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Aristotelean causalities in ecosystem development

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The positivist view of change in nature as due exclusively to material or mechanistic causes appears to be insufficient to describe the development of ecosystems. Positive cybernetic feedback possesses attributes that recommend it as a natural example of Aristotelean formal cause imparting some order to ecosystem flow networks. When positive feedback acts at hierarchical levels above the scale of observation, its effects at the local level appear as the result of a final cause. Ascendency, a mathematical property of any network of ecosystem flows, measures the combination of system size and organization. The observed directions of unperturbed ecosystem development appear to coincide with increases in the system's ascendency, which simultaneously serve to measure the effects of positive feedback when it acts as a formal or a final cause.

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Introduction

Just like the evolving ecosystems the Odum brothers have so lovingly described over the course of their careers, science, also, continues along its own pathway of development. Again like the episodic evolution of the natural world (Gould and Eldredge 1977), the history of science has been punctuated with significant shifts affecting the way we perceive the world around us. At the end of the eighteenth century the universe appeared to be a neat, precise and eternal clockwork. But this outlook was soon clouded by the emerging picture, painted by thermodynamics, of a cosmos that was running down. Critical junctures were later reached as absolute time and determinism lost their concrete appeal through the respective developments of relativistic and quantum mechanics. In biology Darwin described the living world as evolving, and others since, such as Watson (1970) and Prigogine (and Stengers 1964), have interjected filler into the chasm that seemed to separate the chemical domain from the living realm.

Certainly, no one would pretend that our present scientific picture of the world is complete, nevertheless for many ecologists it remains singularly inadequate: The prevailing world-view offered by science today is not ecological in scope. Certain attitudes that have been central to our discipline from its beginnings early in this century persist in influencing how ecosystems are regarded. For example, in keeping with the adage that "the whole is greater than the sum of its parts", a significant number of ecosystems investigators believe that new properties of systems do emerge as one increases the scale of observation. Furthermore, such emergent properties are thought to be autonomous to some degree of their smaller-scale composite processes and even to have the capability of influencing events at lower levels of the organic hierarchy.

Perhaps a majority of ecologists remains perplexed by the tenacity with which some of their colleagues adhere to these attitudes, which they find embarrassing remnants of a simpler era. They regard such notions as helpless naivete at worst or misguided transcendentalism at best. But I submit that through their works the Odum brothers, Eugene and Thomas, have pioneered the way towards providing a natural and rational foundation for this ecological world-view, and furthermore that their designation as Crafoord laureates is a significant indication that the ecosystems perspective is on its way to becoming acknowledged as the next major punctuation mark in the ever-changing narrative of science.

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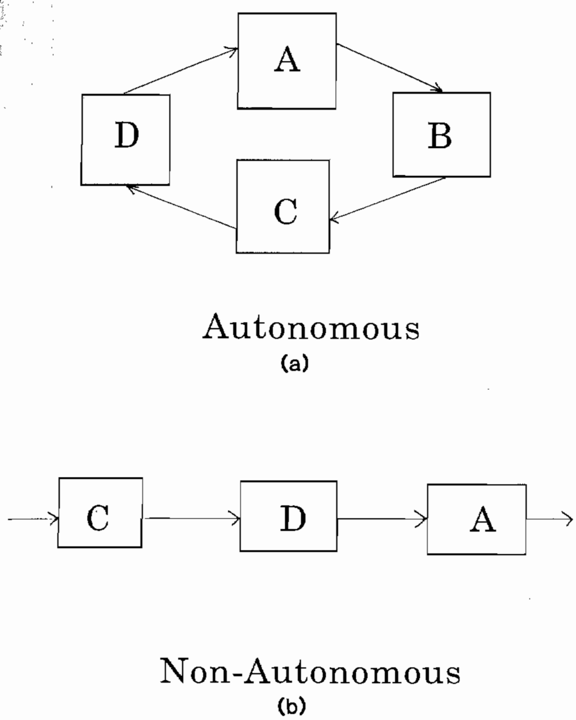


Fig. 1. (a) An ideal, wholly-autonomous causal loop. (b) A strictly non-autonomous chain of cause and effect.

The nature of causality

To see why the ecological perspective is gaining in credibility it is worthwhile to reflect briefly on the nature of causality. Most germane to this discussion is the fact that, with the advent of Newton, heavy emphasis came to be placed on the material and mechanistic aspects of causality. In physics the mechanical mindset has been so pervasive that we persist in referring to the fields of relativistic and quantum *mechanics,* even when the latter discipline deals with phenomena that would have appeared as if out of a nightmare to any scientist of the Enlightenment.

Earlier attempts to describe living phenomena along other than strictly mechanical lines (e.g., vitalism, teleology, Lamarckism) were inadequate in their times to forestall (and largely helped to precipitate) the growing consensus that scientific discourse should be limited to the material and the mechanical in nature. As a result, we have inherited a symbiosis of reductionism and positivism to guide our activities. Of course, no one should turn a blind eye toward the fact that reductionism is adequate to solve most of the problems we encounter in science, nor need we deny the benefits of the rigor that positivism has lent to our endeavors. But we should also avoid becoming ideologues on the subject, for too rigid an application of the reductionistic-mechanistic outlook leads in due course to hypotheses that are every bit (and more) as metaphysical and anthropocentric as those earlier directions for which strict reductionism was adopted to avoid. For example, one reads these days of genes being "selfish" entities (Dawkins 1976) which "direct" the assembly of organisms, or encounters evolutionists who are led to posit the extraterrestrial seeding of DNA to initiate the neo-Darwinian scenario (Crick 1982, Wicken 1987).

For myself, I tend to agree with Salthe (1985) that causality in living systems is more complicated than we would wish to admit. Rather than adopt a defeatist posture, however, I wish to reconsider here what one of the ancients had to say on the subject. Aristotle perceived that the cause of an event was not always simple and identified four categories of causes that could contribute to a single happening: (1) material, (2) efficient, (3) formal, and (4) final (Rosen 1985). In the familiar example of the building of a house the material cause exists in the mortar, lumber and other supplies going into the structure. The laborers and craftsman constitute the efficient cause, while the blueprints, or bauplan, is cited as the formal cause. Finally, the need for housing on the part of eventual occupants is usually taken as the final cause of building the house.

In the modern view of reality mechanical causes are considered efficient in nature, and the notions of formal and final causalities have been left to atrophy. Disappear they might, were it not for the possibility that they might convey best those elements of ecosystems thinking that set the ecological viewpoint apart from the rest of science. In the remainder of this paper I wish to argue that formal and final causes are at work during the course of ecosystem development, that they appear quite naturally, that they can be qualitatively described with the help of cybernetics and hierarchy theory, and that one can actually measure their effects by invoking selected results from network and information theories.

An origin of formal and final agency

Perhaps more than any other individual, Thomas Odum (1971) has long championed the role of the positive feedback, or the reward loop in effecting ecosystem organization. The ideal autocatalytic feedback loop is illustrated in Fig. 1a, where the arrow from A to B is taken to mean that the activity of A positively influences the activity of B – be it through the exchange of material from A to B (as would occur if B were a predator and A one of its prey), or via some more indirect mechanism, such as A modifying the habitat in a way that is propitious to the survival and/or propagation of B. Component B affects C in a similar (but not necessarily identical) way; ditto C and D; and, finally, D augments A in its turn. Following the pathway of material or efficient causality around the loop, one sees that the activity of A affects itself in autocatalytic fashion.

I would like to suggest that what might have begun as a chance configuration of composite mechanisms now possesses attributes proper only to the whole structure.

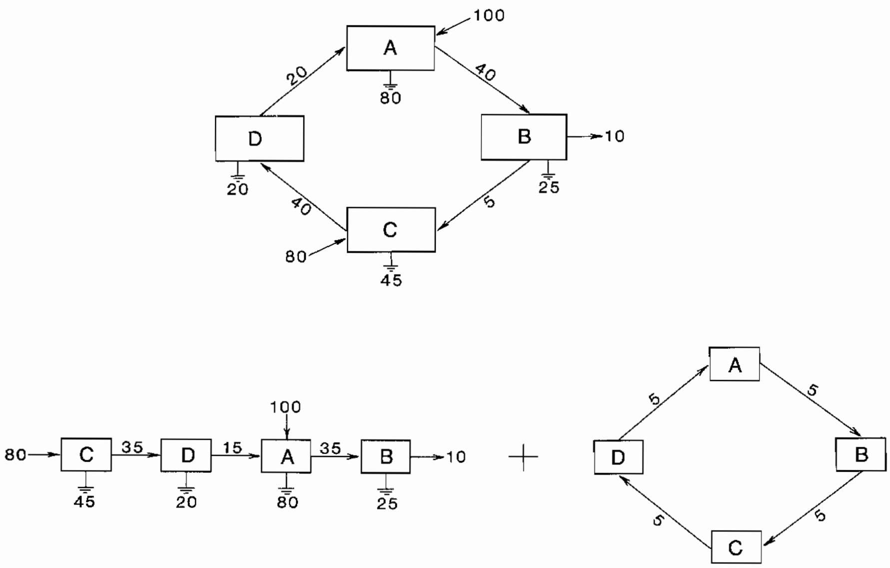


Fig. 2. (a) A hypothetical, but plausible cycle of material causality. Units are arbitrary.
(b) The once-through tree of flows supporting the recycle.
(c) The cycle as abstracted from the network in (a).

Among them I include: (1) autonomy, (2) emergence, (3) growth enhancement, (4) selection, (5) inducement of competition and (6) formality. The ideal loop in Fig. 1a, if it were a depiction of all the causality at work in the system, would be termed autonomous in contradistinction to the strictly non-autonomous chain in Fig. 1b, where an initial cause and final effect are manifest.

To be sure, no such wholly autonomous structure exists in nature, for it would contravene either the second law of thermodynamics or Goedel's (1931) prohibition against logical self-sufficiency. However, the absence of purely autonomous structures is no reason to ignore the degree of autonomy exhibited by configurations that are only partially confined by their contexts. To the possible criticism that the functioning of the loop in Fig. 1a is contingent upon numerous factors at lower hierarchical levels that are not represented, one could rejoin that "to be contingent upon" should not be confused with "is determined by". In a more quantitative vein, I have shown elsewhere (Ulanowicz 1983) how any arbitrary network of material causalities (flows) can be divided into a strictly once-through, non-autonomous tree and a nexus of self-contained loops. Whereas one might encounter a real loop in the form of Fig. 2 (upper), it is always possible to identify abstractly the autonomous component, as in the decomposition into the elements shown in Fig. 2 (lower).

If autonomy is one aspect of a feedback loop's essence, then its epistemological counterpart is emergence. A property is said to emerge if it appears only after an observer increases the scale of his attention. In Fig. 3, if one begins by focusing attention only on those elements within the solid line, then only strictly non-autonomous structure is visible. If, however, the same investigator increases the domain of observation to encompass an entire positive feedback loop, it then becomes possible to discern autonomous behavior.

That a positive feedback loop is growth-enhancing is virtually a tautology. An increase in activity at any node of the circuit is propagated to all members of the loop, including itself. True, such autocatalytic behavior could possibly lead to uncontrolled growth. Furthermore, one wonders why we do not see ecosystems that engage in an "orgy of mutual benefaction" (May 1973). However, ecosystems are notoriously dissipative in their operation, and such leakage acts to attenuate the effects of positive feedback. In fact, one could argue that positive feedback is the only agency with sufficient vigor to persist in the presence of strong entropic tendencies.

Selection is central to the notion of positive feedback as an agency. Any constitutive change in a member of the loop that enhances the catalytic effect it has on the next element will eventually be reflected upon itself, i.e., rewarded. Conversely, changes in a component that impair its catalytic action will diminish their own support. Thus, autocatalysis impresses upon its constituents an asymmetric, ratchet-like form of selection, so

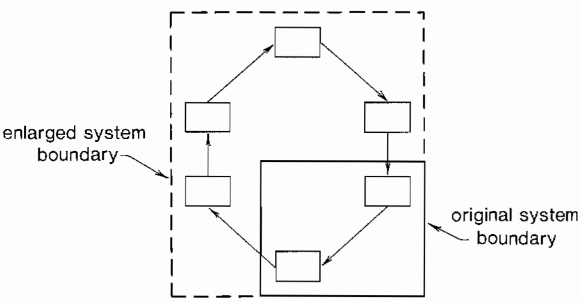
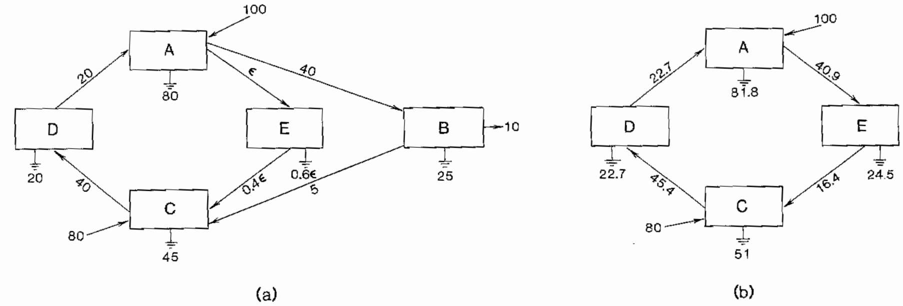


Fig. 3. Positive feedback and associated properties emerge from an increase in the domain of observation.

Fig. 4. (a) A more efficient component E builds a shunt between A and C in competition with B. (b) E displaces B in the loop.



that those changes in the properties of the components that benefit the self-enhancing action of the cycle are the ones most likely to persist. If, as Eddington (1958) suggested, entropy is "time's arrow", then we might as well assert that the asymmetry inherent in positive feedback provides a proximate direction for evolutionary change.

The complement to selection is competition, which autocatalysis is seen to foster. The selective pressure just discussed is not confined to acting only on the internal composition of its members. It places the components themselves at some risk. In Fig. 4a, for example, the element E is interjected parallel to B into the cycle depicted earlier in Fig. 2a. It happens that E is more efficient than B at catalyzing C and is more receptive to the enhancement afforded it by A than is B. The ensuing dynamics virtually insure that E's participation in the loop will grow at the expense of B's, and the latter may shrink to the point of insignificance, or possibly go extinct, as in Fig. 4b. One can imagine the subsequent replacement of members C, D and A by other competitors, and one arrives at the situation where the structure of the system endures beyond the replacement of all its constituents, and where the overall configuration has exerted an active influence upon what those eventual replacements could be.

Proceeding still one step further up the hierarchy, one can employ an argument similar to those just given to demonstrate the likelihood that two or more loops with partially overlapping members (as in Fig. 4a) or with connections to one or more common resources will be forced into competition with one another for those resources.

Autonomy, growth enhancement and the capacity to exert selection pressures are all essential features of an agency. Insofar as this agency is relational, i.e., to the extent that it derives from the dynamical *structure* of its constituents, it may rightly be called *formal* in nature. I suggest that positive feedback is a more satisfying example of formal cause than is a set of blueprints, because the agency inherent in blueprints is obscure at best. The agency in autocatalysis is far more immediate.

To focus on a formal cause at work in a system can lend clarity and conciseness to a narration. Consider, for example what Forrester (1987) and Richardson (1984) say about economic and social systems: "Nonlinearities cause what economists refer to as 'structural changes' in a system. But 'structural change' is usually little more than a term used to cover *unexplainable* (i.e., nonreductionistic) behavior ... We might better speak of shifting loop dominance, ... the process by which control of a system moves from one set of feedback loops to another set, often with dramatic changes in behavior".

But what of final cause? It requires but short reference to the epistemology afforded by hierarchy theory (Salthe 1989). I have just argued that when a feedback loop is apparent at the focal level of the hierarchy, one perceives it as a formal cause. When an autocatalytic loop is acting at a fine scale, it will appear to the observer, along with manifold other agents, in the guise of an efficient cause. Conversely, when the focal system is but part of at least one larger cybernetic loop, that unseen autocatalytic behavior will impress itself on the object system via the boundary conditions. That is, its influence will be perceived at the focal level as *final* in nature.

Quantifying the effects formal and final causes

It is interesting to describe formal and final causes as if they were angels on a pinhead. But if the ecological viewpoint is to have any credibility as a science, it becomes necessary to define at least the consequences of non reductionistic causality in concrete, and especially in quantitative terms. To effect this transition I note that feedback cycles always appear to us as imbedded in causal networks. Therefore, the ways in which the properties of ecosystem networks change should document the formal influence that the autocatalytic cycles are exerting on overall structure. Fortunately, there is growing interest in quantifying the networks of energy and materials as these are exchanged among the constituents of the ecosystem, and these accumulating data should provide fertile substance out of which to mold cogent descriptions of ecosystem development (Wulff et al. 1989).

It is remarkable that a single agency should have both extensive and intensive ramifications upon a system. Earlier we saw how autocatalysis usually acts to increase the level of activity of its components. But the level of activity is a convenient surrogate for the size of a net-

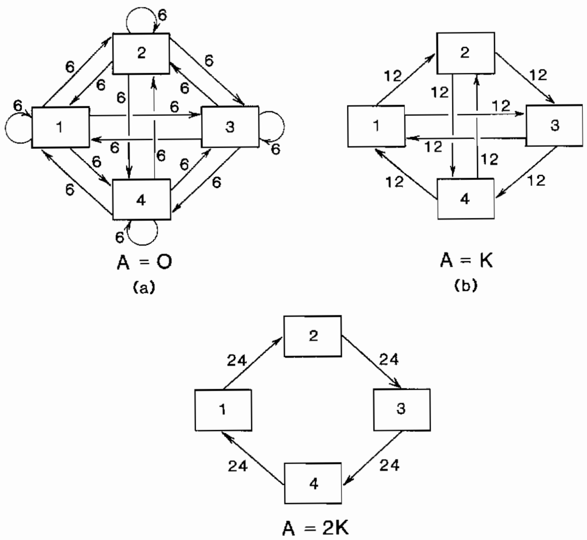


Fig. 5. Three hypothetical networks with equal total throughput but increasing articulation of flow.
(a) Minimal articulation.
(b) Intermediate articulation.
(c) Maximally articulated configuration.

work of exchanges – witness the "gross national product" as a indicator of the "size" of a nation's economy. Hannon (1973) and others have found it useful to use the sum of all the exchanges occurring in a network, or the total system throughput (Hirata and Ulanowicz 1984), as the most straightforward measure of the dynamic extent of an ecosystem.

At the same time positive feedback is enhancing the growth of the ecosystem network, it is also effecting the selection and facilitation of the more "effective" pathways among the species. All other things being held constant, the result of the selection and competition induced by autocatalytic cycles is to create a topologically more streamlined and thermodynamically more efficient network of exchanges. Such streamlining, or articulation of the network is an intensive property resulting from the action of positive feedback. In a well-articulated network each node or species is more highly specialized, which is to say there is less ambiguity about where the species obtains its sustenance and what preys upon it. The measurement of uncertainty is the domain of information theory. Rutledge et al. (1976) and Ulanowicz (1980) have shown how the degree of articulation of a flow network is measured by an informational index called the *average mutual information*:

$$A = K \sum_i \sum_j (T_{ij}/T)\log(T_{ij}T/T_iT_j')$$

where T_{ij} = The flow from compartment i to compartment j,

$$T_i = \sum_j T_{ij},$$

$$T_j' = \sum_i T_{ij},$$

$$T = \sum_i T_i = \sum_j T_j'$$

= the total system throughout,

and K = a scalar constant.

That A characterizes the articulation of a system is demonstrated by the hypothetical networks shown in Fig. 5. In Fig. 5a the system is completely unarticulated in the sense that there is maximal uncertainty (equiprobability) about where a quantum of medium at any node will flow during its next transition. In Fig. 5b there is less choice (ambiguity), because medium leaving each node flows to only two other nodes. Finally, in Fig. 5c one is certain about where the medium in any compartment will flow next. The network (or loop in this last case) is maximally articulated. The values of A corresponding to the three configurations in Fig. 5 track the increase in articulation well.

As pointed out earlier, the effects of cybernetic feedback are simultaneously to increase the activity (size) of the system and to organize the flow along a more articulated set of pathways. To describe this unitary process one seeks a measure that combines a factor of size with a factor of organization. It happens that the units of the average mutual information are identical to those of the (as yet unspecified) scalar K. By choosing K=T one gives dimensions to A commensurate with the size of the system and at the same time makes A the mathematical product of two factors – one relating to size and the other to organization. I have called the resulting index the system's "ascendency". Hence, an increase in system ascendency over time should serve to quantify the effects of positive feedback as a formal cause at work in that system.

If an ecosystem is reasonably protected from major exogenous perturbations, it will pass through an orderly progression of states called succession. Systems in the later stages of the succession are sometimes referred to as "mature" communities. In his seminal work, "The strategy of ecosystem development", Eugene Odum (1969) listed 24 attributes of more mature ecological communities. These properties in turn can be aggregated into four groups. More mature communities are observed to possess, on the average, greater (1) speciation, (2) specialization, (3) internalization and (4) cycling. Considered alone in its turn, an increase in each of these attributes results in a higher value of the system ascendency. (This is no accident. Odum's observations provided me with the phenomenological starting point for this entire narration. In fact, one could begin at this point and read backwards to obtain an approximate chronology of how these ideas came to me.) Thus, ascendency appears to encapsulate the observed directions in ecosystem development as well as the effects of positive feedback operating as a formal agent within the system network. Whence, the quantitative induction: "In the absence of major external perturbations, the tendency in ecosystem development is in the direction of increasing network ascendency".

To summarize, purely reductionistic narrations are inadequate to describe the development of ecosystems. They lack the vocabulary to address the action of formal and final causality in giving these systems their forms. That such causes can arise naturally follows from a consideration of cybernetic feedback in ecosystems. That their effects are concrete and quantifiable is demonstrated by the derivation of system ascendency. It may even be possible to simulate the action of feedback as a final cause of changing population levels by casting the ascendency as the objective function in a optimization algorithm, such as is now under development by Cheung (1985), Chang and Goldman.

It is tempting to use ascendency in normative fashion, but I should like to urge caution in such practice. Ascendency is a surrogate for system efficiency, and just as the desirability of efficiency depends upon its context, one should not rush to use ascendency as a measure of ecosystem health (Ulanowicz 1986a). Any increase in ascendency is counterbalanced by entropic tendencies and exogenous constraints. Fortunately, these countervailing limits are amenable to same calculus as that used to quantify ascendency, and in a recent monograph (Ulanowicz 1986b), I have elaborated these constraints in concrete mathematical terms.

Concluding remarks

I would like to conclude by noting that there are a few who regard the discipline of ecology as "sick" (Simberloff 1981). Still more feel that ecology would best progress by importing viewpoints and technical tools from other disciplines (and I agree to the extent that it always helps to be aware of new developments in any field of study). But I am hardly disappointed in the progress we lately have been making in ecosystems studies. To the contrary, I perceive our field as vital, vigorous and fermenting with new and exciting ideas. I believe ecology is now in a position to turn the tables, so to speak, and I suggest that other disciplines might benefit by adopting elements from our ecological world-view. This is nowhere more apparent than in regard to the fields of economics, developmental biology, cognition and the social sciences, the integration of which Eugene Odum (1977) foresees as the task of ecology. I would like to think that the particular methods I have mentioned here might play a role in achieving that integration, but that speculation is perhaps premature. I am convinced, however, that what these domains do share in common is that they all include causal factors for the description of which the conventional materialist/reductionist approach remains insufficient. They beg the ecological approach, but few are listening.

Let no one infer that I lack an appreciation for what "pre-ecological" science has given us. Its material and physical benefits to those in the developed world have been enormous. But the reductionist postulate has been anything but ennobling to the human self-image. The actions of man remain the actions of molecules. The existing body of thermodynamics says that everything is running down. Economics is known as the "dismal science". The ecological viewpoint also admits much of what is troubling to the human condition, and yet it proffers the additional insights that man is perhaps more than clay, that conditions sometimes improve, and that life seems bent on enduring. These are reasons to hope, and it is on a note of hope that I wish to end.

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