the genetic code to occur in the absence of cells, membranes, triplet codons, or life.

4.4 Evolution Phase IV: Complex Interactions between Dissipative Structures Form

Just as large collections of molecules existing far from equilibrium can spontaneously undergo rearrangements to form organized flow dependent structures, so can collections of interacting dissipative structures. This mechanism can account for the formation of a precellular environment that could have many of the attributes of a living cell, but need not have all of them. In turn, these systems could continue to evolve until a living system resulted. With this model, some interesting possibilities naturally arise. Did different versions of prelife/life first occur from which a founding organism was selected that became the tree of life? Alternatively, did many prelife/life forms appear out of the prebiotic incubator that were very similar and essentially represented a dynamical system that was an attractor, and this form became the founding organism?

The meaning of time again arises when considering the concepts presented in this section. Is there a relativity of time that corresponds to the dynamic hierarchies?

4.5 Evolution Phase V: the Cell

In general, a dissipative structure can be communicating with its' environment in one of three modes: maintaining, growing, or collapsing. Similarly, if a cell does not have sufficient negentropic flow ($dS_e/dt > dS_i/dt$) it must die. It is important to recognize that the flow of energy is controlled by gate keeping functions such as surface receptors that ultimately modulate gene expression and consequently catalytic activity. A cell, with sufficient flow only to maintain a low stable steady state, would be in the G0 stage of the cell cycle. In contrast, if a cell were taking in an excess quantity of negentropic potential the system could destabilize, with the fluctuations of intensive thermodynamic variables going to infinity. The thermodynamic system would bifurcate thus, the cell would have to grow and ultimately divide.

This line of thinking suggests that the cell cycle is a series of phase changes. With sufficient potential, the flow at each transition point destabilizes the system and forces the phase change to the next stage of the cell cycle. In order for a cell in G0 to enter G1, a stimulus must perturb the system in a manner that reconfigures its' interface with its supporting environment in a manner that promotes the transition to the higher metabolic activity associated with G1. This change can only occur successfully when the cell is in an appropriate environment of receptors and their ligands coupled with sufficient energetic potential. These two components represent the negentropic potential.

The G1/S transition represents a phase change in which the high level of metabolic flow is manifested in DNA replication. In other words, the condensation of nucleotide monomers into DNA, and the condensation of amino acids into proteins (histones) serve as sinks for the growing metabolic potential. This sink drives the high degree of flow dependant, cytosolic organization [Melamede and Wallace 1985] that is required for the coordinated replication of the huge lengths of DNA that in addition to replicating, are no longer compacted into relatively static chromosomal structures. The condensation of biochemical monomers into polymers that can serve as a driving force for organization provides a novel insight into what a possible role for “junk” DNA might be. The directional flow of metabolic potential into DNA acts a sink that is increased by “junk” DNA.

The G2/M transition can similarly be viewed as condensation driven. At this stage, the energy dependant mechanics of mitosis and cell division may be partially thermodynamically driven by the condensation of non-chromosomal DNA into a chromosomal structure. A latent heat of organization is released. Again, a potential is generated by energy released as flow dependant structures condense into more stable, less flow dependant, polymers. These phase changes may release energy that can be used by other cellular energy dependant processes. For example, if a cell were in an environment that was promoting cell division it could trigger a new round of cell division. In contrast, if a cell's environment was not sufficiently nurturing, the energy throughput and degree of flow dependant organization of the open system might stabilize at a new lower level.

4.6. Evolution Phase VI: Speciation

In this section, conventional evolution is examined from an open system thermodynamic perspective. Thermodynamically, a species is interpreted as a heterogeneous chemical distribution in the dynamic molecular collection of the biosphere. From this perspective, the individuals that compose a species can be viewed as chaotic oscillations of the chemical distribution that characterizes a particular species. Hence, an individual is a loop of a limit cycle. The dissipative structure-based mechanism for the origin of life can be reiterated to provide an explanation for the formation of new species that characterize evolution. As described by Kondepudi and Prigogine, excess potential and flow can destabilize a dissipative structure and lead to the formation of a new, more complex one. A species could, therefore, be destabilized by its' own success. A successful species must extract ample negentropic potential from its' environment, hence, food supply is a measure of this success. When a sufficient number of individuals in a species are subject to excess thermodynamic flow and its' associated destabilizing affects, the molecular distribution that characterized the species undergoes a non-linear rearrangement that results in the formation of a new species.

If thermodynamic principles are to be extended to the evolution of biological systems, a question that must be answered is “What are the intensive variables of a biological

system that would be expected to have fluctuations approaching infinity prior to the phase change"? Fluctuations that occur in the ratio free radical production to negentropic flow is hypothesized to be an intensive variable in biological systems that is of primary importance. Ultimately, all living systems are based on electron flow. Respiring organisms pass electrons from reduced hydrocarbons to oxygen. Not all the energy that is released by this process is used for the maintenance and growth of an organism. In a healthy species, existing in dynamic equilibrium with its' environment, the entropic term is predominantly composed of biological waste and heat production. When species has an excess of potential (too much food), energy flow is not optimized. The net capacity to dissipate entropy is insufficient. The result of entropy flow imbalance is that entropy is trapped in the system. The trapped entropy manifests itself as a generalized increase in the steady state level of entropy found in the individuals that compose the species. An important manifestation of this increased internal entropy might be metabolically generated free radicals. A lower degree of functional organization is precisely the characteristic that results from excess free radical production. The general quality of a living system, both metabolically and genetically is destabilized by excess internal entropy production. A thermodynamic entropic view of life provides an understanding of why caloric restriction reduces age related diseases such as autoimmune, neuronal degenerative, cardiovascular disease, cancer and increases longevity. All of these imbalances are thought to have free radicals as a component of their etiology. Hence, despite many failures, successful new species emerge from the increased variability found when a biological system is destabilized by excess negentropic flow.

4.7 The Evolution of Body Systems

The evolution of species is characterized by the appearance of organized biological systems such as the digestive, excretory, nervous, immune, endocrine, and reproductive systems. A thermodynamic perspective on the evolution of these systems shows them to be a natural outgrowth of energy flow. The increased entropy production in the universe that resulted in the simplest life forms could again be realized by increasing the negentropic throughput resulting from the evolution of new more complex organisms.

A priori, a first step to increasing negentropic flow into a biological system would be to increase the size of the system. Limits defined by surface area to volume ratios restrain the size of cells and naturally lead to multicellularity. Once single celled organisms existed, they had the capacity to take energy and mass into the system, extract sufficient negative entropy to maintain the system, and to bifurcate when thermodynamically appropriate. Minimal changes could result in simple multicellular organisms such as found in the porifera. The next logical means for enhancing flow would be to increase the capacity for acquiring food and getting rid of waste, hence the early development of digestive and excretory systems. Essentially, dS_e/dT drives a system's variability and the selection of more sophisticated input/output systems that included feedback loops. In order to optimize this flow term, feedback mechanisms are needed so that the ever-changing environment can be

best adapted to. dSe/dt is in reality, the sum of two terms that represent the flow of energy ($dSe(\text{energy})/dt$) and mass $dSe(\text{mass})/dt$. The nervous system can be viewed as the feedback mechanism that monitors the energy flow into and out of a system. Similarly, the immune system may be viewed as a feedback mechanism that monitors a system's mass flow. The endocrine system may be the feedback system that attempts to monitor the interface between a system's entropy production (dSi/dT) and flow (dSe/dt). The reproductive system integrates the flows of the complex system for bifurcation.

5 Aging, Health and Disease

The fundamental properties of life, aging, health, disease, and death may be simply characterized thermodynamically. Initially, aging is the time dependant movement of a system further from equilibrium when the system is young and expanding. The phase of physical growth and differentiation is followed by the return of a system to equilibrium as it ages and dies. The more rapidly a system returns to equilibrium, the more rapidly it ages. Thus, health is the ability of a system to maintain, or increase its' distance from equilibrium. Since living systems, as described in this article, are "simply" a hierarchy of interacting dissipative structures, disease may be viewed as a disproportionate movement of an organized sub-system towards equilibrium. Since all flow dependant structures composing an organism are dynamically interacting with each other, if one collapses, it can have far-reaching consequences. The thermodynamics that underlies a particular set of systemic circumstances may lead to apoptosis of a cell. The death of a cell could lead to the collapse of a previously thermodynamically stable tissue. The underlying loss of organized flow could reiterate and amplify itself through out the hierarchal organized system leading to organ failure and death of an individual that could expand to the loss of a species.

6 Conclusions

If, as proposed, dissipative structures are the foundations on which life is built, the knowledge of their formation and stability provides fundamental feedback to systems that they compose. Biological, political, social and economic systems are all natural outcomes of basic underlying physical principles. Our attempts to maintain the health of these systems must be guided by our understanding of the physical processes that created and maintain them [Lipton et al. 1998].

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