

PROCESS ECOLOGY: A TRANSACTIONAL WORLDVIEW

R.E. ULANOWICZ

Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, USA.

ABSTRACT

A traditional presupposition in science is that nature ultimately is simple and comprehensible. Accordingly, 'theory reduction' is a primary goal in much of ecosystems science – the belief, for example, that ecosystem development can be described by a single covering principle. Recently, however, the theory of complex adaptive systems has challenged the assumption that simplicity is ubiquitous. While students of complexity theory recognize individual constraints that orient ecosystem development, they are skeptical of the urge to identify a single, monistic principle that governs all ecosystem behavior. One approach, called 'process ecology', depicts ecosystem development as arising out of at least two antagonistic trends via what is analogous to a dialectic: one direction is the entropic tendency towards disorganization and decay, which can involve singular events that defy quantification via probability theory. Opposing this ineluctable drift are self-entailing *configurations of processes* that engender positive feedback or autocatalysis, which in turn imparts structure and regularity to ecosystems. The status of the transactions between the two trends can be gauged using information theory and is expressed in two complementary terms called the system 'overhead' and 'ascendancy', respectively. Process ecology provides an opportunity to approach some contemporary enigmas, such as the origin of life, in a more accommodating light.

Keywords:

[AQ1]

1 A WORLD OF OPPOSITES

A subject discussed all too infrequently in ecological discourse is how the worldview that orients ecosystems science tacitly owes much to issues in classical philosophy. One of the very earliest splits in Western philosophy, for example, was between the Eleatic and Milesian schools of Hellenistic thought. The central personality in the Eleatic School was Plato, who taught that the world is composed of eternal and unchanging 'essences'. What one perceives as changes are considered illusory distractions that impede the recognition of underlying essences. The major figure in the Milesian School was Heraclitus, whose famous quotation 'Πάνταρεί' states that the only constant in the world is change. That one can never step twice into exactly the same river is a common exemplar of this dictum.

It should be emphasized that full reconciliation of these two ideals is impossible, notwithstanding the fact that both stasis and change are obvious in nature. (The physicist or engineer might point out that these two concepts are fundamentally different entities, like oranges and apples, because the dimensions of change differ from those of stasis by the inclusion of reciprocal time.) When looking at nature, one perceives neither pure stasis nor complete change. Given sufficient time, no natural object persists indefinitely. Conversely, what superficially appears as change is sometimes conserved when regarded through a different lens (e.g. the momentum of an object moving in the absence of any force).

Tension between the two poles of thought remained equitable down through the centuries, but attitudes that arose with Newton's *Principia* during the Enlightenment tilted the advantage towards the Eleatic perspective. Every law of physics formulated prior to ca. 1960 followed Newton's laws in being strictly reversible in time. That is, if one makes a motion picture of any Newtonian event, an independent party would be unable to distinguish whether the film is being run forward or backward. Temporal reversibility is a particular form of symmetry, and early in the 20th century Aemalie Noether [1] was able to demonstrate the equivalence of symmetry and conservation. So Newtonian physics is completely conservative, and true change cannot occur. Hence, Newtonian nature becomes an Eleatic construct.

Now, virtually anyone can tell immediately whether a motion picture of a living system is being played forward or backward, because living entities age and dead organisms do not spontaneously jump back to life. Such irreversibility is not confined to biology. In fact, soon after the turn of the 19th century Carnot [2] quantified its presence in engineering systems. Carnot's impertinence unleashed major consternation among physicists for the next half century, for how could the wonderful and reversible laws of nature that had been accruing since Newton remain consistent with observations of irreversibility? Since the days of LaPlace [3], it had been assumed that nature at the microscopic level of individual, everlasting particles could be fully described and predicted by Newton's laws. The same system, however, when viewed as a macroscopic assemblage, would behave irreversibly, as Carnot had emphatically demonstrated.

A 'resolution' of this conundrum is commonly attributed to Boltzmann [4] and Gibbs [5] with their formulation of what has become known as 'statistical mechanics'. Boltzmann was able to demonstrate that, if the particles of a perfect gas were stochastically distributed and noninteracting, such an ensemble would behave like an irreversible system. Immediately, this result, obtained under an extremely narrow set of assumptions, was extrapolated across the full hierarchy of nature. A tacit, antipositivist consensus arose not to pursue the issue any further. Meanwhile, empiricists such as Mayer and Joule had measured scalar equivalents that made it appear that energy remains constant in magnitude throughout the universe. To put Carnot in his place, this conservative bookkeeping was deemed to be the *first law* of thermodynamics, whilst the subsidiary nature of Carnot's earlier observation was demoted to becoming its *second law*. The Eleatic slant on nature had been restored.

This extended prolegomena is meant to challenge the common presumption that progress in ecology should proceed by further application of conventional (mostly Eleatic) tools [6]. The need for any radical departure from business as usual might seem like a questionable proposition to some, considering how it was Darwin himself who had opened up 19th century science to history. (He, like Carnot before him, perceived the world as irreversible.) It should be remembered, however, that Darwin had fallen into the shadows by the end of the century. It was not until Fisher and Wright during the late 1920s had rehabilitated Darwin through what is commonly known as 'The Grand Synthesis' that evolution began to eclipse the developmentalism that had prevailed in biology during the previous decades. The Grand Synthesis bore marked resemblance to the earlier one effected by Boltzmann and Gibbs. For one, Fisher applied almost the identical mathematics that had been used by Gibbs to describe an ideal gas in his treatment of noninteracting genetic elements. Furthermore, the cardinal effect of the synthesis was similar to the success of Gibbs – it put the genie of uncontrolled chance back into the bottle. It reestablished a degree of predictability under a very narrow set of circumstances. The result, described by Depew and Weber [7] as 'more like a treaty than a synthesis', put Darwinism back on the track of acceptable Eleatic science.

2 DIRECTIONS IN ECOLOGY

Stimulated perhaps by Schrödinger's [8] essay, *What is Life?*, or more directly by Eugene Odum's [9] 'The strategy of ecosystem development', system ecologists began to explore a number of variational principles as potential descriptors of the trajectory of ecosystem development [10]. In this regard one encounters suggestions that ecosystems develop so as to optimize power [11, 12], exergy storage [13], throughput time [14], synergy [15], or ascendancy [16]. These propositions remain Eleatic in nature, because most variational principles can be considered as a mechanical statement in another guise (e.g. the maximization of the Hamiltonian operator as a surrogate for Newton's second law in mechanics) (The adjective 'Eleatic' refers to the statements as made, not necessarily to the current mindset of the individuals who pronounced them.).

The second law of thermodynamics is decidedly a Milesian statement, and it has contributed to a number of hypotheses for ecosystem development. Some of these follow rather directly, such as Swenson's [17] proposition that ecosystems create entropy at the fastest rate possible. Others, notably Schneider and Kay [18], follow the lead of Hatsopoulos and Keenan [19] by trying to subsume the first law into the second. The priority here is, as expressed by Salthe [20], 'The second law trumps all.' In a roundabout and paradoxical way, the second law is assumed to be the drive behind the creation of order. Biological order becomes a transient phenomenon, the sole purpose of which is to degrade gradients in exergy at the fastest rates possible. Schneider and Sagan [21] deem the tendency toward entropy to be nothing less than 'the purpose of life'.

The advantage of these second law approaches is that they truly open up the world to change. The author, however, worries that such attempts at monism simply sweep inconsistencies to the peripheries. As mentioned above, there is no way to accommodate stasis fully into change; nor is there any simple way to reconcile entities with different physical dimensions. To identify the second law as the agency that drives gravity is to turn a blind eye towards the *negative* contributions that gravity makes when calculating the entropy production of gravitationally collapsing systems [22]. Swenson, as well as Schneider and Kay, focus attention upon the dynamics of the second law and mention the constraints and agencies that modulate the rate of dissipation as an afterthought to be accorded only secondary attention. Unfortunately, in the author's opinion, no new understanding is achieved by this conflation of the causes of order and disorder, and such a procrustean effort at monism does not convey a full image of reality.

The proposition advanced here is that one must face squarely the irreconcilable and agonistic nature of the separate tendencies that give rise to living systems. Such a tension of opposites had dominated both Eastern (Yin–Yang) and Western (Eleatic–Milesian) thought for centuries before the Enlightenment. The neo-Platonic diversion of the past three centuries has provided wonderful tools to describe that part of the universe which is Eleatic in nature, but there is significant danger in thinking that one possesses *all* the answers, just because one is right *some* of the time [23].

But if the scientific enterprise is adequate to address life, how can one quantify the agonistic tendencies that appear in living systems? Perhaps one clue on how to approach the problem is to consider the opposing questions that frame it. First, in order to distance oneself somewhat from the conventional Newtonian approach, one must attempt to answer the difficult question, 'How can things truly change?' Having thus loosened the bonds from novelty, it immediately becomes necessary to attend to the antonymous question, 'How can things remain the same?' The directions defined by the answers to these questions are neither to be conflated nor to be allowed full reign unto themselves. Rather, they will be seen in a 'transactional' relationship with each other, characterized by a degree of mutual necessity. The complementary nature of the transaction allows one to parse out any real systems as to where it stands quantitatively between the poles of order and disorder. Finally, the transactional viewpoint appears to lend clarity to a longstanding conundrum that has plagued Eleatic science – the origin of life.

3 HOW CAN THINGS TRULY CHANGE?

By admitting sundry chance into the description of evolution, Fisher *et al.* were able to include a modicum of change into their Grand Synthesis. But the resulting theory still did not account for true emergence, such as that which occurs with speciation. So how, then, can things fully change? One possible answer is rather straightforward – perhaps all chance is not simple? If one is already dealing with complex systems, why is there any reason to believe that all Eleatoric events must remain simple?

One visionary who argued for radical forms of chance was Walter Elsasser [24]. He suggested that *many* events are unique once and for all time. At first this assertion sounds like an absurdity to the scientist, aware as he/she is of the immense age and scope of the known universe. But once one begins to consider the actual numbers, matters take a different turn: Elsasser reckoned that there are approximately 10^{85} simple particles (give or take a few orders of magnitude) in the known universe, which is reckoned to be about 10^{25} ns old. This means that, at most, 10^{110} simple events could have occurred since the Big Bang. His point was that, if any event has less than 1 in 10^{110} chances of reoccurring, it makes no physical sense whatsoever to pretend that it will.

But are any events that rare? A little combinatorics will reveal that any chance configuration of more than 75 *distinguishable* objects will have less than 1 in 10^{110} chances of reoccurring. Now, an ecosystem with fewer than 75 distinct individuals would be unusual indeed. The possibility that everyone attending a particular INTECOL plenary session will exactly reassemble some day (the various professional ties that bind them notwithstanding) is, for all purposes, zero! One quickly comes to realize that unique events, although vanishingly rare in particular, are in the aggregate not all that unusual. In fact, they are legion! They surround each and every one everywhere, all the time. Scientific training, however, conditions one to ignore such possibility.

Such unique events will be called 'singular', and the reader should note in passing that they are the absolute antithesis of what is commonly referred to as 'mechanism'. Whereas a mechanism is an obligate coupling of two events, there is no way to couple a singular event *meaningfully* with any antecedents. Furthermore, because it is unique, a singular event defies quantification via normal frequentist probability theory.

4 HOW CAN THINGS PERSIST?

Carnot forced upon a reluctant scientific community the reality that common chance causes change and decay. He slowed down the rush pell-mell towards neo-Platonic science. Under the Eleatic, deterministic worldview of Newtonian laws, the existence of even one singular event would be catastrophic. The whole rigid clockwork would collapse. But Elsasser argued that the world is perfused with singular events. It is even conceivable that, within the biosphere, simple chance events might constitute a set of measure zero in comparison with the preponderance of singular events! Suddenly, rather than worrying about how new things could possibly arise, one is faced with the problem of how things can possibly stay the same. And yet the undeniable regularity visible in the world did allow for the construction of a workable Baconian science – mostly by excluding the phenomena associated with living systems. Regularity, however, is visible in life as well. Among the ubiquity of singular events, how can this be?

Of course, one way that objects can persist over time is because they are composed of enduring elements, just as a stone is composed of eternal 'atoms' according to Democritus or Lucretius. A second way, more germane to biology, is through the preservation of information in static material form (e.g. DNA). But strings of molecules out of the context of their immediate living environment are both meaningless and incapable of preserving form. The neo-Darwinian view of evolution paints a purely mechanical picture of change in the living world at the expense of having to ignore all the intermediate agencies that may operate between the molecular genome and the whole organism. It is a blindness that is not unlike that which keeps singular events out of mind. In keeping with the spirit of Karl Popper [25], who opined that a deep understanding of evolution is impossible without an appreciation for true contingency (e.g. singular events), attention now turns to a third agency capable of holding life together, namely configurations of autocatalytic processes.

Before addressing the particulars of autocatalysis, it is first necessary to describe Popper's notion of an agency that can incorporate such disparate extremes as singular events and strict mechanisms [25].

He gave the name ‘propensity’ to the likelihood that a given event will occur in a given context. It is related to, but not identical with a conditional probability. In the limit of isolation (e.g. laboratory or outer space) a propensity degenerates (in the mathematical sense) to a physical force, or mechanism. Obversely, one might consider a rigid mechanism being brought progressively into contact with potentially interfering events, be they singular events, common chance, or other propensities. Such influences are capable of disrupting the action of the force sometimes, but not most times, from engendering its usual consequences.

With Popper’s notion firmly in mind, one can now consider a somewhat exotic variety of autocatalysis consisting of a circular concatenation of propensities, whereby each process usually has a salubrious effect upon the next in the chain. Without loss of generality, one may focus on a conjunction of three processes A, B, and C (Fig. 1). Any increase in A is *likely* to induce a corresponding increase in B, which in turn *usually* elicits an increase in C, and whence back to A.

A didactic example of autocatalysis in ecology is the community that forms around the aquatic macrophyte, *Utricularia* [26]. All members of the genus *Utricularia* are carnivorous plants. Scattered along its feather-like stems and leaves are small bladders called utricles (Fig. 2a). Each utricle has a few hair-like triggers at its terminal end, which, when touched by a feeding zooplankton, opens the end of the bladder, and the animal is sucked into the utricle by a negative osmotic pressure that the plant had maintained inside the bladder. In nature, the surface of *Utricularia* plants is always host to a film of algal growth known as periphyton. This periphyton in turn serves as food for any number of species of small zooplankton. The autocatalytic cycle is closed when the *Utricularia* captures and absorbs many of the zooplankton (Fig. 2b).

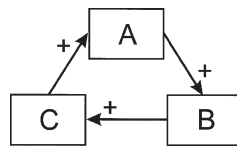


Figure 1: A simple example of autocatalysis.

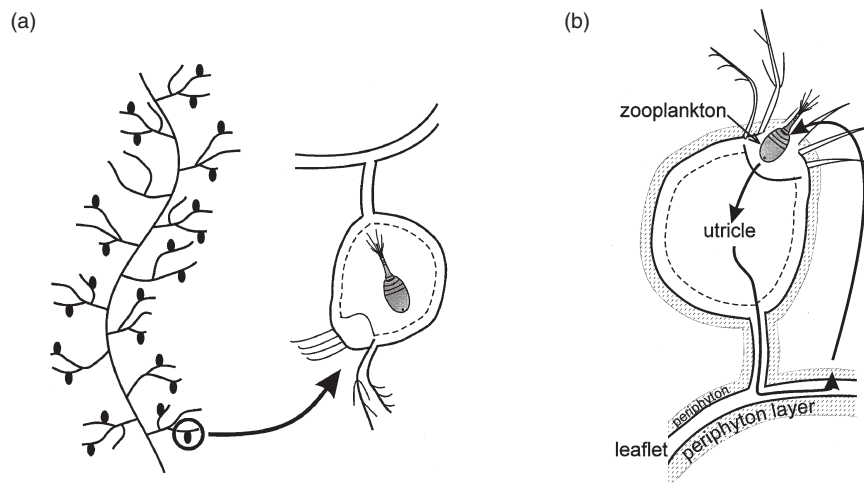


Figure 2: (a) *Utricularia*, a carnivorous plant. (b) The cycle of rewards in the *Utricularia* system.

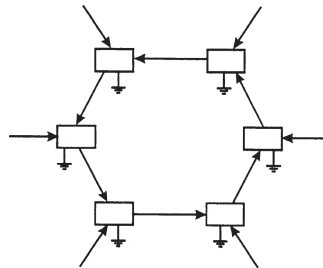


Figure 3: Centripetal action as engendered by autocatalysis.

In chemistry, where reactants are usually simple and fixed, autocatalysis is but another mechanism. As soon as the effect of any process on its downstream counterpart becomes fraught with contingencies (rather than being obligatory), a number of decidedly nonmechanical behaviors arise [27].

[AQ2] Foremost among the properties of an autocatalytic configuration is that it can exert *selection* pressure upon its ever-changing, malleable constituents. To see this, one considers a small spontaneous change in process B. If that change makes B either more sensitive to A or more likely to catalyze C, then the altered B is likely to receive enhanced stimulus from A. Conversely, if the change in B makes it either less sensitive to the effects of A or a weaker catalyst of C, then that perturbation will probably receive diminished support from A. That is, a preferred direction arises in autocatalysis that breaks symmetry and violates the assumption of reversibility, and with it the Eleatic cornerstone, conservation. Furthermore, as elements increasingly engage in autocatalysis, or mutually adapt to their configuration, they depart from their status as independent entities and possibly lose their capacity to persist in isolation. That is, the full cycle manifests an organic nature that belies the assumption of atomism, yet another feature of Eleatic science.

To see how another very important attribute of living systems can arise, one notes in particular that any change in B is likely to involve a change in the amounts of material and energy that are required to sustain it. A corollary to the action of selection pressure is a tendency to reward and support any changes that serve to bring ever more resources into B. Because this circumstance pertains to any and all members of the feedback loop, an autocatalytic cycle becomes, ipso facto, the epicenter of a *centripetal* pattern of flows upon which resources converge (Fig. 3). Thus, without having to possess any visible integument, an autocatalytic loop can *define its own selfhood* as the focus of centripetal flows.

One should note that autocatalytic selection pressure is exerted in a top-down fashion – a macroscopic agency that actively orders its constituent elements. This mode of action violates the assumption of causal closure, the conventional requirement that mechanical actions at smaller levels ramifying up the hierarchy of scales are the only allowable agencies of change.

Another consequence of centripetality is that whenever two or more autocatalytic loops draw from the same pool of finite resources, *competition* among the foci usually ensues. For example, should a new element D happen to appear and connect with A and C in parallel to their connections with B, then if D is more sensitive to A and/or a better catalyst of C, the ensuing dynamics should favor D over B to the extent that B will either fade into the background or disappear altogether (Fig. 4). That is, the selection pressure and centripetality generated by complex autocatalysis (a configuration of processes) is capable of influencing the replacement of elements. That is, a *configuration of processes* strongly influences which objects remain and which pass from the scene. In a reversal of the conventional wisdom that objects direct processes, the latter actually participate in the creation

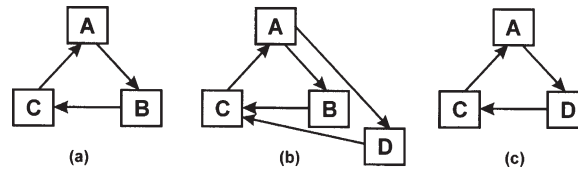


Figure 4: The selection of new element D to replace B. (a) Original system; (b) more effective element D appears in parallel to B; (c) D supplants B.

of their own elements. This inversion of causality suggests a name for such overall ecodynamics – *process ecology* [28].

The attribute of centripetality is an essential feature that, unfortunately, is missing from almost all attempts to describe life. When, for example, Schneider and Kay [18] interpret the second law as the optimal rate destruction of exergy gradients, they make the tacit assumption that competition draws the system towards optimality. As just discussed, however, it is centripetality, a consequence of autocatalysis, that actually drives up the rate of exergy destruction, not the second law.

Finally, it is worthwhile to note how autocatalytic selection sometimes acts to stabilize and regularize behaviors across the hierarchy of scales. Unlike the rigidity of Newtonian *universality*, the effects of a chance event anywhere in the realm of process ecology rarely will propagate up and down the hierarchy without attenuation. The consequences of noise at one level are usually mitigated by autocatalytic selection at higher levels and by energetic culling at lower levels. The universality and uniformity of Newtonian laws are replaced by the *granularity* of the living world, a situation suggested by ecologists Allen and Starr [29]. That is, models of events at any one scale can explain matters at another scale only in inverse proportion to the remoteness between them. Obversely, the domain within which irregularities and perturbations can damage a system is limited. Within the flexible framework of process ecology, chance – even radical, singular chance – does not necessarily unravel a system. In spite of (and paradoxically, because of) such flexibility, dynamical order can persist.

5 A WORLD OF TRANSACTIONS

In order to discern how systems might possibly escape the smothering confines of Newtonian mechanism, the spotlight was pointed at a radical form of indeterminacy that has too long lain in the shadows. Paradoxically, this selfsame entropic tendency which serves to wear down and disorganize living systems provides the only avenue by which they can truly increase in order: singular events are ubiquitous, but the great majority simply make no difference whatsoever in the course of events. A relative few serve actively to disturb and/or degrade existing order, forcing the system to expend work in maintaining itself. An infinitesimal fraction of singular events, however, resonates with existing dynamics and initiates radically new and more effective system behaviors. These new patterns *emerge* quite naturally during the course of process ecology and pose no enigma, as they do within the Eleatic framework of the machine.

Counter to this entropic drift is the centripetal drive that sustains and ultimately increases order. It becomes wholly transparent, then, how living systems could be the outcome of the transactional tension between these two antagonistic drives, in something resembling dialectical fashion [27]. ‘Dialectic’ is used only in a metaphorical sense, but the analogy is an important one. In a Hegelian dialectic, the opposing thrusts are considered to be mutually obligate at the next higher level. In the

biotic realm as well, the ensuing system *requires* a modicum of both opposites. Should either tendency begin to extirpate the other, the system will approach jeopardy.

Because dialectical behavior is not mechanical, it defies algorithmic simulation. It does not follow, however, that all attempts at quantification remain futile. Configurations of processes, for example, readily lend themselves to be represented as networks, and the nodes and arcs of networks conceptually juxtapose elements of stasis and change, respectively. Furthermore, weighted networks of interactions can be quantified using conditional indices developed in information theory [16, 30]. Information theory is key to the quantification, for no other vehicle is known that can quantify both the entropic and the correlative aspects of complexity as complementary terms within the same rubric.

For example, if one defines the transfer of material or energy from prey (or donor) i to predator (or receptor) j to be T_{ij} , the total activity of the system can then be measured simply as the sum of all system processes, $T_{..} = \sum_{i,j} T_{ij}$, or what is called the ‘total system throughput’. (A dot in the place of any subscript denotes summation over that index.) Rutledge *et al.* [30] demonstrated how the coherence between inputs and outputs in the system can be gauged by the ‘average mutual information’ (AMI) between flows as,

$$AMI = k \sum_{i,j} \left(\frac{T_{ij}}{T_{..}} \right) \log \left(\frac{T_{ij} T_{..}}{T_j T_i} \right).$$

As defined, the AMI has the nonphysical dimensions of bits (or nats or hartleys, depending upon the base used in taking the logarithm). AMI can be made to reflect the physical size of the system of interest by setting the scalar constant, k , equal to the total activity of the system, $T_{..}$, to yield a quantity known as the ascendancy, A , where

$$A = \sum_{i,j} T_{ij} \log \left(\frac{T_{ij} T_{..}}{T_j T_i} \right).$$

The drive by autocatalysis towards ever greater performance is then reflected by increases in this system ascendancy.

To gauge the opposing entropic tendency, one begins by scaling the probabilistic ‘entropy’ or diversity of the system flows [31] according to the total system throughput. The result poses an upper limit to the ascendancy and is called the systems capacity, C ,

$$C = - \sum_{i,j} T_{ij} \log \left(\frac{T_{ij}}{T_{..}} \right),$$

where $C \geq A \geq 0$ [32]. Rutledge *et al.* assumed that the amount by which A falls short of C (i.e. the complement of A) is indicative of all the entropic, inefficient and incoherent features of the system of exchanges. Ulanowicz [16] called this complement the systems ‘overhead’, Φ (≥ 0), where

$$\Phi = - \sum_{i,j} T_{ij} \log \left(\frac{T_{ij}^2}{T_j T_i} \right).$$

Hence, by assessing the relative magnitudes of A and C , one can make a quantitative statement about the status of the transaction between ordering and disordering tendencies in any particular system.

It is important to emphasize the complementary nature of ascendancy and overhead. There is no free lunch – if one rises, the other falls. Whereas ascendancy measures the efficiency of system

performance, overhead gauges its 'strength in reserve' from which it can create effective responses to novel circumstances (i.e. its reliability). Given the Eleatic bias of modern science, it is not at all surprising that efficiency and performance are usually emphasized at the expense of reliability. Thus, one frequently encounters subjects like 'optimal foraging theory', or 'optimal reproductive strategy', even when there is evidence to suggest that suboptimal behaviors can actually result in longer persistence [33]. Many today are advocating that society move towards a sustainable mode of existence. Hence, much more attention should be directed towards the (non-Eleatic) features that support persistence.

If the reader is to take away only one conclusion about transactional systems, it should be that one must exercise caution in applying variational methods to living systems. *Pursuing single goals in the living realm*, like pursuing ideological ends in politics, almost *invariably leads to a bad end*. It is possible for a system to attain too high a level of ascendancy or to incorporate too much exergy. It is absolutely necessary to appreciate the full transactional nature of ecosystems and other living assemblages. (It has even been suggested that the pain and destruction wreaked by the great conflicts of the 20th century were consequences of the 'isms' of the day, most of which flowed from the Modernist notion of *natura cum machine*.)

With this caveat firmly in mind, research into single tendencies may then be encouraged. Jørgensen [34], for example, describes the broad plurality in current ecosystem science. Many proffered theories of ecosystem behavior appear to overlap, so that choosing between them is not simply a matter of separating right from wrong. It is necessary that all possible orientors [35] guiding ecosystem development be thoroughly understood. The only thing to avoid while pursuing such research is the adoption of a monist mindset. One must always bear in mind that any living system is the consequence of at least two contradictory propensities.

6 THE ROAD TO LIFE?

One significant advantage to adopting the transactional view on living systems is that it can facilitate deeper understanding of some phenomena that have long appeared enigmatic, like the origin of life. The conundrum of how life arose is to explain how living systems can arise from dead matter [36], which is really rephrasing the same, age-old question, 'How can change proceed from stasis?' Efforts to address the enigma often begin with simple compounds placed in retorts that are then zapped with electrical charges in the hope of creating the building blocks of life. Once the blocks are present, presumably they will assemble into living entities. Then there is Francis Crick and Orgel [37], who was so enamored of the molecule he helped to discover that he simply could envision no earthly origin for it. It must have arrived from extraterrestrial sources! Once on earth, it presumably entrained a whole host of other polymers and enzymes into its service. Both of these approaches, with their Eleatic emphases on objects as the sole source of agency, are akin to expecting Ezekiel's dry bones to suddenly put on flesh and begin to dance. It becomes necessary to introduce Milesian perspectives into the search. Along those lines, process ecology would suggest that the agency behind life is to be sought rather among configurations of ongoing processes.

Howard Odum [38], for example, proposed that *proto-ecological* systems had to already be in place before *proto-organisms* could arise. His scenario was that at least two opposing (agonistic) reactions (like oxidation–reduction) [39] had to be separated and actively transported across a spatial domain that consisted of a region containing a source of energy and another where the entropy created by use of the source can be conveyed out of the system. Such a configuration of processes, via scenarios involving selection like those discussed above, could engender more complicated but smaller cyclical configurations (proto-organisms) to occur. Such a transition poses no particular enigma. Irreversible thermodynamic processes are assumed to engender (and couple with) other processes all the time.

(NB. A change begetting other changes remains dimensionally consistent.) Large cyclical motions spawn smaller ones as a matter of normal course, as when large-scale turbulent eddies shed smaller ones. Corliss [40] suggested that such a scenario might have played out around archaen thermal springs, an idea that recently has found new enthusiasts in Harold Morowitz and Robert Hazen [41]. Thus, process ecology, the notion that objects are created by configurations of processes, provides a far more consistent framework for supporting the origin of life. At the same time, process ecology provides a new avenue for further research on the origin of life.

7 CONCLUSIONS

To fully apprehend the complex behavior of ecosystems requires more than just additional, sophisticated mathematical tools. A wholly new perspective on system development is necessary [42]. One must step boldly out of the Eleatic cocoon that has been fashioned by conventional science to perceive nature through a new lens and to entertain evolutionary suggestions like Popper's to chart out the territory between stasis and change. In this exciting new 'middle ground', objects are not the sole agencies behind change. Processes can beget other processes and configurations of propensities often play the leading role in creating new objects.

The new perspective adds to the old without totally displacing the latter. Research on ecological mechanisms and on individual variational principles remain germane, however, only as long as they are understood to operate within the context of a larger transactional dynamic. No longer is the abyss between stasis and change empty. Ecosystem science, like the world it describes, is in the process of becoming [43].

[AQ3]

ACKNOWLEDGEMENTS

The author would like to thank Dr Sven Erik Jørgensen for his encouragement to write this essay. Helpful comments on the early draft were received from Stanley Salthe. The author was supported in part by the National Science Foundation's Program on Biocomplexity (Contract No. DEB-9981328).

REFERENCES

- [1] Noether, A. & Jacobson, N., (eds.), *Gesammelte Abhandlungen*, Springer-Verlag: New York, p. 777, 1983.
- [2] Carnot, S., *Reflections on the Motive Power of Heat* (trans. 1943), ASME: NY, p. 107, 1824.
- [3] LaPlace, P.S., *A Philosophical Essay on Probabilities* (trans. F.W. Truscott & F.L. Emory, 1951), Dover Publications, Inc.: New York, p. 196, 1814.
- [4] Boltzmann, L., Weitere Studien ueber das Waermegleichgewicht unter Gasmolekuelen, *Wien. Ber.*, **66**, pp. 275–370, 1872.
- [5] Gibbs, J.W. & Zermelo, E., (eds.), *Elementare Grundlagen der statistischen Mechanik; entwickelt besonders im Hinblick auf eine rationelle Begründung der Thermodynamik*, J.A. Barth: Leipzig, p. 216, 1905.
- [6] Simberloff, D., A succession of paradigms in ecology: essentialism to materialism and probabilism. *Synthese*, **43**, pp. 3–39, 1980.
- [7] Depew, D.J. & Weber, B.H., *Darwinism Evolving: Systems Dynamics and the Genealogy of Natural Selection*, MIT Press: Cambridge, MA, p. 588, 1994.
- [8] Schrödinger, E., *What is Life?: The Physical Aspect of the Living Cell*, Cambridge University Press: Cambridge, p. 92, 1944.
- [9] Odum, E.P., The strategy of ecosystem development. *Science*, **164**, pp. 262–270, 1969.
- [10] Mueller, F. & Leupelt, M., (eds.), *Eco Targets, Goal Functions, and Orienters*, Springer-Verlag: Berlin, p. 619, 1998.

- [11] Lotka, A.J., Contribution to the energetics of evolution. *Proc. Natl. Acad. Sci.*, USA, **8**, pp. 147–150, 1922.
- [12] Odum, H.T. & Pinkerton, R.C., Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. *Am. Sci.*, **43**, pp. 331–343, 1955.
- [13] Jorgensen, S.E. & Mejer, H., A Holistic approach to ecological modelling. *Ecol. Model*, **7**, pp. 169–189, 1979.
- [14] Cheslak, E.F. & Lamarra, V.A., The residence time of energy as a measure of ecological organization. *Energy and Ecological Modelling*, eds. W.J. Mitsch, R.W. Bosserman & J.M. Klopatek, Elsevier: NY, pp. 591–600, 1981.
- [15] Fath, B.D. & Patten, B.C., A utility goal function based on network synergism. *Eco Targets, Goal Functions, and Orienters*, eds. F. Mueller & M. Leupelt, Springer: Berlin, pp. 161–176, 1998.
- [16] Ulanowicz, R.E., An hypothesis on the development of natural communities. *J. Theor. Biol.*, **85**, pp. 223–245, 1980.
- [17] Swenson, R., Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution. *Systems Research*, **6**, pp. 187–197, 1989.
- [18] Schneider, E.D. & Kay, J.J., Life as a manifestation of the second law of thermodynamics. *Mathl. Comput. Modelling*, **19**, pp. 25–48, 1994.
- [19] Hatsopoulos, G. & Keenan, J., *Principles of General Thermodynamics*, John Wiley: New York, p. 788, 1965.
- [20] Salthe, S.N., Meaning in nature: placing biosemiotics within pansemiotics. *J. Biosemiotics*, **1**, pp. xx–xx (in press). **[AQ4]**
- [21] Schneider, E.D. & Sagan, D., *Into the Cool*, University of Chicago Press: Chicago, 2005.
- [22] Fang, L.Z. & Li, S.X., *Creation of the Universe* (Chapter 6). World Scientific: Teaneck, NJ, p. 180, 1989.
- [23] Schrader, P. *The Mosquito Coast* (screenplay), Warner Brothers: Hollywood, CA, 1986.
- [24] Elsasser, W.M., Acausal phenomena in physics and biology: a case for reconstruction. *American Scientist*, **57(4)**, pp. 502–516, 1969.
- [25] Popper, K.R., *A World of Propensities*, Thoemmes: Bristol, p. 51, 1990.
- [26] Ulanowicz, R.E., *Utricularia's* secret: the advantage of positive feedback in oligotrophic environments. *Ecol. Model.*, **79**, pp. 49–57, 1995.
- [27] Ulanowicz, R.E., *Ecology, the Ascendent Perspective*, Columbia University Press: NY, p. 201, 1997.
- [28] Ulanowicz, R.E., Ecosystem dynamics: a natural middle. *Theology and Science*, **2(2)**, pp. 231–253, 2004.
- [29] Allen, T.F.H. & Starr, T.B., *Hierarchy*, University of Chicago Press: Chicago, p. 310, 1982.
- [30] Rutledge, R.W., Basorre, B.L. & Mulholland, R.J., Ecological stability: an information theory viewpoint. *J. Theor. Biol.*, **57**, pp. 355–371, 1976.
- [31] Shannon, C.E., A mathematical theory of communication. *Bell System Tech. J.*, **27**, pp. 379–423, 1948.
- [32] Ulanowicz, R.E. & Norden, J.S., Symmetrical overhead in flow networks. *Int. J. Systems Sci.*, **1**, pp. 429–437, 1990.
- [33] Ulanowicz, R.E., & Polgar, T.T., The influences of anadromous spawning behavior and optimal environmental conditions upon year-class success. *Can. J. Fish. Aquat. Sci.*, **37**, pp. 143–154, 1980.
- [34] Jorgensen, S.E., *Integration of Ecosystem Theories: A Pattern*, Kluwer: Dordrecht, p. 383, 1992.

- [35] Bossel, H., Ecological orienters: pattern and process of succession in relation to ecological orienters. *Eco Targets, Goal Functions, and Orienters*, eds. F. Mueller & M. Leupelt, Springer: Berlin, pp. 19–33, 1998.
- [36] Ulanowicz, R.E., Ecology, a dialogue between the quick and the dead. *Emergence*, **4**, pp. 34–52, 2002.
- [37] Crick, F. & Orgel, L., Directed panspermia, *Icarus*, **19**, pp. 341–346, 1973.
- [38] Odum, H.T., *Environment, Power and Society*, Wiley: NY, p. 331, 1971.
- [39] Fiscus, D.A., The ecosystemic life hypothesis I: introduction and definitions. *Bull. Ecol. Soc. Am.*, **82(4)**, pp. 248–250, 2001.
- [40] Corliss, J.B., The submarine hot spring hypothesis for the origin of life on earth. <http://www.ictp.trieste.it/~chelaf/postdeadline.html>, 1992.
- [41] Cody, G.D., Hazen, R.M., Brandes, J.A., Morowitz, H. & Yoder, H.S., Jr., The geochemical roots of archeic autotrophic carbon fixation: hydrothermal experiments in the system citric acid, H_2O -($\pm\text{FeS}$)-($\pm\text{NiS}$). *Geochimica et Cosmochimica Acta*, **65(20)**, pp. 3557–3576, 2001.
- [42] Ulanowicz, R.E., Life after Newton: an ecological metaphysic. *BioSystems*, **50**, pp. 127–142, 1999.
- [43] Prigogine, I., (ed.), *From Being to Becoming*, W.H. Freeman and Co.: San Francisco, p. 272, 1980.

Author Query Sheet

Manuscript No.:ECO-02

Dear Author,

The following queries have arisen during the setting of your manuscript. Please answer the queries using the form below.

Query no.	Query	Reply
AQ1	Please provide a maximum of 10 keywords.	
AQ2	Please confirm if the changes to the sentence 'If that change....' retain the intended meaning.	
AQ3	Is the sentence 'Ecosystem science, like the world it describes, ...' complete?	
AQ4	Please update ref. 20 if details are available.	