Process Ecology: Philosophy Passes into Praxis

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ABSTRACT: *Mechanical reductionism, which deals entirely with homogeneous variables, will constrain and enable the activities of richly heterogeneous living systems, but it cannot determine their outcomes. Such indeterminism owes to problems with dimensionality, dynamical logic, impredictability, and insufficiency. The order in any living structure arises via an historical series of contingencies that were selected endogenously by stable autocatalytic processes in tandem with, and usually in opposition to, conventional external influences (natural selection). The development of living communities thereby resembles a Heraclitean dialectic between processes that build up and those that tear down. Investigating this unconventional dynamic requires metaphysical assumptions that are complementary to those that have guided science over the past three centuries. The new dynamics can be represented in terms of weighted networks of interacting processes, which facilitate the statement of testable hypotheses. Network analysis thereby implements and tests ideas that heretofore could only be addressed as verbal propositions.*

The Chasm

Concern has been growing that the model that has been guiding Western science over the last few centuries may be leading society astray (Cobb 2015). Although science has markedly improved the material lives of individuals, its effects on society as a whole remain mixed. In particular, many are concerned that the human dimension has gone missing from the worldview that has developed. This is not a new concern. C.P. Snow (1963) lamented the chasm that separates the sciences from the humanities. To be sure, there are manifold reasons behind this separation, and space does not permit consideration of them all. Suffice it here to address a particular consensus that arose among the early practitioners of science during the 16th and 17th centuries.

In both the British isles and on the European continent this era was a time of intense clericalism. It is no exaggeration to say that clerics wielded the power of life and death in regard to what could be acceptable elements of the prevailing worldview. Those espousing opinions or observations deemed to be at odds with long-held beliefs about the natural world risked ostracism and occasionally even death. Most are aware of the tribulations of Galileo, Giodano Bruno, and even Newton (who had to hide his heterodox beliefs). It became clear to early scientists that in order to avoid censure, one needed to avoid anything that hinted of the divine, the transcendental, the human, or even the living. Safer to remain engaged solely with the physical and non-living realm.

At the same time there were individuals, such as Francis Bacon, Thomas Hobbes, Edmund Halley, and Leonhard Euler, who saw in the material the crux of all reality and who resented the censorship of the clerics. They reasoned that by attributing ever more causality to material action, they could undermine the pillars upon which the power of the clerics rested. And so a consensus grew between the disparate camps of believers and skeptical reformers that science is best confined to the material and the non-living.

Later material causality also came to dominate a nascent biology. Soon the question arose as to how to regard human phenomena, such as intentionality, aspiration, poetry, and reasoning. To buttress the emphasis upon material agency, these phenomena were declared to be epiphenomena—appearances without any causal efficacy whatsoever—like images on a movie screen.[1] All causality was deemed traceable to material action. This image was almost a neo-Lucretian vision of material particles and the void. And so the chasm deepened.

With the advent of the 21st century the chasm remained. At one end stood the literary critics, artists, poets, theologians, and their ilk, while at the opposite sat the hard materialists, who arrogated all causality to material and mechanical actions and who regarded the humanities as unrelated ephemera. Fortunately, there have always been individuals in both camps who were unsatisfied with the perpetuation of the "no-man's land" between the adversaries and were bold enough to attempt working in the forbidding middle. Physical scientists, like Walter Elsasser (1981), John Wheeler, Robert Rosen, and Stuart Kauffman pointed to the logical inconsistencies of trying to apply a paradigm of homogeneous entities and actions to a wildly heterogeneous world. Their critique was echoed from the other side by philosophers, such as A.N. Whitehead and C.S. Peirce, who roundly questioned the prevailing scientific metaphysics. At issue were inconsistent dimensions, the logic of dynamics, the sufficiency of law, and impredicate constraints.

An Equation for Life?

In science, and especially in engineering, logic is intimately related to the units or dimensions by which quantity and actions are measured. The dimension of time is of particular concern here. The realm of physics is governed by a set of four reversible laws of force. By "reversible" is meant that actions look the same whether played forwards or backwards. Aemalie Noether (1983) demonstrated that such reversibility is logically equivalent to conservation. That is, one can take any reversible law and from it derive a "potential function" that does not change over time. In this regard physics becomes a description of nature in terms of *timeless*, neoplatonic essences, such as mass, momentum, and charge.

By contrast, time plays an intimate role in the dynamics of life, which proceeds by changing from one distinguishable state to the next, usually in irreversible fashion. These transitions between distinguishable states are separated by measurable time and the sequence constitutes a process. In fact, life is itself process (a verb) comprised of other processes. It is decidedly not a thing (a noun) (Popper 1990). Perhaps nowhere is this disparity better illustrated than with Enzo Tiezzi's (2006) description of a dead deer. The thermodynamicist Tiezzi owned and ran an estate in Tuscany that was plagued by deer grazing on his olive trees and grapevines. In frustration, he shot a deer and then was transfixed as he looked down at the dead animal. He asked himself, "What is different about this deer now than when it was alive only tens of seconds ago?" Its mass, form, bound energy, genomes—even its molecular configurations—all these *things* remain virtually unchanged immediately after death. What was missing after death was the *configuration of processes* that had been co-extensive with the animated deer—the very phenomena by which the deer was recognized as being alive.

Despite this manifest identification of life with process, the bulk of effort in biology continues to be devoted to describing the phenomena of living systems, as Ayala (2009) has characterized it, within the framework of "objects moving according to universal laws." Because science deals primarily with equations, one can interpret Ayala's equivalence as the equation, "Life is (=) objects moving according to universal laws." As every beginning student knows, although the appearances of the two sides of an equation may differ greatly in their formulations, both sides must express the same essence—they must have the same dimensions. As the aphorism goes, “one cannot compare apples with oranges.”

Problems arise when one closely examines this putative equation. If life is a process, then it is envisioned as a succession of *different* states, and those states constitute a collection of *heterogeneous* entities. The “universal laws,” as has just been argued, are each reversible in nature, i.e., they deal strictly with timeless conservation. Furthermore, as Gregory Bateson (1972) noted, each law is expressed in terms of variables that are *homogeneous* or *undifferentiated* (e.g., mass, energy, charge, etc.).

So in this putative equation, time (or more accurately rate, [1/t]) is explicit in the dimensions of the left-hand side; whereas it is missing from the right-hand side where the universal laws can be expressed in terms of their unchanging potentials. The dimensions of the two sides are incongruous! Purely and simply, the equation is wrongly cast. A process can only be explicated in terms of other processes, as was evident with Tiezzi’s deer. The conclusion to be drawn, on dimensional grounds, is that an adequate portrayal of life in purely physicalist terms is impossible.

Or is it? It would appear that some of the best minds in science do not agree with this characterization of affairs. Witness, for example, the consensus among Nobel Laureates Murray Gell-Mann, Stephen Weinberg, and David Gross, all of whom agree that causality originates from below and that there is nothing “down there” but the laws of physics (Kauffman 2010). Inquiring minds want to know: (1) can the dimensional argument be defended?; (2) why are the universal laws insufficient to describe the life process?; and (3) how best can one describe the life process in terms of other processes?

Dimensional Inconsistency

Most physicists would at first be unperturbed by the disparity in dimensions between physics and life. It often happens in physics that phenomena to be compared differ in their dimensions, a situation that usually can be fixed in an instant by providing an appropriate conversion factor to equate the dimensions on both sides. For example, in the familiar equation from electricity, E=IR, the voltage, E, and the current, I, are related by the scalar resistance, R, which has the dimensions of voltage/current (or ohms); or the equation for heat conduction, $Q=\lambda\Delta T$, where the heat conducted, Q, is related to temperature difference, ΔT, by the scalar thermal conductivity, λ. Of course, when conditions are not isotropic (the same in all directions), the scalar might have to be replaced by a vector or tensor set of constants, but these are quite tractable conversion devices.

The key feature of physical systems that makes them so amenable to conversion of dimensions is that the principle variables are always homogeneous in nature: Heat (Q) is heat is heat. Voltage may differ in magnitude, but not in kind—likewise, temperature and electrical current. Bateson (1972) called such homogeneous variables "*pleroma,*" to distinguish them from the manifold heterogeneous collection of forms that constitute living systems. As will be argued presently, the enormous number of combinations among heterogeneous collections renders such straightforward conversions intractable. That is, relations between 2 sets of identical tokens can be handled by a scalar, or at worst by vector/tensor, conversion. However, relations between 2 groups comprised of heterogeneous tokens can become intractable, and with very heterogeneous living systems such is almost always the case.

Logical Inconsistency

It was Walter Elsasser (1981) who elaborated on the impediment that is posed by heterogeneity in formulating physics-like laws for biology. It happens that over a century ago Whitehead and Russell in their *Principia Mathematica* demonstrated that the force laws of physics are logically equivalent to operations conducted on homogeneous sets. Elsasser underscored how the same logic is not applicable to operations among members of heterogeneous groups. Elsasser concluded that laws akin to the universal force laws could never arise among the heterogeneous types that constitute living systems.

The arguments of Whitehead and Russell lie beyond the scope of this essay, but the underlying idea can be conveyed by two simple analog illustrations (Ulanowicz 2009). Consider, for example, homogeneous sets of integers as follows: The first set consists of five tokens of the integer 1, the second contains five tokens of the integer 2, the third contains 3s, etc. Now let the set of twos interact with, say, the set of 4s according to some determinate operation. For example, each of the tokens in the first set might be multiplied by a corresponding member of the second. The result would be another homogeneous set of five eights (Figure 1). That is, the result is another determinate, homogeneous set.

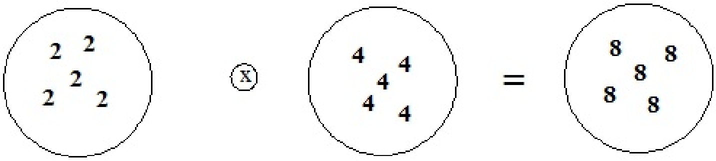

Figure 1. The result of a fixed operation upon two homogeneous sets. The result is a single homogeneous set.

Now consider collections of 5 integers each grouped according to magnitude. That is, the first group contains the integers 1 through 5; the second, 6 through 10; the third, 11 through 15, etc. Each of these aggregates is inhomogeneous; its members are clearly different each from the other. Now let the first group operate on itself according to the same procedure was used in the homogeneous example. One possible result would be the integers 4, 5, 6, 8, and 15 (Figure 2). One notices that these products are scattered across three separate classes. Other combinations would yield similar *indeterminate* results in the sense that they would scatter among several groups.

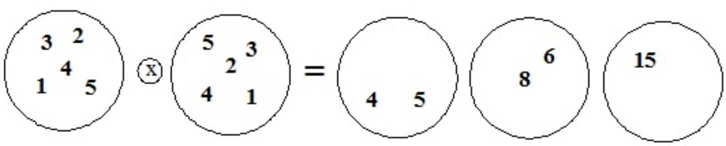

Figure 2. The same operation as in Figure 1 carried out between two heterogeneous groups of integers yields results that scatter across several different classes.

Elsasser concluded that the logic of homogeneous physics is inappropriate to deal with a heterogeneous biology.

Boundary Particulars (laws alone are insufficient)

The intrepid physicist might still insist that one can treat heterogeneous situations simply by transferring all heterogeneity to what is called the "boundary value problem." In order for the fundamental laws of physics to be universal, they must be cast in the very broadest terms, i.e., as universal variables (e.g., Bateson's *pleroma*). But even the simplest of real problems is endowed with particularities. Quantifying those particularities is called the "boundary value problem," and the statement of any real problem is strictly incomplete (and insoluble) until those particulars are clearly stated (Ulanowicz 2013).

For example, one might wish to calculate the trajectory of a cannon ball. The appropriate law would be Newton's second law of motion in the presence of gravity. The specific trajectory and impact point cannot be ascertained, however, until one stipulates at least the location of the cannon, the muzzle velocity, and the angle of the cannon with respect to the earth—all of which comprise the boundary statement. In practice, laws can never be considered on their own. They must always be accompanied by a boundary statement, which is an integral and requisite part of the problem formulation.

If the universal laws are to remain inviolate, they must apply to any and all boundary statements. That is, the boundary conditions are entirely arbitrary, because if one could point to particular boundary conditions which the law could not accommodate, then the law by definition would no longer be universal. In practice, boundary statements that are definitive (clear and unequivocal) give rise to results that are determinate. Nothing, however, prohibits a user from choosing conditions that are contingent or even stochastic (blind chance).

That determinate laws acting on stochastic inputs might yield stochastic results is not troubling to most investigators, because there is a highly effective set of tools called probability theory to deal with blind chance. This mainstream probability theory is predicated on the assumptions that the events of interest are simple, directionless, indistinguishable (homogeneous), and repeatable. However, only an incrementally small fraction of contingent events satisfy all those assumptions.

Elsasser (1969), for example, argues elsewhere that most objects and events in biology are strictly unique, that is, distinguishable and non-repeatable by chance. For example, combined actions of multiple simple chance events can constitute a compound event and such combinations need not be, and usually are not, directionless. Furthermore, Elsasser demonstrates how whenever more than about 80 distinguishable elements or chance events combine, the resulting amalgamation can be referred to as physically unique, because it would take an interval more than a million times the age of the universe before that particular combination could be expected to occur again by chance. Such contingencies can be termed "radical" chance, and the laws of probability theory simply do not pertain to them.

In the opposite direction one finds probabilities that are constrained by external interferences so as to be skewed away from "blind" chance. Thus, when dice are not true, one observes a bias for or against certain values showing, or when a predator ingests a prey item the probabilities are usually skewed from random frequencies of encounter. Such constraint gives rise to what are called "conditional probabilities." Going still further, Popper (1990) writes about "propensities," whereby one favored outcome predominates, but other results may occasionally occur. For example, during the early twentieth century over nine of ten young immigrants to America married someone from their own ethnic group, although a few would venture to take native-born spouses.

One thus sees that Monod's crisp dichotomy between "chance and necessity" is illusory. Instead, reality provides an entire spectrum of contingencies ranging from radical chance at one end to blind chance, conditional probabilities, propensities, and finally to deterministic phenomena. Any and all of these phenomena may serve as boundary conditions on universal laws, and in most cases the natures of the outputs will reflect their corresponding inputs.

Impredicate Boundaries

Because a complete problem statement must encompass *both* law and boundary specifics, whenever one is unable to clearly articulate the boundary problem, the problem remains insoluble. Such a condition becomes very likely to occur whenever one deals with highly heterogeneous systems, because of the enormous and unmanageable number of combinations among the many distinguishable types. This situation is perhaps best exemplified by Kauffman's "exaptations" (Longo et al. 2012). Evolutionary theory suggests that over the course of phylogeny, there is a propensity for organs or structures to emerge that help a given species to adapt to a particular environment. In Popperian fashion, however, it occasionally happens that a structure which arose in response to one set of conditions will come to serve an entirely different function in a different environment. The classical example of such "repurposing" is the evolution of the swim bladder in fish. The cavity, as it originally developed, served as a proto-lung for fishes to survive by gulping air in oxygen-depleted environments, but over time it changed function to serve as a buoyancy regulator. There is simply no way to cast a boundary statement so as to include the innumerable possible such exaptations that might occur.

The foregoing impossibility may be typified as "epistemological" in that one cannot describe and solve the problem, but some would argue that the laws still determine the ontological outcomes. Combinatories among heterogeneous systems, however, render the small number of universal laws insufficient to *determine* those outcomes. The four force laws of physics plus the two laws of thermodynamics number 6, and the number of possible combinations among them is readily enumerated ($6!=720$). Those combinations, though many, pale in comparison with the combinations among an only mildly heterogeneous system (say, $35!\approx10^{40}$). There can be billions of combinations of the heterogeneous system capable of satisfying exactly each configuration among the fundamental laws. The laws are not violated and they continue to constrain possibilities, but they are insufficient to discriminate among the manifold system configurations, each of which exactly satisfies any particular mix of those laws.[2]

Whence Order?

Given the enormous variety of contingencies that may impact a given system and the inability of the fundamental laws to discriminate from among equally possible outcomes, how is it possible for the obvious order in biological systems to arise? Once more, it is recalled that life is process and that processes, once extant, are able to interact with one another. In the course of doing so, they sometimes form stable configurations, which in their turn give rise to accompanying enduring structural forms. (It is too rarely mentioned that it is configurations of processes that create structures.) It is only appropriate, then, to direct the search for manifestations of stable order among what might be called "an ecology of processes." In that vein, the first clue as to how order might arise was provided by Gregory Bateson (1972), who wrote, "In principle, then, a causal circuit will generate a non random response to a random event."

Bateson thus focuses attention upon chains of processes for which the first and last processes are identical, i.e., cycles of processes or causal circuits. In examining such loops, a particular subcategory of cycles is seen to be prominent among living systems and to impart direction to subsequent dynamics: Autocatalysis ("auto" meaning "self" and "catalysis" the act of quickening) is any cycle of processes for which each member process catalyzes the next one in the sequence (Ulanowicz 2013). In Figure 3, for example, if process A facilitates another process B, and B catalyzes C, which in its turn augments A, then the activity of A indirectly promotes itself. The same goes, of course, for B and C. In general, A, B, and C can be objects, processes, or events, but focus here will be upon linkages of processes, and while those linkages can be deterministic (mechanical), the more interesting relationships pertaining to living systems will involve some type of contingencies.

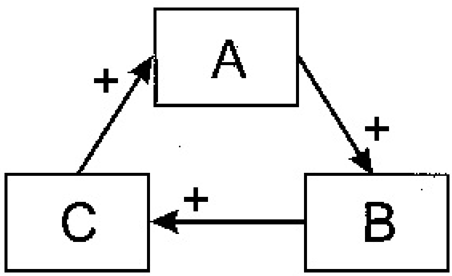

Figure 3: Schematic of a hypothetical 3-component autocatalytic cycle.

An ecological example of autocatalysis is the aquatic community that develops around a family of aquatic weeds known as Bladderworts (genus *Utricularia*, Ulanowicz 1995). All Bladderworts are carnivorous plants, because scattered along the feather-like stems and leaves of these plants are small, visible bladders (Figure 4a). At the end of each bladder are a few hair-like triggers, which, when touched by any tiny suspended animals (such as 0.1-mm water fleas), will open the end to suck in the animal, which then becomes food for the plant. In nature the surface of Bladderworts always hosts the growth of an algal film. This surface growth serves in turn as ready food for a variety of microscopic animals. Thus, Bladderworts provide a surface upon which the algae can grow; the algae feed the micro animals, which close the cycle by becoming food for and benefitting the Bladderwort (Figure 4b).

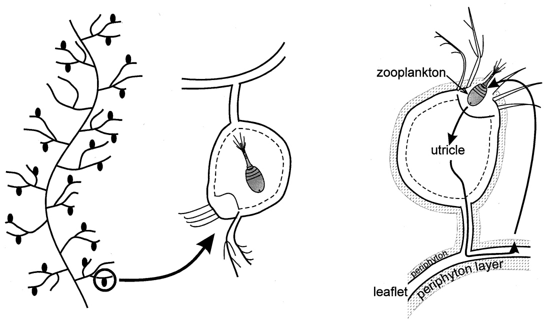

Figure 4: (a) Sketch of a typical "leaf" of Utricularia floridana*, with detail of the interior of a utricle containing a captured invertebrate. (b) Schematic of the autocatalytic loop in the* Utricularia *system. Macrophyte provides necessary surface upon which periphyton (speckled area) can grow. Zooplankton consumes periphyton, and is itself trapped in the bladder and absorbed in turn by the* Utricularia.

Such autocatalysis among living systems, when it interacts with contingent events, can give rise to dynamics not usually associated with mechanical systems (Ulanowicz 2009). Autocatalysis, for example, exerts selection pressure upon all its participating elements. Should there happen to be some contingent change in the surface algae that either allows more algae to grow on the same surface of Bladderwort (e.g., by becoming more transparent) or makes the algae more digestible to the tiny floating animals, then the increased algal activity thereby induced will be rewarded two steps later by more Bladderwort surface. In the process, the activity of all three participants will be increased. Conversely, if the change either decreases the algal population or makes the algae less palatable to the micro animals, then the rates of all three processes will be attenuated. Simply put, contingencies that facilitate any component process will be rewarded, whereas those that interfere with facilitation anywhere will be decremented. Autocatalytic configurations are thus both self-advancing and self- preserving.

A particular phenomenon related to such endogenous selection is fundamental to the life process: Corollary to the workings of autocatalytic selection, any increase of resource taken into any component process is likely to be rewarded. Because such potential reward applies to any member of the cycle, all avenues of resources into the autocatalytic loop will tend to be amplified — a phenomenon that can be termed "centripetality" (Figure 5). For example, such centripetality, or radial attraction, is evident in coral reef communities, which sequester major concentrations of nutrients well over and above those in the oceanic desert that surrounds them.

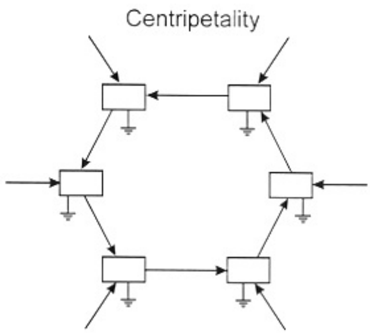

Figure 5: Centripetal action as engendered by autocatalysis.

This ratcheting-up of activity, when accompanied by centripetality, constitutes "growth." Growth, especially in the geometric proportions described by Thomas Malthus, played a major role in Darwin's natural dialectic. Unfortunately, the growth side of evolution has been downplayed by the later disciples of Darwin to the point where it now appears as a given, unworthy of further attention. But Darwin's full transaction is bilateral and might be paraphrased as "Growth proposes, natural selection disposes" (Stanley Salthe, personal communication, 2011). Contemporary discussions of evolution remain preoccupied with the eliminative role of nature, commonly referred to as "natural selection." The enormous advantages imparted to some species via their participation in autocatalysis and its accompanying centripetality remain, however, proscribed from the modernist narrative.

One notable figure who commented on the role of centripetality was Bertrand Russell (1960). He called it "chemical imperialism" and identified the phenomenon as *the* drive behind *all* of evolution. His appraisal is likely not far off the mark. In the conventional narrative competition plays the central role in evolution. The origins of competition, however, derive from centripetality and its eliciting mutualism. Place two autocatalytic systems within a finite resource field and eventually their centripitalities will intersect. That is, competition cannot happen without centripetal drives at work the next level down. It is mutualism that is primary and competition plays a derivative, secondary role.

It should be noted that for autocatalysis to ratchet up its activity, some form of memory or hysteresis is necessary. In the contemporary obsession with DNA/RNA, most readers will likely envision some molecular structure as the manifestation of memory. But one should also remember that the autocatalytic dynamic is itself structured and stable and can function as a rudimentary form of memory. The highly-structured polymers of nucleic acids that now embody memory were likely the products of earlier configuration of processes (Deacon 2011). Once encoding emerged out of those more diffuse forms of process memory, their inherent efficiency and longevity allowed them to extirpate their progenitors (a form of temporal supervenience).

It is necessary to emphasize the contingent nature of autocatalytic configurations as they develop over time. Each new feature of a given autocatalytic repertoire was a contingent event, be it radical, blind, or already ordered in some way, that was selected by the earlier autocatalytic structure. That earlier configuration in turn came into being by a previous inclusion of some earlier contingency and so forth back into the past. The system at any time is built upon a *serial history of contingent events*. The development of the system can thus be regarded as indeterminate, but nonrandom. Any particular inclusion of a contingency is not totally random because it has been selected by the dynamic extant at the time of encounter. An enormous number of other contingencies were not selected because they did not fit the context of the existing autocatalytic structure. At the same time, the exact nature of the next contingency to be selected cannot be specified, in the same way that one cannot predict an exaptation. The pathway of autocatalytic evolution remains indeterminate. The universal laws of physics will always constrain what is possible, but they remain insufficient to determine exactly what will happen in a heterogeneous world.

The reader may find it difficult to envision a process that is nonrandom but also indeterminate. A helpful metaphor for such a process was suggested by physicist John A. Wheeler (1980), who imagined the evolution of science as a parlor game: A number of guests are invited to a dinner party. Dinner is late, and so the hostess bids the company to entertain themselves with a game. They elect to play the game ‘‘20 Questions’’ in which the object is to guess words. One individual is sent out of the room, while those remaining choose a particular word. It is explained to the delegated person that, upon returning, he/she will pose a question to each of the group in turn and these questions will be answered with a simple ‘‘yes’’ or ‘‘no’’ until a questioner guesses the word. After the chosen player leaves the room, one of the guests unexpectedly suggests that the group not choose a word. Rather, when the subject returns and poses the first question, the initial respondent is completely free to answer ‘‘yes’’ or ‘‘no’’ on unfettered whim. Similarly, the second person is at liberty to make either reply. The only condition upon the second person is that his/her response may not contradict the first reply. The restriction upon the third respondent is that that individual’s reply must not be dissonant with either of the first two answers, and so forth. The game ends when the subject asks, “Is the word XXXXX?” and the only response coherent with all the previous replies is ‘‘yes.” At any point in the game, the response is not random, and yet it is impossible at the beginning to ascertain what word will end the game.

The Cosmic Conversation

Wheeler’s metaphor is wonderfully rich and illustrates the nature of evolution beyond the ability of Neo-Darwinism to do so. The rules of the game play a role analogous to the laws of physics—they constrain and make possible. But it is obvious that the rules alone do not specify the final outcome. That comes about via a dynamic that can satisfy the rules in a virtual infinity of different ways. The causality that guides this dynamic is entailed by a conversation that is rife with contingencies. On one side is the questioner, who constantly tries to build a coherent framework that will lead him/her to closure. On the other side of the conversation are the respondents, who are inclined to give answers that will prolong the game.

Wheeler’s model of evolution is not simply that of a monist machine that operates within a milieu of blind chance. Rather, order and form are built by an ongoing inclusion of contingencies into an existing configuration of processes. Such order as has arisen is constantly being impacted by entropic contingencies, most of which are neutral and many of which degrade its form. A rare few, however, lead to new behaviors and improved autocatalytic action. Evolution is truly dualist, not on the sense of Descartes, but rather like the description by Heraclitus, who saw nature as the outcome of actions that build up in tension with those that tear down; or akin to the ancient Tao, where the active agency of Yang is constantly countered by a more passive and conservative Yin.

Within this scenario for evolution can be discerned two levels of causality. The first level plays out among homogeneous entities that obey the universal laws of physics. These laws are not necessarily violated, they simply cannot specify the more proximate constraints that build upon local and historical occurrences and which, going forward, select specific pathways of events. Peirce called these local constraints "habits," while Salthe calls them "laws of matter." More generally, they may be termed "proximate laws," even though such laws are at times quite wide-ranging, like the constraints imposed by the existence of DNA/RNA upon the development of all surviving living forms on earth. In the end it is not the force laws themselves that drive the selection dynamics of living systems like the *Utricularia* community, but rather the mutualistic set of services that the participants perform for one another.

Quantifying Process Dynamics

Life developing according to proximate laws is deeply entwined with contingencies. Dynamical theory was developed to deal with a determinate world and subsequently has been extended to include the realm of blind chance. It is only in the past few decades that the interface between contingency and constraint has been addressed, perhaps most prominently by what is called Bayesian statistics. But if the dynamics of life are fundamentally dialectical, what does that imply about one's ability to quantify living nature? After all, it has been shown that a dialectic cannot be adequately represented in algorithmic fashion (Wegner 1997). Is there any form of quantitative treatment that is applicable both to the amalgam of constraint and indeterminacy as well as to the dialectical dynamics of evolution? If the aim is to implement process thinking as a scientific enterprise, it is necessary to translate the philosophical notions surrounding process into a quantitative lexicon.

It happens that an appropriate quantitative metaphor for intertwined constraint and indeterminacy exists in the notion of network. A network consists of a collection of *distinguishable* entities or states called nodes—a heterogeneous mix. These nodes relate to each other across links that join interacting pairs. The nodes and links form what is called a *graph* (Figure 6a). If the links represent influence in only one direction, each is represented by an arrow indicating that direction, and the resulting network is called a *digraph* (Figure 6b). If those arrows can be quantified by some magnitude, the network then becomes a *weighted digraph* (Figure 6c).

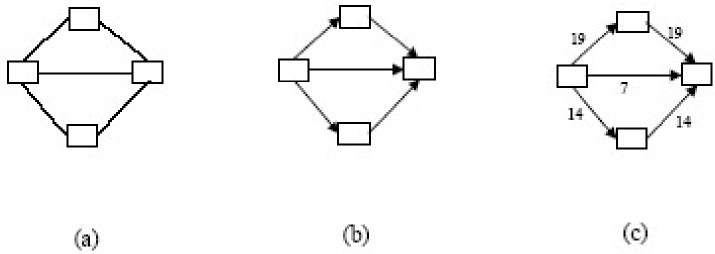

Figure 6: The hierarchy of networks: (a) Simple graph, (b) Digraph, (c) Weighted digraph.

The crucial relation to process theory is that a link can also represent a transition from one state to another—an event. In this way a concatenated pathway among states will depict a *process*—a particular progression of events. The network as a whole then represents a configuration of processes. Some of the constituent processes double back on themselves yielding feedback loops, some of which could be autocatalytic configurations.

Since about 2000 there has been an explosion of the scientific literature devoted to the study of networks. Unfortunately, almost all of this work has been devoted to explaining patterns of networks in the prevailing vocabulary of mechanics. "What are the mechanisms behind the generation of small-world networks?" or "What leads to the development of scale-free networks?" are typical research agendas. There exists an apparent blindness to the indeterminacy inherent in networks, which perhaps could have been expected. Marshall McLuhan (1964) warned how with the introduction of a new medium, people remain at first mesmerized, not perceiving its nature and full potential. He liked to cite IBM as a small company that started out thinking that its occupation was building machines for business. It was not until the company discovered that it was actually devoted to processing information that the enterprise finally took off.

It is the same with the current obsession for treating networks solely in mechanical terms. To be sure, mechanical constraints are manifest in networks. If one is at any node in a network, it usually happens that any one node is usually constrained from interacting with a substantial number of other nodes in the very next step. Figure 7 depicts the major trophic transfers (who eats whom, and at what rates?) in the mid-Chesapeake Bay ecosystem. The microzooplankton (extremely small invertebrate organisms, node 7), for example, feed only four other nodes (8, 11, 12, and 13) and for various reasons are constrained from serving as food to any other compartments. That is, in ecology a particular node interacts directly with only a few other nodes. At the same time, however, any given node usually relates to more than one other node and which of those nodes it will interact with next can remain *indeterminate*. One does not know a priori whether the next microzooplankter will be eaten by a mesozooplankton (8), an oyster (13), a mya clam (12), or some other bottom-dwelling suspension feeder (11). Networks depict, then, not a determinate world, but one that is partially constrained and otherwise free to change—a very appropriate metaphor to depict process dynamics.

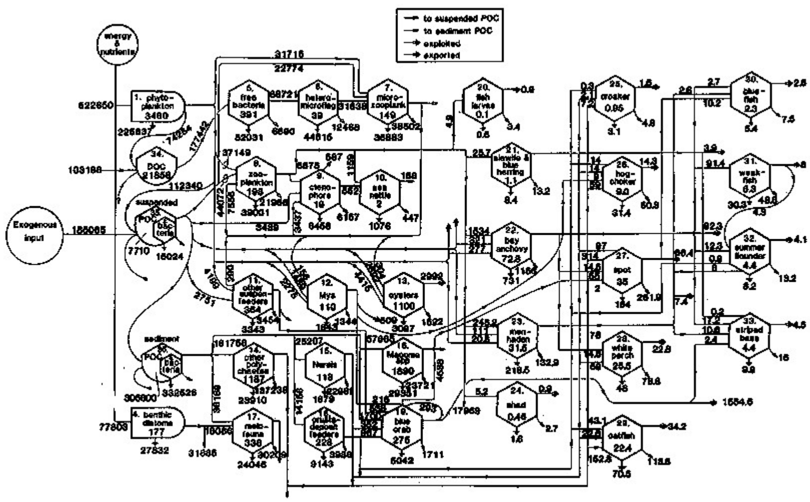

Figure 7: Carbon flows among the 36 major trophic components of the mid-Chesapeake Bay ecosystem. Arrows indicate flows from prey to consumers as measured in mgC/m2/y. Numbers inside nodes are the estimated densities of that taxon in mgC/m2.

The question then arises whether there is any way to parse activity within a network according to constraint and indeterminacy? One can readily envision networks characterizing the extremes of constraint and indeterminacy. For example, in the digraph of Figure 8a, if one is at any node, it is wholly indeterminate as to which node will next be visited. There are *no* constraints, only indeterminacy. Figure 8b, however, represents the other extreme. All transitions are determinate and equiponderant.

There is no indeterminacy. But how to quantify how far, in general, a given network lies between these extremes?

It is beyond the scope of this article to elaborate mathematically the appropriate measure. Suffice it to say that information theory applied to networks allows an investigator to define a "degree of order" *a*, that characterizes the percentage of activity occurring under constraint in any given network.3 For any weighted digraph the degree of order will lie within the interval from zero to one. For example, for the network in Figure 8c, *a* ≈ 0.333. The measurement of *a* thus permits one to track how much order exists in a configuration of process as it either develops or degenerates.

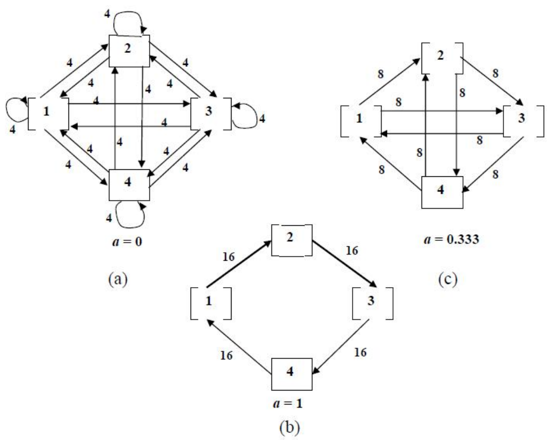

Figure 8: (a) A four-component network with no constraints (a = 0) and maximal indeterminacy. (b) A four-component digraph that is fully constrained (a = 1). (c) An intermediate network with both constraint and indeterminacy (a = 0.333).

When the measure *a* was applied to a collection of ecological weighted digraphs, it was originally thought that an ecosystem would develop over time in the direction of increasing *a* (Ulanowicz 1980). This hypothesis was not confirmed. Rather, ecosystems networks representing trophic processes in a myriad of habitats and environments showed a surprising consistency in their degrees of order at around 40% (Figure 9). Such near-constancy suggests that a particular balance is being struck between internal order (and efficiency) and freedom (often in the guise of redundancy of pathways or inefficiencies).

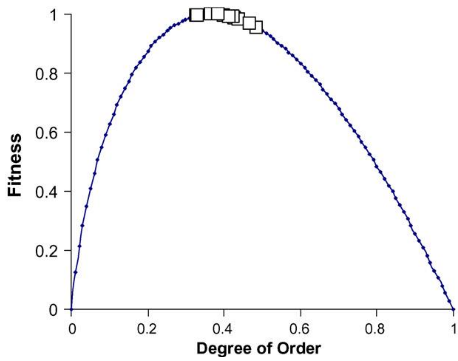

Figure 9: The clumping of articulated ecological trophic networks around the "degree of order" a = 0.40. (Fitness is measured as -alog(a), and represents the potential of the system to evolve further as the product of the system's order [a] times its relative disorder, [-log(a)].)

Discovering a balance instead of a progression prompts one to ask why the efficiency (and order) of ecosystem networks does not increase beyond a certain point—why is efficiency not maximized? The balance seems to be demonstrating that systems can become too efficient for their own enduring survival. When a system is disrupted by a novel disturbance to which it has not adapted, its ability to reconfigure to meet that challenge depends on how many new repertoires it can fashion from among its mix of processes that hitherto had appeared as useless or inefficient. A system that is allowed to grow efficient without bound is one that will relinquish its "strength in reserve" and become brittle (Holling 1986) and highly vulnerable to collapse in the face of new disruptions. The balance represents a tradeoff between the mutually exclusive properties of efficiency and reliability.

The necessity of retaining inefficiencies contradicts the conventional wisdom that always advocates maximal efficiency. An example of too much efficiency exists in the economic realm where the efficiency of the market is considered a *sine qua non*. Allowing unfettered market efficiency can lead to social instabilities due to inequities and monetary crises (Lietaer et al 2009).

It becomes clear that a full articulation of the natural dialectic comes about only through an unconventional emphasis upon process thinking and its expression in terms of quantitative networks.

Process Ecology

One way to summarize the process narrative as presented above is to compare it with the metaphysics that was foundational to the prevailing mechanical/material worldview. Although it is not possible to summarize scientific metaphysics as it currently exists, Depew and Weber (1995) did compile a list of assumptions that formed the basis of the worldview over most of the last three centuries: Nature, at one time or another, had been assumed to exhibit:

a) **Closure**—Only material and mechanical causes exist.

b) **Atomism**—Systems can be broken down into component parts, those elements studied in isolation, and the ensemble behavior will reflect the aggregate of the individual behaviors.

c) **Reversibility**—the laws of nature are the same looking either forward or backwards in time.

d) **Determinism**—Given some small amount ε, the behavior of a system can be predicted to within a range of δ.

e) **Universality**—The laws of nature apply always and everywhere with respect to time and space.

In the preceding development of the transactional scenario for ecosystem development, three fundamental axioms were assumed (Ulanowicz 2009):

i) **Contingency**—Systems are continually being impacted by arbitrary events that cannot be framed in lawful fashion in closed form.

Essentially, this axiom posits chance as an ontological reality. It's not that such chance events actually break any laws; it's that the laws as such are insufficient for determination and the accompanying and necessary boundary statements are impredicate.

ii) **Feedback**—Processes, via interaction with other processes, are capable of influencing themselves.

This is a radical assumption. It specifically violates closure and the Aristotelian prohibition against circular reasoning. It permits mereology in general (Juarrero 2015) and opens the way for autocatalysis and its associated behaviors, which are fundamental to the behaviors of living systems.

iii) **History**—Systems differ from one another according to their histories, some of which is recorded in their material configurations.

This assumption accepts what Darwin assumed about the natural world. History cannot be formulated wholly in terms of reversible laws.

Of particular note, each of these statements is the antithesis of one of the fundamental assumptions that guided Enlightenment physics: Chance is the opposite of determinism; feedback violates closure and history negates reversibility. Atomism and universality simply have no counterparts in the revised metaphysics. In a world where relationships are primary, atomism either doesn't exist or serves no useful function. Agency in the new scheme takes the form of configurations of processes that are not universal, but rather contingent and circumscribed in both time and space.

Also of importance, assumptions *a* thru *e* undergird a collection of simplified, homogeneous, weakly-interacting models that portray the dynamics of systems that are prone to decay and fall apart. For example, the ideal gas model formed the basis for the conclusion that the ultimate fate of the universe is "heat death," or a rarefied collection of low-frequency photons. Assumptions *i* thru *iii*, to the contrary, support a dynamic that builds up organized activities and structures. Both dynamics are active aspects of nature and are in tension with one another in dialectic fashion—the Yin and Yang of existence.

It seems difficult for the Western mind to accept, accustomed as it is to a monist conception of reality, that two conceptual tendencies in tension should coexist. It accords, however, with Eastern legacy that agonistic tendencies should each rest upon complementary principles. Besides, in the larger realm complementarity segues into mutual obligation in Hegelian fashion. That is, at the focal level, the two drives directly oppose one another. At higher levels, however, autocatalysis requires the noise of contingency to progress, whereas more efficient forms of autocatalysis tend to dissipate resources at higher rates (Ulanowicz and Hannon 1987).

The three fundamental axioms (*i—iii*) when supplemented by the corollary notions that (*iv*) configurations of processes function as agencies and (*v*) the dynamics of creation are transactional comprise what Ulanowicz (2009) has named "process ecology."

Bridging the Chasm

To summarize, this discussion began by pointing out that the sciences and the humanities were separated by a gaping chasm within which the natural phenomenon of life could not be adequately addressed. It has always been assumed on the part of science that, given enough time, it would eventually expand to fill that chasm. This may in the long run prove to be the case, but it remains doubtful that the metaphysical foundations of current science are sufficient to that task. Equating life wholly to matter moving according to universal laws violates logical consistency. Life and associated phenomena involve changes that differ dimensionally from motions described by reversible laws.

So what in the end will fill C.P. Snow's chasm? It is perhaps premature to say, but because life is process and not simple motion, any satisfactory theory will perforce require some elements from process thinking. But process narratives have been heretofore almost exclusively qualitative and philosophical in character. Science, however, demands the quantitative and the propositional. One entry for process thought into the domain of science would be to cast ensembles of processes in the metaphor of networks, as is done in systems ecology. Doing so renders the relational and heterogeneous aspects of process philosophy teachable, quantifiable, and testable.

Many in the humanities may bristle at the thought of quantifying what until now has remained purely qualitative narrative. That reaction is likely born of the distrust that many in the humanities share for the totalizing effect that mathematics had purportedly imparted to a deterministic model of the world. But such fears are clearly unfounded in process ecology. Processes are almost never deterministic, and any mathematics that would faithfully describe their behaviors would of necessity remain indeterminate, allowing for the freedom that is required for creativity.

Process ecology represents the entry of process thinking onto the stage of scientific praxis.

ENDNOTES

1. To this writer it has always appeared as either ideology or intellectual sloth that phenomena that guide human action upon the material world be proscribed from legitimate scientific consideration.

2. Premonition of this circumstance was provided by Prigogine's (1978) examples of indeterminate bifurcations.

3. If T_{ij} represents the effect of node i upon node j, then

$$a = -\{\Sigma_{i,j}T_{ij}\log([T_{ij}\Sigma_{k,l}T_{kl}]/[\Sigma_k T_{kj}][\Sigma_l T_{il}])\}/\{\Sigma_{p,q}T_{pq}\log(T_{pq}/\Sigma_{k,l}T_{kl})\}.$$

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