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Ecosystem Dynamics: a Natural Middle

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Abstract *Conflicts between science and religion revolve about fundamental assumptions more often than they do facts or theories. The key postulates that have guided science since the Enlightenment appear to be wholly inadequate to describe properly the development of ecosystems. An emended set of tenets adequate to the ecological narrative also significantly ameliorates the adversarial nature of the dialogue between scientists and theists.*

Key words Causality; Chance; Divine action; Ecosystem; Free will; Origin of life; Process ecology; Theodicy

In the burgeoning dialogue between scientists and theologians, discussions all too often follow a similar script: On one side sit the physicists, who, eager to engage their theologian counterparts in useful exchange, look out into the realms of particle physics or cosmology to describe phenomena that lie somewhat outside the tenets of "normal" science. Across from them, sit the theologians, who examine scripture and doctrine for clues and connections that might accord to some degree with the observations their physicist counterparts are making.

There appear to be several problems with this frequent scenario. First, while both parties may be filled with good intentions, the posture of the discussants resembles that of two parties at the start of a pistol duel—standing some distance apart with their backs toward each other, peering into the distance beyond. Second, the discussions commonly focus upon phenomena, facts and theories, rather than upon any disparities in the axioms that define the ways the two groups pursue their activities. Third, when physicists regard their strange realms, their perspective resembles that common to Eastern religions, i.e. directed beyond everyday perception.[1] Meanwhile, their theologian counterparts mostly come from the "book" religions of Judaism, Christianity, and Islam. Each of these is predicated upon historical events and is actively concerned with how matters transpire in the world of immediate perception. Christianity, in particular, is concerned with *incarnate* realities. The net effect is that the participants fail to focus upon the mesoscopic realm of immediate experience where a more fertile ground might await sowing.

To be sure, not all dialogues between scientists and theists fit this mold. There exist theologians who take the dogma of biological evolution at face value and explore the ramifications of those tenets for believers.[2] Conversely, there are

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physicists willing to reconsider the axiomatic foundations their endeavors.[3] Largely, however, attempts to see the world through the eyes of one's counterpart are the exception rather than the rule. Nor, for that matter, do all conversations proceed under an aura of goodwill. All too often dialectics represent attempts by one side to seize the domain of the other. Witness the material reductionists Richard Dawkins[4] and E. O. Wilson,[5] who posit a material, mechanical and genetic basis for the persistence of religion. Similarly, creationist Phillip Johnson[6] and Intelligent Design advocate Michael Behe[7] seek to portray the universe as resulting directly from a script written by an engineer-God. Material reductionists view any agency other than those explicitly material or mechanical as illegitimate and illusory. Literal creationists, for their part, insist on interjecting a personal agency as immediately responsible for the form and order of material systems. One is thereby led to ask whether any middle ground might exist that could provide a theatre wherein members of both camps could arrive at some mutually respectable compromise?

Ecology as neglected middle

In an effort to foster productive dialogue between scientists and theologians, it might be helpful if attention could be re-directed toward phenomena that lie intermediate to the lifeless world of elementary particles and the transcendental concerns of the theologian. Here the realm of biology seems most relevant, but interest in biology has been strongly slanted in recent decades towards the microscopic realm of the genome, and even more narrowly towards the role of the macromolecules involved in reproduction (e.g. DNA). The scales with greatest potential for hosting fruitful discussions are, however, those of everyday existence—that is, those about whole organisms or collections thereof. Such is the domain of ecology, or more precisely, the realm of ecosystem science—the study of the relationships of populations of organisms with each other and with their physical environment. Although some ecologists hold that the behaviors of ecosystems are largely determined by genetic events,[8] most find that such tight control strains credibility. Perhaps the renowned developmental biologist, Guenther Stent, phrased those doubts most aptly:

> Consider the establishment of ecological communities upon colonization of islands or the growth of secondary forests. Both of these examples are regular phenomena in the sense that a more or less predictable ecological structure arises via a stereotypic pattern of intermediate steps, in which the relative abundances of various types of flora and fauna follow a well-defined sequence. The regularity of these phenomena is obviously not the consequence of an ecological program encoded in the genomes of the participating taxa.[9]

Thus, the science of ecology provides a promising body of phenomena, but what about the fundamental assumptions that guide how ecologists view ecosystems? Are their basic assumptions about how to observe ecosystems significantly different from those that have guided science for the past 300 years?

In general, it cannot be said that most ecologists see the need for a new framework, but a growing body of ecosystems theorists would disagree. They point, for example, to the widespread belief that there is something *special* about ecological phenomena. Why else would investigators in other disciplines take pains to cloak their endeavors in the mantle of ecology? One encounters, for example, books on ''the ecology of computational systems,''[10] and entire institutes are devoted to the ''ecological study of perception and action.''[11] Some have even accused ecosystem science of resting upon theological underpinnings.[12] Such allegation is hardly surprising, when one considers how Arne Naess purports that ''deep ecology'' affects one's life and perception of the natural world in a profound and ineffable way.[13] Profound? Yes, but, as should become apparent below, maybe not as ineffable as Naess contends.

What follows is an attempt to outline briefly a set of rational assumptions regarding how ecosystems operate that departs substantially from the prevailing scientific consensus that has evolved from studying the inanimate world. It should be emphasized at the outset, however, that this new foundation remains entirely within the boundaries of the natural, requiring neither transcendental nor numinous referents. As prelude to the revised postulates, it becomes necessary first to elaborate those beliefs about how nature works that have prevailed since the dawn of the Enlightenment. As the axioms of the Modern worldview are enumerated, the conflicts they elicit with religious beliefs will be mentioned in passing. Observations on how *complex* ecosystems behave reveal that their dynamics often accord poorly with the orthodox postulates. The exceptions themselves suggest how prevailing beliefs need to be amended if science is to apprehend fully what is transpiring; that is, how the current foundations may indeed be obscuring a more fecund way to observe living systems. As the ecological postulates gradually emerge, it should also become clear how several of the most contentious issues that have plagued the relationship between science and theology simply evaporate. The new ecological framework appears to provide a *neutral* ground whereupon the skeptic can continue to pursue the search for a richer, entirely natural narrative of living systems that, nevertheless, does not logically preclude (as does metaphysical naturalism) those theological extrapolations that materialists reject. That is, the ecological formulation does not impugn the intellectual dignity of either side in the science/religion conversation.

While the ecological vision may suggest to the theist an uninterrupted transition from the natural to the numinous, it nonetheless demarcates those domains of both science and religion that properly remain autonomous of each other, for as Karol Wojtyla suggested, it would not benefit anyone were science to expropriate religion or vice- versa.[14] The remaining tensions actually enrich both sides: ''The rise of a critical spirit purifies [religion] of a magical view of the world . . . and exacts a more personal and explicit adherence to faith; as a result, many persons are achieving a more vivid sense of God.''[15] Alternatively, the theist's rejection of mechanistic reductionism rescues science from an exaggerated minimalism that has come to hinder it from achieving what the late Karl Popper called an ''evolutionary theory of knowledge'' about living systems.[16]

Normal science

In order to express more clearly how the ecological viewpoint differs from the postulates that delimit ''normal'' science, one must first elaborate the consensus guiding contemporary scientific endeavors. This is no easy task, given as how the suite of assumptions that any particular individual (consciously or tacitly) makes while pursuing science can vary enormously from one investigator to the next. Furthermore, even if one were able to identify a suite of common postulates, it is well-known that each individual weights those assumptions differently and sometimes radically so.[17] Thus, while engineers are inclined to esteem the predictability a given formulation might provide and to worry little about how universally it might apply, evolutionary biologists are likely to invert these values when judging their own narratives. As a way around such seemingly insurmountable diversities, the approach here will be to recall a consensus from an earlier era when there was virtual unanimity among scientists as to how the world operates and to enumerate the tenets that prevailed at that time. Although it will quickly become apparent that no one still accepts *all* of the classical axioms, it should likewise become obvious how the overwhelming majority of scientists is still guided by one or more of the postulates. It will then be argued that *none* of those tenets accords with how events transpire in ecology, so that by any measure an alternative framework is required.

Concerning an era when there was widespread agreement on the nature of things, the early Nineteenth Century represented the apogee of Newtonian thought. This consensus had been building in the wake of Newton's *Principia*, written more than a Century earlier. According to Depew and Weber,[18] there were four (sometimes tacit and often overlapping) points of agreement under which legitimate science was to be practiced, and foremost among them was the assumption of causal *closure*. That is, licit explanations of natural phenomena could refer only to mechanical or material causes. Not only is any reference to the supernatural strictly forbidden, but also any mention of Aristotelian final cause, because the latter could segue all too easily into Thomism. The exemplar of scientific description had become Newton's *Principia*, which (quite by accident)[19] had provided a full accounting of the movement of the heavenly spheres in purely mechanical and material terms.

A second postulate that gained favor in the wake of Newton, not wholly unrelated to closure, is the idea that nature is *atomistic*—a notion that can be traced back at least to Democritus (4th Century BCE.). Not only did this assumption entail the belief that there exist fundamental, unchanging smallest material units, but also that these units could be built up and taken apart again. There are at least two thrusts to this tenet: The first is reductionism—that the proper direction of scientific exploration is to be analytical (explanations of larger phenomena are to be sought exclusively among events at smaller scales). Thus, Carl Sagan, in summarizing his television show on biological evolution declared, ''These are some of the things that *molecules* do!'' The second impulse concerns decomposability—that in breaking a system into subunits, nothing of essence is lost thereby. When atomism is combined with closure, the outcome is akin to the dictum of Lucretius (1st Century BCE), ''There are atoms, and there is the void''—nothing more.

That systems are decomposable relates in its turn to yet a third important Newtonian assumption, namely that processes are inherently *reversible*. While this premise might seem strange to anyone familiar with the impermanence of biological phenomena, it should be noted that, until quite recently, all known physical laws and equations were perfectly symmetric with respect to time.[20] At the turn of the last century, Aemalie Noether not only pointed out this fact, but also demonstrated how such symmetry is tantamount to conservation over time.[21] Since the conservation of one attribute or another (e.g. mass, energy, etc.) is usually postulated in most contemporary investigations, the assumption of irreversibility is thereby implicitly invoked. It should be noted further, that any narrative predicated solely on the strongly conservative (*sensu physico*) formal laws of physics is incapable of addressing true change. In such a neo-platonic world, nothing *essentially* new can possibly arise.

In the decades following Newton's astounding success at predicting the movements of the spheres a number of similar accomplishments in fields such as chemistry and electricity ensued, giving rise to the consensus that the laws of nature, once fully elaborated, were sufficient to predict all phenomena. Nature is *deterministic*. Given precise initial conditions, the future (and past) states of a system can be specified with arbitrary precision. So enamored of their own successes were the mechanists of the early 19th Century that Pierre Laplace was able to exult in the unlimited horizons of the emerging mechanical worldview.[22] Any ''demon'' or angel, he exclaimed, that had a knowledge of the positions and momenta of all particles in the universe at a single instant could invoke Newtonian-like dynamics to predict all future events and/or hindcast all of history. There was significant theological fallout from the belief in mechanical determinism. If natural laws were sufficient to explain all events, how could God possibly intervene in nature? To what purpose prayer? The only role that a Creator could play under such a scenario was that of prime mover. Many who accepted mechanistic determinism but chose to continue professing a belief in the Supreme Being as Prime Mover came to be known as Deists, and Deism was believed to have been prevalent among the founders of the American nation.[23]

Finally, related to the confidence placed in the determinism of the laws of nature was yet a fifth postulate—the belief that they also are *universal*.[24] That is, they are assumed to apply everywhere, at all times and over all scales. Since mathematical physics on numerous occasions has been able to predict phenomena before they were observed, or even imagined, some physicists have taken this to mean that the laws of physics are applicable without regard to scale. Thus, one encounters physicists who talk about ''point- sized black holes''—collections of so much mass in infinitesimally small spaces that the gravity the mass generates will not allow light or other radiation to escape. These theoreticians have extrapolated the equations relating mass, gravity and light arbitrarily close into a mathematical ''singular point'' (a point where the mathematical behavior becomes pathological), and they believe that the relationships retain their validity in this uncharted realm. A similar extrapolation is the attempt by other physicists to marry quantum theory with gravity, when the characteristic dimensions of the two phenomena are so blatantly disparate.[25]

Perhaps by this juncture the reader grows impatient with what might seem to be a litany of outmoded notions. After all, Laplace's apotheosis of Newtonian possibilities lies almost two hundred years in the past. In the interim, the scientific view of the world has changed in many significant ways. Indeed it has; in fact, it was a mere six years after Laplace's pronouncement that the French engineer Sadi Carnot reported on the behavior of steam in engines that threw the dictum of reversibility (and conservation) into serious question that to this day remains largely unanswered (statistical mechanics notwithstanding.) Later in the Nineteenth century Darwin, influenced by how past events were being treated in the field of geology, introduced history and true change into biological dynamics. It really was not until early in the following century, however, that the development of relativity and quantum theories finally awoke most scientists to the circumscribed reaches of universality and determinism. As a result of these challenges, no one talks anymore about inhabiting a Newtonian universe. The evolutionary nature of science, however, means that assumptions are never entirely extirpated. Closure, for example, remains a potent requirement of the neo-Darwinian version of evolutionary theory, which has been scrupulously crafted to reference only material and mechanical causes. Atomism (and reductionism) still dominates the underpinnings of biology—witness the preponderance of molecular biology today. Even reversibility (often in the guise of conservation) is applied in procrustean manner to concepts like energy, in ways that can mislead one about the nature of reality.[26] Despite the expanding roles that chance and contingencies play in the scientific endeavor, a considerable number of scientists still yearn for the security and power that once was promised by determinism. They respond by denying chance. If only the depth and precision of one's observation were not so limited, they maintain, in principle one could predict what now appear to be random behaviors. Chance, especially that occurring at macroscopic scales, is thereby considered by many as an epistemic shortcoming, not an ontological reality.[27]

While each of the first five Newtonian axioms survives today and retains some applicability (albeit within circumscribed domains), it is the tenacity with which some cling to the universality of physical laws that persists, in spite of developments since Laplace, to plague the dialogue between science and religion. Very many continue to maintain that physical laws remain exhaustive in their explanation of nature. This belief motivated Carl Sagan to emphasize triumphantly in his foreword to the book, *A Brief History of Time*, Hawking's conviction that there is simply nothing left for a Creator to do.[28] It was also doubtless what drove Philip Hefner, director of the Zygon Center for Religion and Science, wistfully to express his doubts by saying that God just does not have enough ''wiggle- room'' to act in the world.[29]

Process ecology,[30] a new dynamic

If unbroken determinism should place roadblocks along the paths of those who might otherwise become theists, the possibility of contingencies has a history of vexing the scientist. Chance has never nestled comfortably within the framework of science. Most scientists, if they ponder the nature of chance at all, usually associate it with the advent of quantum theory around the beginning of the 20th century. Perhaps they might recall Boltzmann's earlier struggles to convince the world that chance operates freely among molecules. Whatever connection they might make, it will almost invariably be associated with the netherworld of microscopic scales, where normal science has developed quantitative tools to cope with the appearance of stochasticity among simple, decoupled events. Confining the action of chance entirely to the microscopic can render up some rather bizarre narratives, however. For example, in evolutionary theory one's attention is constantly shifting back and forth, in almost schizoid fashion, between the contingencies of microscopic phenomena and the regular, lawful macroscopic behaviors of organisms and environment. To mitigate the sharp edges of such a bifurcated narrative, some philosophers of science have suggested letting the genie of chance out of its bottle in the microscopic and allowing it to range everywhere. Prominent among these have been Alfred North Whitehead,[31] Charles Saunders Peirce,[32] Karl R. Popper,[33] and Daniel Simberloff.[34]

Popper has been particularly explicit in his rejection of determinism at larger scales. He accommodates contingency among *macroscopic* phenomena by suggesting that Newtonian-like forces are special cases of more general, ubiquitous agencies that he calls ''propensities''. In his view, conventional forces are but idealizations that can exist only in perfect isolation. The object of experimentation, therefore, is to approximate isolation from interfering factors as best possible. In the real world, however, where components are loosely, but decidedly coupled, it is better to speak instead of the tendency for a certain event to occur in a particular context. Such tendency, or propensity, is related to, but not identical to, conditional probabilities.

To gain a feel for how propensities might operate, one could begin by considering the hypothetical ''table of events'' depicted in Table 1, which arrays five possible outcomes, b_1, b_2, b_3, b_4, b_5, according to four possible eliciting causes, a_1, a_2, a_3, and a_4. The outcomes, for example, might be several types of cancer, such as those affecting the lung, stomach, pancreas, or kidney, while the potential causes might represent various forms of behavior, such as running, smoking, eating fats, etc. The values in the table would represent the number of cases in which cancer b_j was observed in individuals pursuing activity a_i. In an ecological

Table 1 Frequency table of the hypothetical number of joint occurrences that four ''causes'' ($a_1 \ldots a_4$) were followed by five ''effects'' ($b_1 \ldots b_5$)

	b_1	b_2	b_3	b_4	b_5	Sum
a_1	40	193	16	11	9	269
a_2	18	7	0	27	175	227
a_3	104	0	38	118	3	263
a_4	4	6	161	20	50	241
Sum	166	206	215	176	237	1000

context, the b's might represent feeding by predator j, while the a's could represent the sustenance (measured in convenient units of mass or energy) of host i.

One notes from the table that whenever condition a_1 prevails, there is a propensity for b_2 to occur. Whenever a_2 prevails, b_5 is the most likely outcome. The situation is a bit more ambiguous when a_3 prevails, but b_1 and b_4 are more likely to occur in that situation, etc. Events that occur with smaller frequencies, e.g. [a_1, b_3] or [a_3, b_5] result from what Popper calls ''interferences.'' He chooses not to dwell on the particular nature of interferences, but one may assume that they can be either regular, lawful phenomena occurring at other scales, or unique, irregular events that qualify as instances of true chance.

To bring the notion of propensity into still clearer focus, it is useful to ask how the table of events might appear, were it possible to isolate phenomena completely; that is, were it possible to impose further constraints that would keep both other propensities and the arbitrary effects of the surroundings from influencing a particular action? If this is possible, the result should look something like Table 2, where every time a_1 occurs, it is followed by b_2; every time a_2 appears, it is followed by b_5, etc. That is, under isolation, such as one might find in a laboratory situation, propensities degenerate into mechanical- like forces. It is interesting to note in Table 2 that b_4 never appears under any of the isolated circumstances. Presumably, it arose in Table 1 entirely as the result of external interferences or out of interactions among the various propensities. Thus, the propensity for b_4 to occur whenever a_3 happens is an illustration of Popper's assertion that propensities, unlike forces, never occur in isolation, nor are they inherent in any object. They always arise out of a context, which invariably includes other propensities.

The interconnectedness of propensities highlighted by the existence of b_4 prompts consideration of an unsung aspect of contingencies—namely, that they are not always simple in nature.[35] Chance events can possess distinct characteristics and can be rare, and possibly even unique in occurrence. The implicit convention, however, has been to regard chance events as virtually point-like in extent, instantaneous in duration, and generic in character. Each one is like the next. Such were the disturbances that Prigogine and Stengers assumed when they wrote about macroscopic order appearing via microscopic fluctuations.[36] Perturbations, however, can come in an infinite variety of distinct forms, and any

Table 2 Frequency table as in Table 1, except that care was taken to isolate causes from each other.

	b_1	b_2	b_3	b_4	b_5	Sum
a_1	0	269	0	0	0	269
a_2	0	0	0	0	227	227
a_3	263	0	0	0	0	263
a_4	0	0	241	0	0	241
Sum	263	269	241	0	227	1000

given system might be quite vulnerable to some categories of disturbance but relatively immune to others.

Even should disturbances come in different flavors, it is still assumed that tokens of any particular type of disturbance will occur repeatedly. Repetition of phenomena is the Baconian cornerstone of normal science. Thus, chance as it is normally understood in evolutionary theory is tacitly assumed to be simple and, therefore, repetitive. As soon as one allows contingencies to be complex, however, the possibility arises that some contingencies might be *unique* once and for all time. In fact, it follows that the world could be rife with one-time events. As soon as one ceases to regard contingencies merely as simple point-events, but rather as configurations or constellations of both things and processes, then elementary combinatorics argues for the existence of unique events. If, for example, it is possible to identify n different things or events in a system, then the number of possible combinations of events varies roughly as n-factorial.[37] It does not take an inordinately large n for $n!$ to become *immense*. Elsasser called an immense number any magnitude that was comparable to or exceeded the number of events that could have occurred since the inception of the universe.[38] As an estimate of this magnitude, he suggested one multiply the approximate number of protons in the known universe (ca 10^{85}) by the age of the cosmos in nanoseconds (ca. 10^{25}). The result is 10^{110} conceivable events. Although this magnitude is truly awe-inspiring, it should be noted that it is dwarfed by the number of combinations possible among only 80 distinct entities. It is often remarked how the second law of thermodynamics[39] is true only in a statistical sense—how, if one waited long enough, a collection of gas molecules that escaped from a bottle would spontaneously segregate themselves back into the bottle. According to Elsasser's calculations, however, if the number of particles exceeds 80 or so, the *physical* reality is that they will *never* do so.

Since propensities always exist in a context and because that context very often is not simple, one must face the overwhelming likelihood that unique events are occurring continually. Nor are solitary events rare; they are legion. Perhaps fortunately, the overwhelming majority of one-time events happens and passes from the scene without leaving a trace in the more enduring observable universe. On occasion, however, a singular contingency can interact with a durable system in such a way that the system readjusts in an *irreversible* way to counter the disturbance. The system then carries the memory of that contingency as part of its *history*, and no amount of waiting is likely to bring about an uncontrived repetition of what has transpired.

While it is convenient that Popper's notion of propensity encompasses law-like behavior, generic chance and unique contingencies, all under a single rubric, such generality does not obviate a fundamental problem that persists: ''What keeps the organized world from falling apart or being overwhelmed by ubiquitous stochasticity?'' For well over a century science has dealt uncomfortably with chance by relegating it to small scales and by showing that the reliability of the world can be maintained if stochastic events there are both rare and uncoupled. Obviously, such circumstances do not hold in the ecological theatre, so one must search for other factors.

One clue comes from earlier in this essay where, regardless of the natures of any eliciting interferences, proceeding from Table 1 to Table 2 involved a transition from less-constrained to more constrained circumstances. It is the progressive appearance of constraints, then, that one associates with the term "development." A second clue emerged when it was noted how b_4 in Table 1 could arise purely because of interferences among propensities. That is, important types of behavior can result from *configurations of processes* acting in concert. Because the arguments that immediately follow have emerged out of the study of networks of ecosystem trophic processes,[40] they form the crux of what appropriately could be called *process ecology*.[41]

The seminal example of a configuration of processes that can engender progressive system constraints is that of autocatalysis.[42] Here autocatalysis is defined as any manifestation of a positive feedback loop whereby the direct effect of every link on its downstream neighbor is positive. Without loss of generality,[43] attention is focused on a serial, circular conjunction of three processes A, B, and C (Figure 1). Should these processes happen to involve only very simple, immutable chemical forms (as is usually the case in chemistry), then the autocatalytic cycle will function in wholly mechanical fashion. That is, any increase in A will invoke a corresponding increase in B, which in turn elicits an increase in C, and whence back to A.

Matters become quite different, however, as soon as the elements engaged in the processes become complex (i.e. plastic in form and function, as one normally encounters in biology and ecology). Plastic entities are those that possess many nearby, almost identical forms, each of which exhibits small, contingent changes in function that allow the entity to continue its role in the autocatalytic loop, albeit with incrementally more or less effectiveness. In accord with Popper's notion of propensity, it would be more appropriate under these circumstances to say that the action of process A has a *propensity* to augment the second process B. That is, the response of B to A is not prescribed deterministically. Rather, when process A increases in magnitude, most (but not all) of the time, B will also increase. B tends to accelerate C in similar fashion, and C has the same effect upon A.

A didactic example of autocatalysis in ecology is the community that builds around the aquatic macrophyte, *Utricularia*.[44] All members of the genus *Utricularia* are carnivorous plants. Scattered along its featherlike stems and leaves are small bladders, called utricles (Figure 2a). Each utricle has a few hair-like triggers at its terminal end, which, when touched by a feeding zooplankter, opens the end of the

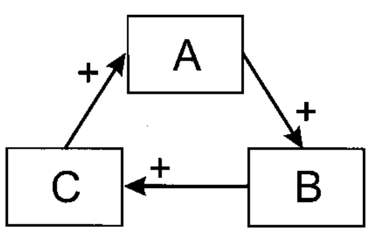

Figure 1 An autocatalytic configuration of three processes

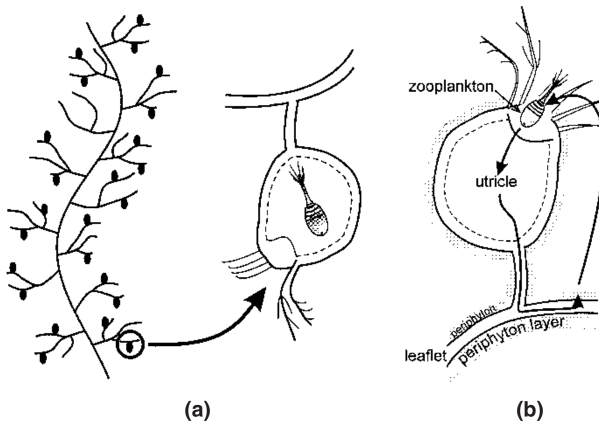

Figure 2 (a) *Utricularia*, a carnivorous plant; (b) the cycle of rewards in the *Utricularia* system

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 (Figure 2b).

Autocatalysis gives rise to several system attributes, which, as a whole, distinguish its behavior from one that can be decomposed into simple mechanisms. Most germane is that such autocatalysis is capable of exerting *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 a more effective catalyst of (C), then the transition will receive enhanced stimulus from (A). Conversely, if the change in (B) either makes it less sensitive to the effects of (A) or a weaker catalyst of (C), then that perturbation will likely receive diminished support from (A). Three things are notable about such selection. (1) That it acts on the constituent processes or mechanisms as well as on the elements themselves. (2) That it arises within the system, not external to the system. (3) That it can act in a positive way to select *for* a particular system result (greater autocatalysis), rather than always *against* the persistence of an individual organic form. The first attribute defeats attempts at reductionism, while the latter two distinguish autocatalytic selection from the ''natural selection'' of conventional evolutionary theory.

It should be noted, 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 process (B). Whence, corollary to the selection pressure is the tendency to reward and support those changes that serve to bring ever more resources into (B). As this circumstance pertains to any and all members of the feedback loop, any autocatalytic cycle becomes the epicenter of a *centripetal* configuration, towards which as many resources as available will converge (Figure 3). That is, the successive development of an autocatalytic configuration appears to resemble an active agency that pulls progressively more resources unto itself. Even in the absence of any spatial integument (as required by a related, but more mechanical scenario called autopoeisis),[45] the autocatalytic loop itself defines the focus of flows.

Centripetality in its turn guarantees that whenever two or more autocatalyic loops exist in the same system and draw from the same pool of finite resources, *competition* among the foci will necessarily ensue. In particular, whenever two loops share pathway segments in common, the result of this competition is likely to be the exclusion or radical diminution of one of the non-overlapping sections. For example, should a new element (D) happen to appear and to 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 (Figure 4). That is, the selection pressure and centripetality generated by complex autocatalysis is capable of guiding the replacement of elements.

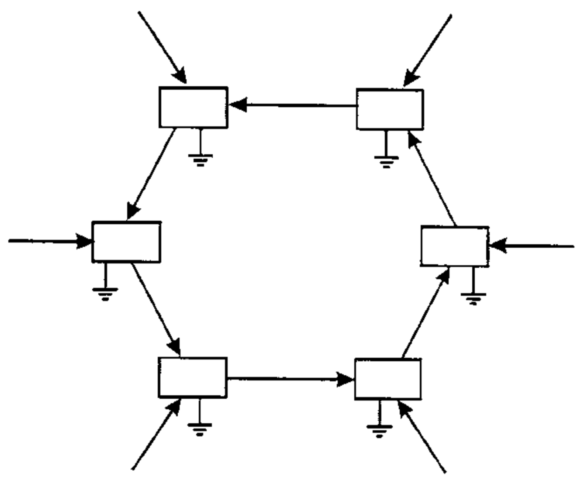

Figure 3 Centripetal action as engendered by autocatalysis

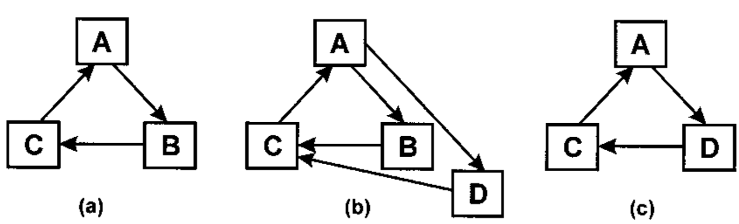

Figure 4 The selection of new element (D) to replace (B)

Of course, if (B) can be replaced by (D), there is no reason why (C) cannot be replaced by (E) and (A) by (F), so that the cycle (A), (B), (C) could eventually transform into (D), (E), (F). This possibility implies that the characteristic lifetime of the autocatalytic cycle generally exceeds those of most of its constituents. The incipience of the autocatalyic form before, and especially its persistence beyond, the lifetimes of most of its constituents imparts causal priority to the agency of the configuration of processes. True, the inception of the feedback loop can be interpreted as the consequence of conventional mechanistic causes. However, once in existence and generating its own selection pressures, those instigating mechanisms become incidental to the selection agency that arises. Any argument seeking to explain the behavior of the whole system entirely as the result of shorter-lived constituents erroneously ignores the ascendant agency of the configuration of processes, which winnows those ephemeral and transitory mechanisms.

Ever since Democritus, the aim of rational explanation has been to portray all processes as the consequence of universal laws that act on eternal and unchanging fundamental atoms. This reductionist agenda has worked reasonably well at atomic and sub-atomic scales, but, once one enters the mesoscopic realm, the hierarchy of durabilities undergoes an inversion. That is, at the mesoscales, it is the larger *configurations of processes that are most enduring*, and their (usually smaller) constituents appear by comparison merely as transients. Hence, the most natural direction for causality to act at intermediate scales is from the persistent configurations of processes towards their transient constituents, whose creation the former mediate.

There is nothing explicitly transcendental about this inversion of modalities. Over the course of several years, for example, the cells of the human body (save for the neurons) all pass from the scene. Over the duration of about eighteen months, virtually all the chemical atoms in the body have been exchanged with the external world. Nonetheless, the individual should remain recognizable to its mother, even if the latter has not seen her offspring in ten years. It should be emphasized that the top-down nature of autocatalytic influence (selection) opens the door to a wholly new dynamics of systems, because now the effects of a chance perturbation at any scale need not ramify unchecked over the whole universe. Irregularities will encounter selection processes at larger scales that attenuate their propagation farther up the hierarchy. As a result, the world, full though it may be with stochastic singularities, is not doomed to fall apart.

Not only do autocatalytic systems not disintegrate, whenever the randomness of their environments wanes to a degree, the natural tendency of the autocatalytic activities is to increase their regulation of the system. The centripetality of autocatalytic systems mentioned above is one example of this inexorable propensity, as is the appearance of temporal regularities or periodicities among living behaviors. In 1969, Eugene Odum enumerated 24 characteristics of more mature, coherent ecosystems,[46] and I have traced a number of them to autocatalysis at work in the ecosystem.[47] Furthermore, the latter used information theory to construct a quantitative metric, called the system ‘‘ascendency’’ to encapsulate most of Odum’s attributes as they are portrayed within networks (configurations) of exchanges among the members of an ecosystem. In keeping with Popper's extrapolation of Newtonian dynamics into the complex realm of living systems, I offer the phenomenological observation, ''In the absence of major perturbations, ecosystems exhibit a propensity towards configurations of ever-greater network ascendency.''[48]

Uninterrupted progressive constraint would lead to stasis, however. For a system to continue to evolve, or even to persist, it must also retain sufficient degrees of freedom, as manifested by processes and elements that do not contribute much, if anything, to its current configuration of autocatalytic relationships. In the face of perturbations, the system can borrow from these sundry elements to restructure itself creatively. One can draw again upon information theory to define what is called the system ''overhead,'' which provides a measure of these degrees of freedom.[49] System overhead is (literally) complementary to the ascendency. Whereas ascendency encompasses all that is structured, coherent and efficient in a system; overhead comprises all that is disordered, incoherent, and inefficient with respect to the system's current environment. Although these two attributes stand in agonism to each other, significant amounts of both are necessary for the system to persist and change. Hence, the relationship between ascendency and overhead resembles somewhat a Hegelian dialectic.[50]

Finally, just as the effects of singularities rarely propagate to larger scales without attenuation, there are more conventional reasons (having to do with the relatively greater concentrations of energies at lower scales), why the effects of a perturbation also usually diminish at levels below the origin of the disturbance. Whence, the radius of effect for any given chance event is delimited both from above and from below. As a result, the notion of universality does not hold the same cachet for the ecologist that it does for the physicist. The ecologist considers that virtually all laws and events can affect only limited domains of time and space. It is not as if anyone were contending that any fundamental law of physics is contravened outside certain ranges of space and time. It is just that its contributions to explanations wane drastically several orders of magnitude beyond the scales where the law was formulated. As regards ecological narrative, therefore, laws are not considered to apply uniformly throughout all of nature. Instead, nature appears to be *granular*, that is, its spectrum of spatial and temporal scales resembles a mosaic wherein each cell delimits the utility of a particular set of laws.[51]

Some may object that the dynamics of process ecology seem at first blush slightly more complicated than those proffered by neo-Dawinism. That is, it seems to fail the test known as Occam's Razor, which, all other evidence being equal, gives the advantage to the simpler explanation of events. There is little question but that the neo-Darwinian dynamic is about the simplest imaginable, but that is far from the whole story. Physicists, for example, prefer to judge a problem in its entirety, which includes its boundary constraints in addition to its working dynamics. In faithful Newtonian tradition, Darwin took pains to place natural selection external to his dynamics.[52] One's attention is thereby diverted away from the Darwinian boundary constraints, which remain arbitrarily and inexorably complicated. In the ecological scenario, by contrast, much of the selection has been incorporated as an active formal agency into the internal dynamics, leaving a much less complicated boundary value problem. By all appearances, then, the slightly more complicated dynamic of process ecology more than pays for itself and provides a less-complicated narrative of the *overall* problem.

An ecological framework

The reader may have noticed how the ecological dynamics just described accord with *none* of the five postulates that characterize the Newtonian worldview. In fact, a preliminary sketch of the axioms underlying the emerging ecological worldview becomes feasible purely in terms of how the new dynamic differs from the Newtonian schema: First, it seems obvious that ecosystems are *open* to the influence of contingency and non-mechanical agencies. Spontaneous events may occur at any level of the hierarchy at any time. Mechanical causes usually originate at scales inferior to that of observation, and their effects propagate upwards. Second, higher- level agencies, like autocatalyic selection, propagate downward.[53]

Opening natural systems up to top-down influences should not be viewed as the first nudge down a slippery slope into Aquinas' vision of God as final cause. Although theists are at liberty to extrapolate in that direction, materialists are likewise free to insist that matters stop well short of that end. Furthermore, materialists should feel no misgivings about accepting wholly natural manifestations of final cause, like those that the pagan Aristotle had originally suggested. One could speak of a non-reductive materialism (or naturalism) as being compatible with organic systems theory.[54] For their part, it is unlikely theists would want to relegate God's entire agency to eschatological ends. Popper, after all, allows natural chance to arise at any level, and a repleted theology would discern God's actions at all scales as well.

Ecosystems cannot easily be broken into smaller units, but rather are *organic* in composition, and their behavior precludes any unreserved belief in atomism and reductionism. As Popper noted, propensities never exist in isolation from other propensities. It further appears that communication between propensities provides opportunities for clusters of them to reinforce each other mutually and thereby grow successively interdependent. As a result, the observation of any component in isolation (if possible) reveals regressively less about how it behaves within the ensemble. It should be noted also that the ecological framework provides for two distinct levels of organic behavior: Traditionally organic behavior has been confined to discrete *organisms*, which exhibit definable, self-generated boundaries and nearly pre-determinate scenarios of development (cf, the ''autopoeisis'' of Maturano and Varela[55]). The kernel of organic behavior, however, is defined by dynamical cohesion, centripetality and downward internal selection, all of which characterize a larger class of more loosely-structured *organic systems*, like ecosystems and social communities.[56]

By casting the analogy known as organicism in terms of the broader notion of organic system, one eliminates those oppressive connotations justifiably eschewed by so many.[57] Furthermore, statements like Sagan's, to the effect that evolution is something that only molecules do, now appear misleading at best. What entities may arise or which ones might persist within a given context is strongly influenced by that context, which operates *as an active agency*. When components of organic systems are extirpated, one should look not only to the stochastic agency of natural selection for a cause, but also to the more immediate structure of processes in which the element was embedded. In many instances, it plays the more significant role. As Popper suggested, organisms are not just collections of objects. Organic agency derives not simply from material forms, but more importantly from the conjunctions of processes, which those forms host. Theists will likely see in such configurations of processes a prefiguring of what they call ''soul'' or what natural philosophers have called ''entelechy''. Materialists, however, are free to demur by noting how these constellations and the agencies ensuing there from remain wholly dependent upon and inseparable from their material substrates.

It must be recognized that ecosystems, like other biotic systems, are *historical*. Irregularities (either simple or complex) often engender discontinuities, which degrade predictability into the future and obscure hind casting. The effects of past discontinuities are often retained (as memories) in the material and kinetic forms that result from adaptation. Time takes a preferred direction or *telos* in ecosystems—that of increasing system constraints, or higher ascendency. The attribute of history should provide little with which theists and materialists might disagree: History, of course, is central to the ''religions of the book.'' Furthermore, history was already written into biology by Darwin, and recent perspectives have only reinforced the importance of the historical in contemporary evolutionary theory.[58] Nonetheless, some refractory Newtonians remain, who prefer to ignore the existence of history in nature, because it precludes their goal of ultimate control.

The degree of control one can exert over nature segues into the next important assumption about ecosystems: They are not deterministic machines; rather they are *contingent* in nature. Any biotic agencies active within ecosystems resemble propensities more than mechanical forces. Unlike with history, the existence of contingencies in ecodynamics creates ambiguities that lead to contention. As noted, some materialists continue to hold that no holes exist in the causal fabric of nature—that chance is but an illusion owing to the observer's ignorance and not a true discontinuity in events. Other materialists readily embrace the stochastic in nature. They simply contend that causality terminates behind each singular event. Theists should feel no reluctance to agreeing with the materialists in an overwhelming number of cases, and especially in those instances that give rise to trauma, pain, and suffering. However, they would not be believers, did they not see behind some minority of irregularities the finger of God affecting events, big or small. Exactly which instances might figure into the ongoing conversation between God and nature (and humankind by inclusion) would remain, perforce, purely a matter of faith.

Lest the reader dismiss this reasoning as but another ''God of the gaps'' argument, two things should be emphasized. The first is the *necessity* of chance in a dynamical, living universe. Without random events, there can be no real change, no true development. In Godelian fashion, it is futile to attempt to construct a system of deterministic laws that is fully closed.[59] Discontinuities must appear somewhere. The second factor is the sheer *ubiquity* of chance. The fabric of causality manifests holes everywhere, at all levels. In the full panoply of events, arbitrarily close to any phenomenon that conforms to a law, one can find gaps that, by virtue of their uniqueness, never can be covered by any conceivable law.[60] It follows that any active action of God would not be limited to the jiggling of microscopic fluctuations. Such is the demeaning image of a tinkerer. With a causal fabric that is replete with holes, nature becomes permeable to coordinated actions over all spatial and temporal scales (not excluding the future).

As for the final discrepancy, it has already been noted how events and laws in the realm of ecology are *granular*, not universal. Models of events at any one scale can explain matters at another scale only in inverse proportion to the remoteness between them. It should be repeated that the assumption of granularity is not that laws are necessarily violated at remote scales, but merely that they become ineffective at controlling remote events relative to agencies that are immediate to those happenings. The obverse of this assumption is that the extent to which irregularities and perturbations can damage a system is usually circumscribed. Chance does not necessarily unravel a system; the various granules are not entirely autonomous of one another. Links in the form of propensities exist between granules to interlace a latticework of organization throughout the universe. The resulting fabric, however, is never so rigid as to preclude an *abundance* of ''wiggle room.''

Work, not friction

The late Karl Popper was adamant that philosophical constructs be capable of ''doing work,'' that is of solving problems.[61] The work done by the ecological framework is to mitigate several ostensible conflicts between science and theology. Two such issues concern free will and prayer. The Enlightenment faith in determinism precluded any room for free will, because in the Newtonian framework mind can be only epiphenomenal to the material activities of the brain, which activities were assumed subject to unwavering physical laws. Whence it became fatuous to entertain that an individual was capable of exerting any semblance of free will. Not only does the ecological worldview open up the future by accommodating contingency, but also in recognizing the granularity of matters, it emphasizes the looseness among the several layers of phenomena that separate the firings of neural synapses from those higher-level, slower cognitive functions directly involved in decision making.[62] Free will no longer poses a conundrum to either agnostic or theist.

As for prayer, Newtonian determinism effectively rendered it futile; for, even if God could hear entreaties, the Prime Mover could not respond without intervening against the grain of divinely ordained inexorable laws. Two-way conversation was unthinkable. Now, however, sufficient flexibility is available for intervention anywhere and everywhere. As a result, Prigogine has suggested that, in a world of non-deterministic dynamics, it becomes possible to speak in terms of a dialogue between humankind and nature. For the believer, a limited indeterminacy provides a rational opening for a full exchange between God and humankind.[63]

No one is pretending that the ecological worldview (or any replacement that soon may follow) can vanquish the specter of evil in the world (theodicy) that prevents so many from opening themselves to religious belief. However, the new vision does alter somewhat the nature of the problem, because the ecological worldview accepts the stochastic, the inefficient, the redundant, the incoherent, and all the other phenomena that fall under the rubric of ''overhead'' as *necessary* for creativity. Anyone who cannot accept the existence of gaps in nature forfeits any hope of fully apprehending the living world,[64] for without marginal perturbations, disruptions and petty evils, systems cannot improve their performance. They cannot become better organized. So theodicy becomes less the ontological issue of why *any* evil is allowed, and the question becomes more one of magnitude: Why is *great* evil allowed to persist?

Above it was suggested how believers might not want to attribute the agency of God to every chance event that arises. One tradition among many of the faithful holds that God's will can be expressed either actively or passively (cf. *kenosis*[65]), and such belief extrapolates smoothly from the ecological narrative. Philip Hefner, however, finds such ''selective divine determinism'' unacceptable, saying that it renders ''both nature and God unreliable.''[66] Hefner notwithstanding, it would appear that the ecological version of organic systems theory provides nature with sufficient reliability to persist. As for God, there seems even less reason why divine action and/or response should be automatic than that humans should function as wind-up toys for their Creator.

Opposite the question of evil lies the issue of life, or more precisely, of how life could possibly have arisen in a universe thought to consist of only dead material. One approach has been to seek out inchoate precursors of life among quiescent matter.[67] The ecological axioms, however, allow for yet a different take: Physicists and cosmologists have begun to converge upon the dynamics of processes that brought the universe into existence.[68] After the initial Big Bang, subtle asymmetries led to the self- selection of various enduring forms out of an initial homogeneous substrate, and with them appeared certain regularities in their interactions. Through successive feedback, the forms and their interactions grew quite precise and stable, and the physical world with its accompanying laws eventually took shape.

This cosmological narrative remarkably parallels that of the development of contemporary ecosystems. Similarities grow even more intriguing after it is pointed out how numerous ecosystem-like feedbacks among pre-biochemical elements were likely to have been already in place to facilitate the appearance of the first proto- organisms.[69] The most relevant actions in the genesis of matter appear to follow much the same developmental scenario as that which gave rise to life. Although by hindsight, matter may now appear quite regular and laws may seem to have been extant since the Big Bang, the emerging consensus is that these, too, were interjections along the course of the *history* of the physical universe. So by comparison, the arrival of life was no more (or less) exceptional than was the appearance of matter, and the necessity to explain how dead matter directly becomes animated simply vanishes[70].

Hope, not despair?

In ''Deeper than Darwin'' John Haught likens both natural and theological discourse to the reading of a novel.[71] One can choose to read a book at the superficial level of its printed words. Such a literalist reading of religious texts characterizes fundamentalism in general, as well as its particular manifestations, like Creationism. When the story of the natural universe is read in literalist fashion, the result is the algorithmic vacuity espoused by Dawkins or Dennet. At the literal level, irreconcilable conflicts between the two readings are inevitable. Haught recommends instead that one read each novel in search of any deeper significance it might portend. His message for scientific literalists is that their zeal to exclude any phenomenon that could possibly be extrapolated into the transcendental can blind them to many wholly natural relationships that might lead to a more elegant and coherent picture of nature. His corresponding warning to religious literalists is not to ignore the richness with which scientific insights can infuse theology.

Haught is optimistic that, once the books of the natural and the sacred are both read at sufficient depth, all fundamental conflicts will vanish. Process ecology demonstrates that one need not proceed to very great depths before those differences ameliorate significantly. Furthermore, contentions evaporate without the necessity of either discipline to abandon the core of their beliefs or to demean those of their counterparts. For the materialist, process ecology provides a wholly natural, self- contained narrative of the phenomenon of life. For the theist it provides a springboard from which one can proceed to deeper levels of meaning without forsaking rationality. The deeper view of nature that process ecology reveals is one of a nearly balanced agonism between two tendencies. One propensity is the drift of the second law towards the dead and disordered that has precipitated a ''cosmology of despair'' so fashionable among academics.[72] Its opposite is the drive towards ever more organized and coherent configurations of processes, such as earmark the presence of life. The virtual parity of these agonists in the framework of process ecology lends intellectual license to those who would choose to entertain a universal ''cosmology of hope.''[73]

Endnotes

1 It comes as no surprise that some of the more interesting parallels with religion that physicists have drawn come from Zen Buddhism. See: Frijthof Capra, *The Tao of Physics:*

An Exploration of the Parallels Between Modern Physics and Eastern Mysticism (Boston: Shambhala Publications, 1975).

2 For example, John F. Haught, *God After Darwin: A Theology of Evolution* (Boulder, Colorado: Westview, 2001).

3 For example, James F. Salmon ''The role of 'complexification' and chemical self-organization for a process philosophy of nature,'' *Chemical Explanation: Characteristics, Development, Autonomy,* ed. Joseph A. Earley (Ann. NY Acad. Sci., 288 (2003): 345 – 352).

4 Richard Dawkins, *The Selfish Gene* (New York: Oxford University Press, 1976).

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6 Philip E. Johnson, *Darwin on Trial* (Downers Grove, Illinois: InterVarsity Press, 1991).

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13 Arne Naess, ''Deep ecology and ultimate premises'' *Ecologist* 18 (1988): 128 – 131.

14 Karol Wojtyla, ''Address of Pope John Paul II'' *Science* 207 (1980): 1165 – 1167.

15 Ibid.

16 Karl R. Popper *A World of Propensities* (Bristol: Thoemmes, 1990).

17 Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962).

18 David J.Depew and Bruce H. Weber, *Darwinism Evolving: Systems Dynamics and the Geneology of Natural Selection* (Cambridge, MA: MIT Press, 1994).

19 R. S. Westfall, *The Life of Isaac Newton* (Cambridge: Cambridge University Press,1993) and Robert E. Ulanowicz ''Beyond the material and the mechanical: Occam's razor is a double-edged blade'' *Zygon* 30:2 (1995): 249 – 266.

20 Replacing t with -t in any equation leaves it unchanged, i.e. a film of the motion looks the same if run either forwards or backwards.

21 *Aemalie Noether, Gesammelte Abhandlungen*, ed. Nathan Jacobson (New York: Springer Verlag, 1983).

22 Pierre S. Laplace, *A Philosophical Essay on Probabilities.* (Mineola, NY: Dover Publications, 1996)

23 Garry Wills, *Inventing America* (Garden City, NY: Doubleday, 1978).

24 Robert E. Ulanowicz, *Ecology, the Ascendent Perspective* (New York: Columbia University Press, 1997), 23. This postulate was not included among the four listed by Depew and Weber but was added by REU after consultation with those authors.

25 Steven W. Hawking, *A Brief History of Time: From the Big Bang to Black Holes* (New York: Bantam, 1988).

26 Robert E. Ulanowicz, *Ecology, the Ascendent Perspective* (New York: Columbia University Press, 1997), 23. While it is true that energy always leaves a residual, it is less clear whether the quantitative amount of energy is always conserved after any transaction. Some feel that conservation of energy in strict quantitative terms is more a matter of useful bookkeeping than a reflection of reality.

27 David Bohm, *Quantum Theory* (Mineola, NY: Dover, 1989); Bernard C. Patten, ''Out of the clockworks'' *Estuaries* 22:2A (1999): 339 – 342; and Stanley N. Salthe, ''Problems of macroevolution (molecular evolution, phenotype definition, and canalization) as seen from a hierarchical viewpoint,'' *American Zoologist* 15 (1975): 295 – 314.

28 Ibid., 25.

29 Philip Hefner, ''Why I Don't Believe in Miracles,'' *Newsweek* (1 May 2000).

30 The word ''process'' is being used here according to its thermodynamic meaning and not in the sense of Whitehead. In thermodynamics, the distinction is made between ''state'' variables, which are conservative and independent of pathway, and ''process'' variables, which, by contrast, are non-conservative and depend upon the specific (historical) pathway traversed by the system in phase space.
31 Alfred NorthWhitehead, *Process and Reality*, corrected edition, eds David Ray Griffin and Donald W. Sherburne (New York: The Free Press, 1978).
32 *Charles S. Peirce: The Essential Writings*, ed. Edward C. Moore (Amherst, NY: Prometheus, 1998).
33 Ibid., 16.
34 Daniel Simberloff, ''A succession of paradigms in ecology: essentialism to materialism and probabilism,'' *Synthese* 43 (1980): 3–39.
35 Robert E. Ulanowicz, ''The organic in ecology,'' *Ludus Vitalis* 9 (2001): 183–204.
36 Ilya Prigogine and Isabel Stengers, *Order out of Chaos: Man's New Dialogue with Nature* (New York: Bantam, 1984).
37 n-factorial (denoted as n!) means the number n multiplied by n-1, multiplied again by n-2, and so forth, until the integer 1 is reached. Thus $5! = 5 \times 4 \times 3 \times 2 \times 1 = 120$.
38 Walter M. Elsasser ''Acausal Phenomena in Physics and Biology: a Case for Reconstruction,'' *American Scientist* 57:4 (1969): 502–516.
39 One way of conceiving of the second law of thermodynamics is to consider it the tendency for ordered structures or configurations to decay into disorder. Thus, a crystal of dye placed in a glass of clear water (the ordered separation of solid dye from liquid water) will gradually diffuse to mix throughout the liquid (a disordered mixture of dye and water.)
40 ''Trophic processes'' in ecology refer to a consumer eating a host.
41 Ibid., 30.
42 Robert E. Ulanowicz, ''On the ordinality of causes in complex autocatalytic systems,'' *Chemical Explanation: Characteristics, Development, Autonomy* ed. Joseph A. Earley *Proc. NY Acad. Sci.* 988 (2003): 154–157.
43 A common form of argumentation in mathematics and science whereby the attributes exhibited by a particular example are considered shared by all possible similar situations. Here the properties of autocatalysis observed in a three- component cycle of processes is assumed to apply as well to an autocatalytic cycle of any number of processes.
44 Robert E. Ulanowicz, ''*Utricularia's* Secret: the Advantages of Positive Feedback in Oligotrophic Environments,'' *Ecological Modelling* 79 (1995): 49–57. The common name for the genus *Utricularia* is the bladderwort family of aquatic plants.
45 H. R. Maturano and F. J. Varela, *Autopoiesis and Cognition: the Realization of the Living* (Dordrecht: D. Reidel, 1980). Although the organic behavior described here bears many similarities to autopoesis, it is much looser in nature. Maturano and Varela were focussed upon the more mechanical-like nature of whole organisms. Hence, an autopoetic system is always bounded by a self- made integument, and its development follows a tightly scripted course. Neither requirement applies to the ecological systems under consideration.
46 Eugene P. Odum ''The Strategy of Ecosystem Development,'' *Science* 164 (1969): 262–270.
47 Robert E. Ulanowicz, *Growth and Development: Ecosystems Phenomenology* (New York: Springer-Verlag, 1986).
48 Robert E. Ulanowicz, ''Life after Newton: an ecological metaphysic,'' *BioSystems* 50 (1999): 127–142.
49 Robert E. Ulanowicz and Jeffrey Norden, ''Symmetrical overhead in flow networks,'' *Int. J. Systems Sci.* 21:2 (1990): 429–437.
50 Ibid., 26.

51 Timothy F. H. Allen and T. B. Starr, *Hierarchy*. (Chicago: University of Chicago Press, 1982).
52 Ibid., 18.
53 Stanley N. Salthe, *Evolving Hierarchical Systems: their Structure and Representation* (New York: Columbia University Press, 1985). Robert E. Ulanowicz, *Ecology, the Ascendent Perspective* (New York: Columbia University Press, 1997).
54 Suggested to the author by Ian G. Barbour.
55 Ibid., 45.
56 Ibid., 35.
57 Ibid.
58 For example, Daniel R. Brooks, Joseph T. Collins, and Janine N. Caira, *Principles and Methods of Phylogenetic Systematics: a Cladistics Workbook* (Lawrence, KS: University Press of Kansas, 1984).
59 Kurt Gödel ''Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme, I,'' *Monatshefte für Mathematik und Physik* 38 (1931): 173–198. Gödel's famous ''incompleteness theorem'' precludes the construction of any wholly self- referencing formal system.
60 Law requires repetition. Cf. the Born-Caratheodory formulation of the second law of thermodynamics, which says that arbitrarily close to any state of a system lies another state that cannot be reached by a reversible process. That is, reality is not a compact continuum, but rather a ''complex manifold'' in a fractal sense. See Constantin Carathéodory, ''Investigation into the foundations of thermodynamics,'' *Math. Ann., Berlin* 67 (1909): 355–386.
61 David Edmonds and John Eidinow, *Wittgenstein's Poker* (New York: Harper Collins, 2002).
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63 See also Ilia Delio, OSF, ''Does God 'Act' in Creation? a Bonaventurian Response,'' Metanexus: Views. 2002.12.02. < http://www.Metanexus.net > for an alternative approach.
64 Ibid., 16.
65 The idea that God sometimes exercises love by withdrawing from intervention. John F. Haught, *God After Darwin: A Theology of Evolution* (Boulder, Colorado: Westview, 2001)
66 Ibid., 29.
67 Teilhard de Chardin, *Man's Place in Nature* (New York: Harper & Row, 1966).
68 Eric J. Chaisson, *Cosmic Evolution: the Rise of Complexity in Nature* (Cambridge, MA: Harvard University Press, 2001).
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70 Robert E. Ulanowicz, ''Ecology, a dialog between the quick and the dead,'' *Emergence* 4:1 (2002): 34–52.
71 John F. Haught, *Deeper than Darwin: A Prospect for Religion in the Age of Evolution* (Boulder, CO: Westview, 2003).
72 John F. Haught, *Science and Religion: in Search of Cosmic Purpose* (Washington, DC: Georgetown University Press, 2001).
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