BEYOND THE MATERIAL AND THE MECHANICAL: OCCAM'S RAZOR IS A DOUBLE-EDGED BLADE

by Robert E. Ulanowicz

Abstract. To confine scientific narrative to only material and mechanical causes is to ensure incomplete and at times contrived descriptions of phenomena. In the life sciences, and particularly in the field of ecology, causality takes on qualitatively distinct forms at different hierarchical levels. The notion of formal cause provides for entirely natural and quantitative explanations of ecosystem behavior.

Keywords: Aristotelean causality; ecosystem development; formal cause; hierarchy theory; Newtonianism.

The pages of this journal are devoted to fostering dialogue between scientific and religious thought. No single accident in Western history has had greater impact upon this dialogue than the writing of *Principia* by Sir Isaac Newton.

Some may point to the Copernican revolution and the tribulations of Galileo as earlier points of departure for Western science from the patronage of the Church. But there is little evidence that Copernicus, a Polish monk, was ever troubled by or because of his views. Galileo's problems, by contrast, were indeed dire; but the case could be made that the intensity of his conflicts with the Sacred Congregation were essentially due to a clash of personalties. The heliocentric worldview addressed mainly the issue of humanity in nature and by hindsight posed little threat to essential beliefs. More direct challenges to dogma concerning the world and its Creator had been posed by the materialist philosophy of Thomas Hobbes and the mechanical outlook of René Descartes. But prior to Newton, materialism was

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embraced by few for want of something approaching concrete demonstration.

By what reason could one possibly call the intentional writing of a work, especially one so monumental and elaborate as *Principia*, an accident? However, the central reason why *Principia* now looms monumental was that it was nowhere as elaborate as Newton had intended, and therein lies a most intriguing story (Westfall 1980).

THE ORIGINS OF NEWTONIANISM

In 1684, Sir Christopher Wren and Edmund Halley, both ardent natural philosophers, had wondered whether connection could be made between the inverse-square law of attraction and the elliptical shape of planetary orbits. During January of that year, they met at Oxford with Robert Hooke to inquire of him whether a rigorous connection were feasible. Hooke asserted that he already had demonstrated as much, but he intended to keep his proof secret until others, by failing to solve the problem, learned how to value it!

Being somewhat disappointed by Hooke's response, Halley that next August found himself in Cambridge and decided to put the same issue to Newton. Newton likewise claimed to have solved the problem but feigned to have mislaid the proof. Newton became sorely distressed when Halley told him of Hooke's claim to have solved the problem, for there already existed at the time a strong mistrust of Hooke by Newton that was to grow eventually into bitter enmity.

Halley and Wren decided to press the question, and Wren offered as prize a book worth forty shillings to the one who could provide him with a proof within two months. When Newton tried his demonstration anew, he was greatly dismayed to find it flawed. Immediately, he set into a feverish labor to put matters aright, and this effort absorbed him for months as the books of *Principia* took form. In his preoccupation and haste, Newton abandoned his usual style of presentation. As a religious individual (albeit one with secret heterodox beliefs), and as someone with a strong interest in alchemy, Newton had habitually woven manifold references to his religious views and alchemistic notions into his narrations of natural philosophy and mathematics. But the enormity of the task and his absorption by it, doubtless fueled by the fear that any day Hooke might beat him to the goal, simply left him no time for such diversions. Besides, he could always return later and write in his beloved elaborations.

Of course, Newton won the race that wasn't, and he retired for a while in exhaustion that bordered on nervous breakdown. After

Principia was published, Newton did indeed begin a revision in his normal style, but history meanwhile was marching forward, entraining him in its wake. Newton's "minimalist" narration of celestial mechanics was just what the materialists were awaiting. It provided a predictive description of the movements of the spheres without any recourse whatsoever to supernatural agencies. Newton became a legend in his own time (and ours as well!) and basked in the approbation of the materialists, whose reputations he inadvertently had swelled—all of which made his intended elaboration of *Principia* something of a problem. Such additions did not appear in any of the three editions published during his lifetime (although the General Scholium was appended to the second edition). The existence of his efforts at a complete unabridgment remained unknown until they appeared among those of Newton's papers not discovered until earlier this century.

THE NATURE OF CAUSALITY

Thanks to this devoted alchemist, science has never been the same. *Principia* marked the dawning of the Enlightenment, and the elements of Newtonian thought suffused the entire eighteenth century. Charles Darwin, for one, was strongly influenced by Newton, whose heritage can be seen in neo-Darwinian scenarios to this day (Weber et al. 1989; Depew and Weber 1994). Minimalism and mechanics guided the founders of the new American nation (Wills 1978). Central to the revolution that Newton inadvertently began was the new and much simplified conception of universal causality that emerged. In a development that would have delighted Hobbes and Descartes, the consensus arose that only two origins of change exist in the natural world—the material and the mechanical. All other notions were deemed either antiquated or unorthodox (for example, vitalism). Thus it was that at the beginning of the nineteenth century Pierre Laplace (1814) could exult that any observer knowing the positions and momenta of all particles in the universe at any instant could employ Newtonian dynamics to foretell the course of all events forever thereafter.

The problem with criteria that delimit "legitimate" science is that the results of their application always are equivocal. True enough, the stricter they become, the greater one's confidence that spurious causes for phenomena will be rejected. However, the greater too becomes the likelihood that cogent and useful natural descriptions will be wrongly proscribed. The crux of my argument is that to confine scientific explanation *entirely* to material and mechanical causes, a tenet often zealously enforced, eventually impedes our understanding of natural phenomena.

The Enlightenment restrictions on causal explanations were intended to distance scientific from religious thought, and this they most certainly did, opening for awhile a veritable chasm between the two. Lest anyone mistake my intentions, I believe that the autonomy of the two systems of belief is proper and of advantage to all concerned (cf. Wojtyla 1980). But some inflated antagonisms between science and religion persist, fueled by many reasons. Not the least of these is the too stringent demarcation of legitimate science (cf. Kuhn 1970).

Those who championed Newton parted company with the ancients by declaring natural cause to be simple in origin. Aristotle, for example, saw more than just material and mechanical (efficient) cause behind every event. In addition, he identified categories of formal and final causality. Thus, when a house is built, one may point to the bricks, mortar, and wood as the material cause of the structure; the workers who assemble it as the efficient agents; the blueprint in the mind of the architect as its formal cause; and the need for housing on the part of its occupants as its final cause. An example more to the point: When a battle is fought, it is with material weaponry and ordnance that are set into action by individual soldiers (efficient agents). The main concern of officers and generals is with the juxtaposition of their armies with those of the enemy and with the terrain that separates and surrounds them both (that is, the formal conditions that guide the actual conflict). On still another level, the armies march toward each other for final reasons that are economic, social, or political in nature.

Both examples reveal to some degree a connection between hierarchy and non-Newtonian origins of causality. So long as one confines observation to a relatively narrow window of time and space, or else believes the universe to be self-similar at all scales, then a Newtonian description will suffice. As soon as one takes explicit account of scale, however, matters immediately become less clear. Laplace, for example, considered atoms as naught but planets writ small, and concluded that the future, in principle, is predictable. The pioneers of quantum physics, on the other hand, discovered unpredictability in a microscopic world quite different from anything Laplace could have envisioned. Elsewhere, the neurophysiologist slices through neurons in a person's brain or administers psychoactive drugs and declares that the brain is nothing more than a complex machine. The developmental psychologist, who observes the emergence of language and other higher mental processes over a longer duration, sees that which remains beyond the ability of any machine to create. Science cannot abandon the domain of such nonmechanical action entirely to the supernatural.

If one looks at the entire spectrum of natural phenomena, the contemporary picture is of a world open to causality only at its peripheries. That is, causes may originate either in the netherworld of subatomic particles, or perhaps at extracosmological dimensions. From these extremes causes propagate in closed form toward those domains more proximate to our own experience. We are enjoined, however, from thinking that a cause may somehow originate at some intermediate scale. In contrast, Karl Popper (1990), whom many regard as a conservative figure in the philosophy of science, urges us to adopt quite a different view of reality. He presents a world that is *open* at all levels. At any focal scale agencies exist that are fully determined neither by events at lower levels (reductionism) nor by those above (hierarchicalism). The universe as Popper conceives of it might best be called "holarchical."

None of which is to say that agencies at different scales share the same nature. As has been mentioned, Aristotle regarded a given event at different scales of observation and concluded that explanations at each level could be qualitatively different. Let us return for a moment to the earlier digression on Newton's *Principia*, which now serves as a convenient parable. In a strictly material sense there remain the original manuscripts and printed copies of *Principia*. Newton himself was undeniably the efficient agent in writing and propagating his works. One might even go so far as to equate the network of neuronal connections in Newton's brain with the mechanical cause behind this course of events. Newton, hero, genius, and individual agent, strikes out and changes the course of history in much the same way that Napoleon altered the map of Europe. But Tolstoy had reservations about Napoleon as an individual hero, and this similar portrait of Newton is equally suspect.

Newtonian science was the product of Newton's social milieu. This is not to deny Newton's genius or his preeminence in the foundation of classical dynamics. But the greater part of Newton's reputation derives from how *Principia* altered the way physical science was pursued for the next two centuries (and how biological research is conducted until this day!). Had matters followed the course Newton, the Arian and alchemist, probably intended, his legacy would loom nowhere as large as it does today.

But *Principia* told the right story at the right time—the "right" story in the eyes of the materialists, that is, those whose credibility it suddenly enhanced. There was a larger network of natural philosophers in place, ready and eager to accept, magnify, and help propagate Newton's work in the form he unintentionally provided. This social structure had obvious reciprocal effects upon Newton as well. The second and third editions of *Principia* did not appear in the unabridged form, connecting his principles to the supernatural, that he had started to prepare. Thus, the larger social nexus appears as the primary agency in fashioning the fame and meaning of *Principia*. Newton's role in what ensued was in large measure accidental. In true Goedelian fashion, the prominent role of social agencies in creating the Newtonian paradigm belies the very tenets it spawned.

MUTUALISM AND FORMAL CAUSE

It is the elaboration and quantification of macroscale agency that will constitute the remainder of this brief essay. I begin by asserting that causation arising *at* the level of system description is usually more formal by nature than it is material or efficient. To claim that formal causes are nonmaterial is not to deny that they are contingent upon material substance. Rather, it is to hold that the material substrate provides a wholly insufficient description of what gives rise to the phenomena in question. This is because formal cause usually derives less from material form (for example, a solid object or organism body) than from the temporal and spatial juxtapositions of *processes*. As Popper (1990) so aptly put it, "Heraclitus was right: we are not things, but flames. Or a little more prosaically, we are, like all cells, *processes of metabolism;* nets of chemical processes, of highly active (energy coupled) chemical pathways."

If formal cause is to reclaim its rightful role in science, then it becomes necessary to describe both (1) how it acts autonomously of material and mechanical constituents and (2) how its action can be rigorously quantified. Both demonstrations must pertain to a wide variety of situations, for already it has been hinted how formal cause is effective in systems as disparate as social environments or coupled chemical pathways. Thus, it becomes necessary to proceed for a while in very general (that is, abstract) terms.

The most common manifestation of formal agency is as indirect mutualism. Chemical autocatalysis is the example of indirect mutualism most familiar to readers. For purposes of this discussion, I will refer to all forms of indirect mutualism simply as "autocatalysis." Autocatalysis is a special case of positive feedback wherein an increase in the activity of any member in a directed cycle of processes engenders an increment in the activities of all other "downstream"

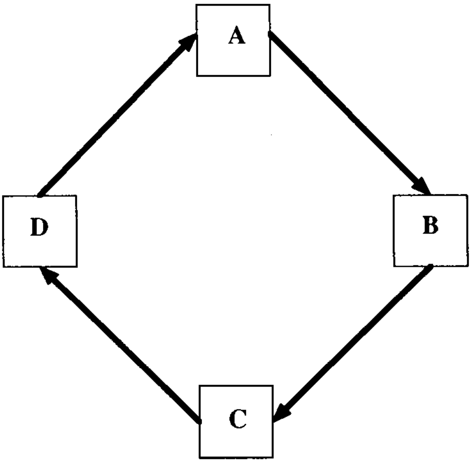

Figure 1. A four-member autocatalytic loop of processes.

elements of the loop, including itself. A four-member autocatalytic cycle is depicted schematically in figure 1. An increase in activity *A* leads to a growth in the level of activity *B*, which in turn causes the rate of *C* to rise, and so forth, until the effect propagates back to its origin, *A*, that is, it becomes self-reinforcing. This portrayal of autocatalysis is hardly new, but most accounts usually go on to identify the cycle of processes as a "mechanism." I argue instead, that to call autocatalysis a mechanism is to follow blindly the lead of those who created Newton's legacy. Within the Newtonian framework analogies to machines are almost never scrutinized; they are the postulated way of doing business. To see why mechanism is a highly inappropriate description of autocatalysis, it becomes necessary to consider several of the less-heralded properties of autocatalysis (Ulanowicz 1989).

Almost by definition, autocatalytic configurations are *growth enhancing* in the sense that greater activity is fostered. (In economics, growth is equated with an increase in activity, for example, the GNP.) An increment in the activity of any member engenders greater activities in all of the other elements. Such a configuration results in an increase in the aggregate activity of all members engaged in autocatalysis over what it would be if the compartments were decoupled.

What is not always made explicit, or often not even recognized, is that an autocatalytic configuration also exerts *selection pressure* upon the characteristics of all its constituents. If a random change should occur in one member such that its catalytic effect upon the next compartment is accelerated, then the effects of that alteration will return to the starting compartment as a reinforcement of the new behavior. The opposite also holds—should a change in an element decrement its effect on downstream elements, it will be reflected upon itself in negative fashion. There is an *asymmetry* to autocatalysis that ratchets all participants to ever greater levels of performance.

In particular, if the change in a compartment should accidentally bring more necessary resources into it, thereby allowing it to operate at an elevated level, then such acquisition will be rewarded. Because selection pressure favoring the acquisition of resources applies to all members of the configuration, the loop itself becomes an attractor of material and energy—a tendency that most appropriately can be called (to use the term coined by Newton) *centripetal*. Taken as a unit, the autocatalytic cycle is not simply reacting to its environment; it also actively creates its own domain of influence.

There is nothing that restricts the selection pressure of autocatalysis to act only on a fixed set of constituents. For example, if *A*, *B*, *C*, and *D* are four sequential elements making up an autocatalytic loop and if element *E* (1) appears by happenstance, (2) is more sensitive than *B* to catalysis by *A*, and (3) provides greater enhancement to *C* than does *B*; then *E* either will grow to dominate *B*'s role in the loop or will displace it altogether (figure 2). Similarly, if element, *B* should happen to disappear for whatever reason, the configuration of remaining elements will pose its constraints upon what may act as a substitute, *E*, for the missing link. (It was highly unlikely, for example, that a demonstration by Hooke would have been as universal in scope as *Principia*, nor would it have imparted sufficient momentum to the materialists' agenda. It is not, as Glansdorff and Prigogine [1971] would have us believe, that all fluctuations are equally likely to determine the course of radical change in a metastable configuration. Only a subset of possible perturbations can mesh with the larger context. In hierarchical terms, influence is always a two-way street!)

By simple induction, one may proceed from replacement of *B* by *E* to the successive replacements of *C*, *D*, and *A* by, say, *F*, *G*, and *H* until the final configuration, *E-F-G-H*, contains *none* of the original elements. In this sense, the action of the autocatalytic loop is said to be *immaterial* (in both the figurative and literal senses of the word) of its constituents. An important corollary is that the duration of the autocatalytic form is usually longer than that of its constituents. This is not as transcendental as it may sound. The reader's body is composed of cells that (with the exception of neurons) on the average did not exist seven years ago. The residencies of most chemical constit-

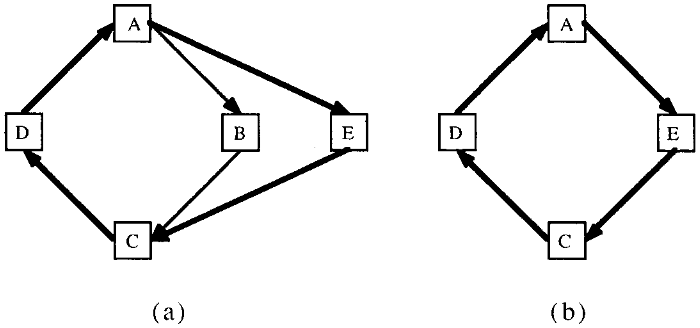

Figure 2. Immigrant compartment *E,* more effective in the autocatalytic loop, displaces former member *B.*

uents in the body are usually of even shorter duration. Yet most readers will be recognized by friends they haven't met in the last ten years.

This issue of temporal scale is very important. On a short enough time scale, it is always possible to emphasize how *prescribed* surroundings select system replacements. At the same time, one may describe in mechanical fashion how material variations in the substitutes determine consequent system behavior. (Such is the neo-Darwinian narrative.) What is missing from this short-term depiction is the asymmetry that governs replacements into the system. Some substitutions are preferred over others, *such preference being established by the existing autocatalytic form.* The bias often is only incremental over the short run, but it accumulates (reflexively!) over time to the point where, in the longer run, the case for material and mechanical determinism grows frail. Development over the duration of the autocatalytic configuration appears guided more by formal than by material influences.

These considerations on emendments and replacements also illumine the active role that autocatalysis can play in the little-understood process of *creativity*. There are two prerequisites before structure *A-B-C-D* can metamorphose into *A-E-C-D* (figure 2). First, the metastable structure must possess sufficient coherency in order to function as a discriminator of potential substitutes, that is, it must be capable of exerting selection pressure. Second, a variety of replacements, whose generation and availability are not strictly controlled by the dynamic configuration, must appear in independent and sometimes stochastic fashion. It is often recognized that creativity requires a threshold of order before it can occur (Atlan 1974), but it is less commonly apprehended that failure and uncontrollability (the antitheses of mechanical operation) are likewise required. This last statement becomes all the more startlingly antimechanical when rephrased: In order for living systems to adapt and persist in uncertain environments, part of their very essence must be acausal. Unlike with machines, it becomes impossible to specify fully the behavior of living systems in terms of their components (atomism).

Autocatalysis, then, is an example of formal causality with properties not possessed by the material and mechanical sort (Ulanowicz 1990). The emergence of selection pressure, centripetality, persistence, and the potential for creativity from within the system impart to the developing system a degree of autonomy from material cause that no machine possesses. Doubtless, many will persist in characterizing autocatalysis as a mechanism, but in so doing they are engaging in a gratuitous procrustean exercise—forcing autocatalysis to fit into a Newtonian bed by cutting off its head and members!

As a concrete example of autocatalysis, one could cite the evolution of Newtonian determinism in conjunction with Newton's writing of *Principia.* The problem with *Principia* as parable, however, is that discussion of it quickly becomes laced with emotional terms like "dualism" or "soul" and evokes earlier arguments about mind and matter or idealism versus materialism. Certainly, these issues are at the core of philosophy, but as regards the legitimacy of formal cause, their importance only becomes a distraction. Thus, human psychology, sociology, or even economics are too laden with human actions and intentions. At the other end of the hierarchy, ontogeny (at least as currently practiced) is focused almost exclusively on the material determinism of the genome. Fortunately, midway along the hierarchy of living systems lies the domain of ecology. Presumably, ecosystems existed before the advent of sentient organisms upon the earth, so it is appropriate to consider ecosystems apart from human ideas or intentions. As for decoupling ecosystem phenomena from molecular determinism (cf. Wilson 1975), Roger Lewin (1984, 1328) recalls that the developmental biologist Gunther Stent was moved to remark, "The regularity of these [ecosystem] phenomena is obviously not the consequence of an ecological program encoded in the genome of the participating taxa."

Most examples of indirect mutualism in ecology are subtle and require lengthy description. One exception is the *(a) Utricularia-(b)* periphyton-*(c)* zooplankton complex found in subtropical, nutrient-poor lakes (Ulanowicz 1991). *(a) Utricularia,* or bladderwort, is a genus of aquatic vascular plant growing from the bottom of clear lakes. *(b)* On the surfaces of its stems and blades grows a community of diatoms, or microscopic plants that amass as a visible film, called periphyton. *(c)* Feeding on and among the periphyton are numerous small (ca. 0.1 mm) crustaceans and insect larvae, collectively termed zooplankton (return to *a*). Finally, parts of the *Utricularia* blades consist of small bladders (ca. 1 mm dia.), called utrica, that function to capture and digest zooplankton in their near vicinity. An increment in any one of these three populations, say the zooplankton, would contribute to the growth of its "downstream" partners. That is, more zooplankton would be available to the planktivorous grass that would grow to provide more substrate for the periphyton that nourish the zooplankton, etc.

QUANTIFYING FORMAL CAUSE

Of course, it does not suffice merely to enumerate the properties of autocatalytic configurations and to cite qualitative examples of such cycles. If an agency belongs under the purview of science, one must be able to quantify its effects in some concrete way. What is so convenient about ecosystems is the relative ease with which one can quantify Popper's "nets of . . . highly active (energy coupled) chemical pathways." Ever since the example set by Lindeman (1942), it has become the *modus operandi* of at least one school of American ecologists to describe ecosystems in terms of compartments, both living and nonliving, that exchange material and energy with each other at palpable, measurable rates. That is, these ecologists devote themselves to answering the questions Who eats whom? and By how much?

Baird and Ulanowicz (1989), for example, have catalogued the magnitudes of 177 transfers of carbon among the thirty-six major compartments of the Chesapeake ecosystem. If one measures such a network of flows at two separate times, how then does one quantify the influence of autocatalysis as manifested by any differences? To become more explicit, the flow from component i that enters some other compartment j will be denoted by T_{ij}. One of the primary effects of autocatalysis is to increase the aggregate activities of all loops. Aggregate activity is an "extensive," or size-dependent, property of a flow network and is quantified simply by summing all T_{ij} in the system. This sum is what economists have termed the *total system throughput*. It is related to the more familiar gross national or domestic products. Thus, one effect of autocatalysis is to increase the total system throughput.

Of course, autocatalysis influences flow structure in other ways, too. In particular, selection pressure operates to augment those

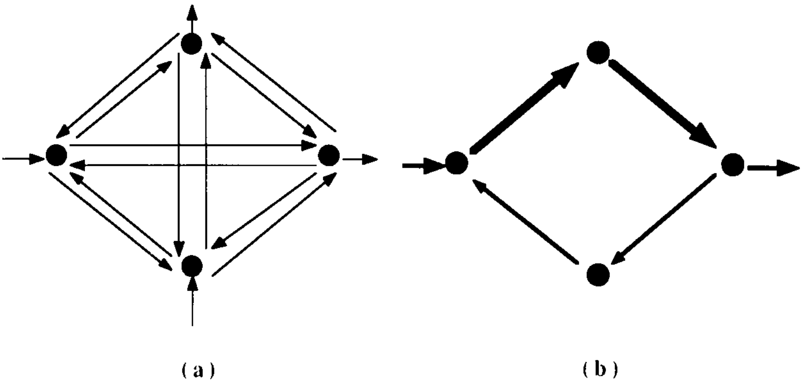

Figure 3. The effect of autocatalysis is to winnow the set of processes down to those most effective in promoting autocatalysis; at the same time, it augments the aggregate system activity.

connections which favor autocatalysis at the expense of those that are less engaged in mutualism. In the end, a network that has been influenced by autocatalysis becomes dominated by a small number of larger flows that are unambiguously linked (figure 3).

To quantify the winnowing effects of autocatalysis, we turn to the discipline of information theory. (The reader interested in the mathematical details is referred to Ulanowicz [1986].) If flow among the system compartments were wholly unconstrained (as is almost the case in figure 3a), then one could invoke the well-known Shannon-Wiener formula to estimate the mean indeterminacy of where a particular quantum of medium may be in transit. If, however, there are constraints upon transfers within the system, such that a particle in a given compartment is more likely to flow to certain elements than to others, then a *reduction* occurs in the mean indeterminacy of transfers by a calculable amount that information theorists call the "average mutual information" of the flow structure. Such constraints may be structural (for example, algae don't eat sharks); or they may be dynamical, as when autocatalysis makes certain transitions more probable than others. The average mutual information of the configuration in figure 3a is less than that of 3b. The greater the constraints on the flows, the higher the mutual information of the flow structure.

Average mutual information is an intensive (size-independent) property of the network. But the effects of autocatalysis are both intensive and extensive; that is, autocatalysis augments the activity level at the same time it streamlines the structure of the flow configuration. To amalgamate both aspects, one simply scales the mutual information index by the total system throughput. The product is called the network "ascendency." In systems that are free of major perturbations, the influence of autocatalysis should accrue, so that one may describe the direction imparted to evolution by formal causes (Ulanowicz 1986) as follows: *An autonomous system, in the absence of major perturbations, evolves in the direction of increasing network ascendency.*

Like any statement of such sweeping generality, this one has its qualifications. No system can grow and develop without limit. The constraints on the drive toward ever-higher ascendency can themselves be quantified using information theory (Ulanowicz 1986 and 1989). Increasing ascendency, on the one hand, denotes more *internal* coherence and greater stability of the role that each component plays in the overall system behavior. On the other hand, with higher ascendency also comes stricter inflexibility and a higher likelihood that the system will be unable to adapt to novel *external* perturbations. Hence, the point eventually is reached where the tendency toward higher ascendency is balanced by the disordering effects of background perturbations. The indeterminacy that remains after one has accounted for the flow constraints is called the system "overhead." One can show mathematically that ascendency and overhead are mutually exclusive in the sense that a relative increase in one comes at the expense of a decrease in the other. In the context of system persistence, however, both are necessary. One sees in the tradeoff, therefore, echoes of a Hegelian dialectic between those agencies that impart order to a system and the countervailing tendencies toward disorder.

Consonant with the diminished role for mechanical determinism, this description of evolution is insensitive to particular mechanisms. Such is the character of any narration quantified by information theory. In this regard, ascendency resembles the thermodynamic index "entropy." A single value of system entropy may correspond to a virtual infinity of system configurations. Similarly, a given increase in ascendency identifies neither a suite of mechanisms nor the particular formal agencies that account for the increment.

Nonetheless, ascendency provides what heretofore was unavailable—a quantitative way to follow the effects of nonmechanical agencies in structuring systems. For example, it has long been observed that ecosystems follow a more or less repeatable progression from pioneer, inchoate configurations to more complex, developed stages—a process known as "ecological succession." That is, more developed ecosystems seem to be made up of a larger number of elements (species) which, in the aggregate, exchange more material and energy with each other over less equivocal routes. Furthermore, as ecosystems undergo succession, they decrease both their losses to the external world and their dependencies on imported resources (Odum 1969). These changes all are reflected as increases in the system's network ascendency (Ulanowicz 1980). Thus, it now is possible to inventory an ecosystem at a given time, return at some later date to repeat the measurements, then actually quantify the degree of ecological succession (or retrogression under impacts) that transpired during the interim.

CONCLUSION

The identification and quantification of autocatalysis as formal agent provides for a deeper understanding of the nature of evolutionary development. It's not that neo-Darwinian explanations of evolution are categorically incorrect; but because they are cast in the strict Newtonian mold, they perforce remain incomplete (Weber et al. 1989). They all involve an abridged description of the environment that precludes formal agency. Neo-Darwinism forces the narrator to excise from their extended hierarchical context only those phenomena that can be explained by simple and immediate causes.

In fairness it should be acknowledged that much understanding can result from isolating phenomena. Such is, after all, the basis of laboratory procedure, which will continue to effect enormous progress toward our understanding and partial control of the world about us. But no one should pretend, as many do, that minimalism will lead to a full picture of nature. The pragmatist may argue that minimalism is necessary because only the simplest of interactions are within our analytical capabilities to describe, but this excuse is likewise beginning to wane. For example, a major preoccupation in economic and ecosystem studies is the quantification of indirect causalities (for example, see Leontief 1951; Hannon 1973; Patten et al. 1976; Wulff et al. 1989). Autocatalysis is a specific genre of indirect causality.

To recapitulate, the Newtonian paradigm with its adumbrated conception of causality is inadequate to the task of fully describing evolutionary behavior. Scientists should reconsider whether other forms of causality, such as the Aristotelean notions of formal and final causes, should regain their legitimate roles in the description of natural phenomena. Appropriate conceptual and quantitative apparatus for reincorporating formal causality into scientific discourse are now available.

I have taken the conservative course and limited the nature of autocatalysis to that of formal agent. Others (such as Salthe 1993) perceive of autocatalysis in the guise of final cause, and one can see intimations of a direction toward an unspecified end in the phenomenon of centripetality. It should come as no surprise, therefore, that the legitimacy of final cause in the natural order of things is also being reconsidered (Rosen 1991).

I would like to reemphasize the potential cost of *not* expanding the domain of acceptable causes. At the risk of being repetitive: Just as too liberal an interpretation of causality can lead to unwarranted deification of most natural phenomena, so can overzealous conservatism foster intemperate reification of legitimate qualia. A case in point is that of Francis Crick (1982), who became so obsessed with the material reality of the genome and had attributed to it such powers to order other biological events that he became unable to conceive of DNA as the product of a sequence of other natural processes. He suggested that its presence on earth must be the result of extraterrestrial seeding! Not quite as radical is the popular notion of the "selfish gene" (Dawkins 1976), whereby to the molecular genome is attributed behavior properly exhibited by the some or by biochemical subsystems thereof. I submit that identifying the structural properties of biochemical or ecological interactions as the agencies behind development appears by comparison far less contrived, while remaining wholly within the realm of natural description.

In the end, what inferences might one draw from these considerations on ecology and causality regarding the relationship between science and religion? Perhaps the first connection that many readers will leap to is that between the regulatory properties of autocatalysis as described above and the Gaia hypothesis of James Lovelock (1979), which often is presented with decidedly metaphysical overtones. Lovelock provides evidence and possible scenarios for how the earth's biosphere, via biogeochemical cycles, constitutes a formal agency akin to autocatalysis. This agency regulates conditions on the planet so as to make the persistence of life possible. Lovelock named this behavior "Gaia" after the Greek goddess of the earth. For many of his followers, reverence is due Gaia, for it is she who sustains humanity and other life on earth.

Gaia comes about as close as possible to the utopian wish of many readers for science to subsume religious belief. (Others, such as Thomas Berry, also point toward a new religion of ecology arising.) The curious thing is that few ecologists (this writer included) seem willing to step forward and don the mantle of priesthood in the new order. It is not through any doubts about the plausibility of bioenvironmental self-regulation that we demur. Furthermore, most ecologists already preach the necessity to respect and care for the life-sustaining processes on the globe. Rather, their reluctance has more to do with a historical issue that is almost as old as ecology itself.

About the turn of this century, Frederic Clements suggested that the regularities one observes in ecosystem behavior qualifies such systems as "superorganisms" (Clements and Shelford 1939). Most ecologists reject Clements's notion out of a skepticism born of reductionism. One needn't profess reductionism, however, to question Clements's ordinal judgments. Certainly, the capacity for some regulation of self and environment is a prerequisite for living systems to survive for any appreciable time. (It is also a necessity too often ignored by evolutionary ecologists!) This organic attribute alone, or even when it is coupled with the enormity of the biosphere and the duration of its processes, is, however, insufficient to confer upon the global ecosystem an ontological status above that of an organism or a species. The Babylonian prayed to the sun that warmed and sustained him. The fact that the sun is so enormously larger than was the petitioner and endures for epochs before and beyond this transitory being does not mean that the sun can begin to compare with the Babylonian, or even any higher animal, as an entity of complexity and adaptability. Perhaps Depew and Weber (1994) said it all best when they wrote how Clements had it backward: Ecosystems are not superorganisms; organisms are superecosystems!

The arguments about indeterminacy and creativity advanced above imply that the diversity of human nature alone is sufficient to guarantee that religion never will be wholly subsumed by science (or vice versa, for that matter). These two fields of human knowledge will always retain some autonomy from each other; yet they will remain closely coupled. The nature of ecosystems as evolutionary processes as just discussed might suggest what form this connection could take.

To be sure, at one time almost all adherents of either religion or science believed (and many still maintain) that their community possessed absolute and immutable truths. But if postmodern criticism has taught us nothing else, it has taught us that scientific paradigms shift and that faith is a living (and thereby growing and evolving) virtue. Like the tendencies toward order and disorder that yield organic ecosystems, science and religion appear to lean against one another as elements in a Hegelian dialectic. At one level, there always will remain a basic tension between the modes of thought. Science will continue to prune religion of that which is magical or superstitious. The religious community will always articulate virtues that in the end delimit the practice of science. There is no escaping the discomfiture that such interaction will continue to impart to any and all.

Fortunately, a dialectic never occurs on only one level. Just as a direct competition between two populations can become synergistic at the higher level of the ecosystem, so the interaction between science and religion can, at the next level, turn mutualistic. Faith in the transcendent can sustain the arduous pursuit of scientific knowledge far beyond the motivating powers of social and financial rewards. Even those scientists without belief in the metaphysical exhibit a faith in secular principles. Such faith often can be an advantage when engaging in (unfortunately, oft-neglected) inductive scientific pursuits.

Looking in the other direction, the rise of a critical spirit so fundamental to progress in science exacts a more personal and explicit adherence to faith; as a result, many persons are achieving a more vivid sense of God (Vatican II 1965). There are also the new avenues for religious thought that are opened by secular scientific pursuits. For example, Prigogine and Stengers (1984) were quite convincing when they wrote how contemporary descriptions of developmental processes free the human mind from the bondage imposed by Newtonian determinism. Humans need no longer be perceived as automata forced to act in rigid synchrony with the all-pervasive mechanical clockwork. We are now free to pursue a new "dialogue with nature." Nor has the allure of such newly discovered freedom escaped the notice of the theologian, for whom the idea of "God as the designer of wind-up dolls in a deterministic universe subject to divine coercion" was as much blasphemy as it was an affront to human dignity. In fact, many of the elements of "process theology" bear marked similarity to the program by which Prigogine suggests we pursue our new dialogue with nature (Haught 1984).

After a prolonged gestation, a traumatic parturition, and a stormy adolescence, it would appear that science may finally be on its way toward a mature relationship with its progenitor, religion.

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