SKETCH OF A LOGICAL DEMONSTRATION THAT THE GLOBAL INFORMATION CAPACITY OF A MACROSCOPIC SYSTEM MUST BEHAVE ENTROPICALLY WHEN VIEWED INTERNALLY

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Abstract. This paper attempts to sketch out in what way macroscopic information must be entropic. If this can be shown, a larger science, of infodynamics - the study of uncertainties, can subsume thermodynamics and information theory. It is crucial for these purposes that a finite observer be stipulated for all informational exchanges, and, in order to achieve the desired result, that observer must be located inside the supersystem that contains the object systems it interprets. KEYWORDS: dissipative structures, hierarchy, semiotics, uncertainty.

I. Introduction.

The basic premise of this paper is that configurations that could potentially carry information *are* not information unless they have meaning (see Dretske, 1981 for a beginning sense of the meaning of meaning) for an observer. The paper will turn on the semiotic distinctions of sign, observer and referent. The logical movement will be from externally observed information→ observer → semiotics → internalist perspective → macroscopic information acting like an entropy.

Unpacking the term 'macroscopic information', we find that 'macroscopic' implies the scale of an observer, who is therefore introduced right away. An implication from hierarchy theory (Salthe, 1985) is that microscopic information cannot be directly detected by a macroscopic observer, only macroscopic configurations, which would be informed only indirectly, in a molar way, by microscopic initiating conditions. So, there is reason to believe that all material information is macroscopic as far as we, macroscopic, observers are concerned.

Our observer here will have only finite capabilities for detecting information, being limited, e. g., as organisms can be by biology and culture, and as scientists are by theory. Thus, even though, if they are physical systems and can therefore assume an uncountable number of states, only some of these will register and function as information, depending on the categories of the observer.

Concerning 'information', I will base my sense of it on Dretske (1981), who takes it to be the most highly specified digital content an analog percept can have. So, if the observer detects ice cream, it registers that fact and not also that the object is a kind of slush, or that it is one of the states of some liquid, or, in a still different way, that it is a product of cows or of some factory, or, in a yet different way, that its retina has been disturbed by certain light rays. Its own detectors are transparent to it. The nature of the observer is paramount here, as we can see further from the fact that it might be important to an observer that the ice cream be vanilla instead of chocolate, in which case there is even more highly specified information in the system, and ice cream *per se* would not be what that information is.

Any analog interaction between observer and object can contain an almost indefinitely large amount of digital information, and it is the observer that cuts this down to a size determined by its structure and interests.

'Information', in the sense of the total information in a global system, means its information capacity ($C_{max} = p \ln p$, conceived as the degree of environmental uncertainty it potentially affords its subsystems, S, and which is, potentially at least, calculable by our observer), plus the amount by which that has been reduced by information, H_i, about their local environments stored in its subsystems. H_i is defined as the difference between the global maximum potential information carrying capacity, C_{max}, and the average behavioral disorder local subsystems display, C_i:

$$H_i = C_{max} - C_i \quad .$$

This locally stored information, H_i, forms part a subsystem's organization - something near to what Collier (1990) calls its "intropy".

H_i is that which reduces environmental uncertainty, perhaps by changing the coherence between the system and aspects of its local environment, perhaps, e. g., as sketched by Ashby (1956), by restrictions on mappings from one onto the other. This could perhaps change the surprisal (Dretske, 1981) of their states relative to each other. But these mappings must involve actual physical alterations of system, S_i. Increases

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in H_i might involve some change in microstates, perhaps an increase or decrease in their number, or some change in the probability distributions of possible states. For our purposes here further details on these matters are not needed.

From this point, I will for a while consider only a single subsystem, referred to as the object system S_i. The global system generates its relevant local environment, its umwelt (von Uexkull, 1926). So, total information, H = environmental C_{max} + object system H_i. The implied knowledge of probabilities necessitates an observer of the same scale as the object system, but outside it (capable of measuring it) and in contact with (parts of) its umwelt. So the behavior of a system and of aspects of its environment are observed and recorded in global H (which is, but is not acknowledged by the observer to be, a construct located as stored information, H_o, in the observer). The observer cannot see into the reference subsystem (i. e., cannot directly measure H_i), and does not attend to its own behavior either. H in this situation is the construct of an external and transparent observer of object systems and their relevant umwelts.

C could be applied, variously, to diversity, as in local ecosystems; versatility, as in language; variability, as in population studies; variety as in systems responses - Ashby's (1956) principle of requisite variety. These represent (or, as reflected in object system behavior, measure) environmental uncertainties at these various scalar levels. However, C_{max} refers to the maximum potential capacity of the relevant environments, and none of these estimates that. C in these cases can be related instead to the actual uncertainty of the relevant environment, estimated by C_i. (There are at present real problems in calculating C_{max} for most natural systems). Note that uncertainties here refer to a particular, limited set of states that local environmental systems would be constrained to occupy in some sequence or concatenation, as determined by categories of the observer. There may be more or less of them, and their patterns of appearance may be more, or less, orderly.

H_i in the same systems would be located, respectively, in the populations making up the diversity, in speakers and listeners, in individuals in a population, or within an object system. These would be the object systems of different scale observed respectively in the different cases noted, part of whose organization would be represented by H_i, the difference between maximum and apparent actual environmental uncertainties - were the former subject to estimation.

Before anything concrete could be done, one would need estimates of C_i and H_i. Take a local ecosystem for example. We can assume from Ashby's principle of requisite variety that diversity (D) measures some of its environmental uncertainty. The more uncertain an environment potentially could be, the more would biological systems have diversified to dissipate that information. We know, however, from ecology, that behaviorally more uncertain environments (as in the arctic) are associated with ecosystems having communities of relatively *low* diversity. From thermodynamic principles, these can be taken to be relatively immature systems (having few types, whose tokens form relatively unpredictable configurations), while the more diverse ones are relatively more mature (Salthe, 1990). We would need to consider not only diversity but some estimate of the residual environmental uncertainty, U, not absorbed by diversity. So, C_i would be estimated by D + U. Knowing D, U can be roughly estimated by the roughly reciprocal relationship of U and D implied by ecological facts (such as the one noted above) and by the implications of Ashby's principle of requisite variety - so, roughly, UD = 1.

Now, in relation to H_i, since each species adds its mite of information to the global store, we could observe the behavioral uncertainty, C_x, of populations X, Y, Z in the ecosystem's biological community, giving us, really, just the basis for another estimate of C_i - but from a different scalar level, from information stored within the system, not, as with D, information taken at its surface. We could measure, over seasons, items like changes in population size, density, area occupied, population structure, and so on, giving us $C_a + C_b + C_c \ldots + C_n / n = C_x$ for each population, X, from which we could derive the mean of means, C_{xyz}, that estimates C_i in this, microscopic, case. Since this estimate is developed from a lower scalar level than the diversity based one, it represents information embedded inside the diversity information, and we would want to know how the macroscopic and microscopic estimates correlate. In the absence of any significant correlation, we would be back to square one; in the presence of a tight correlation, we might begin probing for some reflection of H_i, especially if there is a suggestion of an interesting regression between the two. Having H_i (relationship between U + D and C_{xyz}) and C_i (U + D and/or C_{xyz}, we can estimate C_{max} and obtain a rough estimate of H for the relevant local environment. All of this is crude, but that in itself has no bearing on the point of my subsequent argument.

II. Must a Capacity, C, Behave as if It Were an Entropy?

No. As local measures viewed from outside (as in U + D or C_{xyz}, for example), *on the contrary*: thus, continuing the earlier examples, diversity can level off and even decrease in senescent ecosystems (Odum, 1969), versatility and variety always level off at optima (Conrad, 1983), and population variability can decrease with increased intensity of selection (e. g., Salthe and Crump, 1977).

Since the system's behavior is interacting with that of relevant portions of the supersystem, C_i must appear to decrease over time as the system's H_i increases as it "learns" to maintain its favored states in spite of supersystem fluctuations (see Ulanowicz, 1986, for an interpretation, "ascendency", relevant to this). Indeed, in systems surviving in an environment, much of their stored information, H_i, will be involved in the behavioral matchings summed up by Conrad (1983) as "adaptability". If the period of observation includes the transition to senescence of the system, then its variety of behavior, now more accurately measuring C_{max} because it has become less buffered, should again increase (Salthe, 1990). But note that, *simply with continued observation in a given mode, the behavior of the system becomes more and more predictable to the observer from that perspective*. So the increase in H can be both in the system, H_i, *and* in the observer, H_o. Therefore, some of the decrease in C_i would be apparent only if carried by, e. g., elimination of mistaken measures or correction of misinterpretations of rare states).

Note that the kind of uncertainty we have here is that generated by the search for an analog coherence between observer and object system. It requires that some information theoretic concept of 'knowledge' be developed. I would start from discussions in Dretske (1981) of the digital notions of concepts and beliefs. He takes concepts to be coordinations between input and output. Beliefs are what emerge when such coordinations are replicated, and knowledge needs to be constructed out of the success beliefs may or may not have in their ventures at generating matchings with environmental configurations.

Note that C_i will decrease as system H_i increases by way of "learning". This will take place during the system's immaturity and early maturity, but after this, C_i will begin to increase again with senescence as the more and more rigid and inadaptable system increasingly fails to damp the effects of supersystem fluctuations. But C_i will still continue to decrease as the observer's H_o increases as it learns increasingly to anticipate the system - even to some extent in its senescence. (For the moment we can pretend for relative simplicity that the observer is always at some optimal stage of maturity).

At this point we need semiotics. Using the semiotic triad (of C. S. Peirce - Fig. 1), system behavioral variety, C_i, can be taken as a sign of the uncertainty of the system environment for the observer, who is involved in a system of *interpretance*. This word includes the notion of 'interpreter', but goes beyond that to the developing and evolving system of discourses of which the interpreter is only a part.

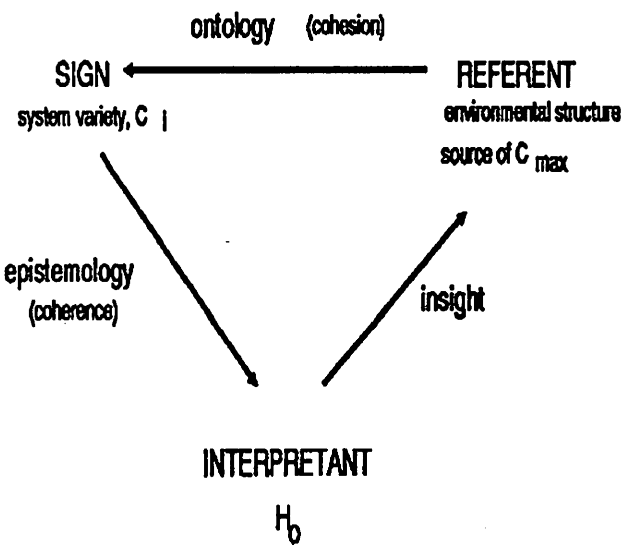

Figure 1. The Peircean semiotic triangle, interpreted from the point of view of science. The interpretant is a complex notion, being that system, which includes interpreters, that interprets signs. It is embedded in a higher scalar level, changing system of interpretance, approximately identifiable with a discourse. Coherence refers to the coherence between the observer and the object system; cohesion to the unity of the object system and its environment, that is, cohesion between the sign and its referent, in this case with the sign as part of the referent.

Roughly, although the entire structure is epistemological, epistemology in the narrow sense is involved in the relation of the sign to its interpretant, the momentary and local manifestation of the system of interpretance. Ontology is involved in the meaning of the sign - the relation of cohesion between the sign and the signified referent. For example, is the sign a necessary part of the referent, like smoke in relation to fire? Is it a picture of it, like a shadow? Or is the relationship purely arbitrary - like some kind of correlation or covariance, or the result of conditioning?

The relation between the interpretant and the signified referent is one of insight (Peirce's "abduction"), presumably made possible by structural (analog) matching or coherence between the interpretant and the referent (which then needs to be explained, of course, perhaps partly by selection, partly by a primitive developmental systematicity). So we have, in this, scientifically oriented, application, (first) ontology, (second) epistemology and (third) insight. (One could argue in other kinds of applications, e. g., for insight being first, ontology second and epistemology third).

In any case, there is feedback from insight to epistemology within a system of interpretance, and, riding on this, ontology, because it links them, is seen to be the regulation of epistemology by way of insight, just as epistemology is the regulation of insight by ontology. In that way ontologies impose their rule in science even while being socially constructed. Ontological factors are needed to be postulated just for there to *be* something that varies for someone. Note, however, that they do include categories of the observer; ontology is not independent of epistemology and insight.

If we are worried about ontology being treated this way, as observer dependent, I would note that science is hardly ever concerned with ontics anyway, but with being able to demonstrate something (Latour, 1987), while those who pay for it are concerned with how to use it. Only philosophers have been interested in ontology. These do, however, seem to include some scientists, - those evolutionary biologists, for example, who want to know the "real" sequence of events in the past.

Collier (1990) has called the ontological aspect of organization "enformation", which can here be interpreted using scalar hierarchy theory to be in part an array of environmental affordances for the object system, supplying its cohesion, that can to some degree be grasped by an observer outside the system. Wicken (1989) uses Denbigh's term "integrality" for this "extensive" aspect of organization. It is what allows the system to have its place, and therefore its form and behavior, in the supersystem it is part of.

The other aspect of system organization, Collier's "intropy", is the degree to which the behavior of the reference system has become more predictable, both through its own increasing success in predicting environmental fluctuations (thereby enhancing the stability of its favored states) and through the increasing familiarity of the observer with the system, both conceived as the reduction of environmental C_{max} by stored information, H_i. In other words, in the face of increasing coherence between observer and object system states, we cannot tell whether the object system is getting better at matching environmental variety by way of cohesion with it, thereby becoming intrinsically easier to predict (and increasing its H_i in the process), or the observer is getting better at predicting system behavior through better coherence with it, increasing H_o - i. e., we can't know the partitioning of H.

This reduction of object system variety, its intropy, is clearly, then, an epistemological aspect of organization. Wicken (1989) deals with it as "intensive" and, appropriately, as the result of constraints. My point here is that these constraints involve *both* system-environment links *and* anticipation in selective observation so that energy is not wasted seeking object system states irrelevant to the observer's interests.

III. In the Next Section the Observer Begins to Sink into the Observed Situation.

By affecting the apparent amount of variety in the system's environment reflected in C_i, the observer becomes part of that environment, implying a generalized uncertainty principle. At the same time the environment comes to include in C_{max}, in a stronger form, the observer's ignorance of most of the mutual environment of both itself and the object system. This is made evident in unexpected environmental responses (including those of the object system) to the observer's probes (Rosen, 1985). If it had absolute information about them, this could not happen. The observer necessarily becomes aware, through estrangement, of its own involvement, as well as its own peculiar scale and associated limits on observation, and has effectively entered the supersystem along with the object system. This entry may be as subtle as the dissolution of a previously unknown boundary.

If the observer, then, is inside the environing supersystem, its own behavior amplifies the uncertainty of the system as a whole even while it gains local information about the object system (Nicolis, 1986). This could be given an entropic interpretation, including the necessity for a greater gain in surrounding uncertainty, C_{max} (by way of a kind of wave front spreading) than the amount of local decrease in uncertainty, C_i, gained by the observation itself - as in Morowitz (1968). Here we have a generalized recursion - seeking information generates increasing potential ignorance, as (for an extreme example from biology instead of the usual electron) when some fish collectors used to detonate or poison whole reefs in order to obtain specimens of kinds they were interested in. More subtle effects like this are continually happening in the field and the lab.

IV. If You Decrease Observed Variety (D + U, or C_{xyz}) by Knowing Something, This Would Not Decrease the Amount of Uncertainty, C_{max}, to be Faced When Needing to Know More.

Every knowing is of a local configuration of the semiotic triangle (e. g., Geertz, 1983). If we seek new knowledge - especially new kinds of knowledge - the detailed configuration of the semiotic triangle changes, and we are back to square one in terms of how much ignorance we have to overcome. As knowledge from different perspectives accumulates in the observer's storage, H_o, the maximal total amount of knowledge possible (or H if C_{max} could be totally converted to H) must continue to increase because ignorance of new situations remains maximal (unchanging) with every new viewpoint. So, C_{max} remains the same while H_o continues to increase. Hence, H must continue to increase, irrespective of senescence in the observed system, the supersystem or the observer [senescence is describable, in fact, as the result of informational overloading (Salthe, in press)]. Why is this? It is a matter of logic; the relative amount of H we need in order to know C_{max} will not change because the *acts* of seeking knowledge generate ever new possibilities of, and necessities for, further knowledge. This in turn is simply because probing a system requires taking new perspectives on it at least occasionally, and because of the unknown repercussions of observation itself.

Also, with the observer now in the supersystem, any entity in it might logically be an observer too. And *its* attempts at knowing also have repercussions on the system. Information stored in these other observers, H_j, H_k, H_l, adds to the effective C_{max} of the system surrounding the object system as far as that system, and the observer, are concerned because it biases their (S_j, S_k, S_l's) behavior as that impinges on the object system in ways the observer is not privy to. The observer may get knowledge, but of a system that no longer exists as it was because its own activity, and also the unknown activities of other systems, has changed the global situation insofar as it is accessible to a local observer within the system.

I will call this situation the *principle of continuing confusion* with respect to determining the meanings of signs from the internalist perspective. (This would lead, incidentally, to the Popperian notion of the ultimate refutation of all theories). It results from the observer wading around in the same supersystem surrounding an observed system. Seen from within like this, surrounding potential uncertainty, C_{max}, must always remain at least as large as it was, and so, therefore, must an entrained system's actual behavioral variety, C_i, during its developmental maturity. This behavioral variety is what allows for the stability of the object system's states which the observer stores in its H_o and uses to identify the object system. So, much of the increase in H_i in the object system does not really decrease C_{max} as it is available to the observer as C_i - probably only some portion of it does, and that temporarily. But the continuing decrease in C_i relative to C_{max} brought on by familiarity with the reference system does allow the observer to continue to identify it in the different backgrounds generated by changing perspectives. That identity is built somewhat in the way we come to appreciate an object's overall "contour" (Buchler, 1955 - see Singer, 1983), which we construct from its "integrities" in different orders of observation.

There is a necessary mismatch here, with the environment always being somewhat more capable of generating new states than any finite system trying to match them, which system can never, then actually obtain the requisite variety needed for stability against environmental perturbations, even if it were to be able to continue in mature condition indefinitely. Conrad (1983), for example, notes that any system with strong cohesion must in fact exist in a less cohesive supersystem, so that its very being is linked to perturbations caused by supersystemic fluctuations.

An example from evolutionary biology illustrates these ideas. Letting adaptation be a metaphor for knowledge, 'clever' adaptations like mimicry, or niche construction (Odling-Smee, 1988) altering the environment in some way favorable to the kind of organism that does it, will not result in the long run in less intense selection pressures, allowing the population to grow unlimitedly. New environmental constraints will impose new selection pressures that will effectively control populations of the organism in question in one way or another. Every new "gimmick" invented by a kind of organism will be countered in this way. In this sense the environment in Darwinism is taken to be inexhaustibly complex - Darwin's "tangled bank". This seems to show that within Darwinism itself there is a cryptic acknowledgement of what I call the internalist viewpoint.

And what of something like organismic form? Its continuing direct deformation by environmental context is well-known, as is its instability in the face of new selection pressures. Unless a biological population is so small that no new environmental context is possible during observations, its phenotypic variability must remain inexhaustible, even despite canalization, habitat selection, niche construction *and* the increasing familiarity of the observer (which is always with something only somewhat relevant to new observations - limited as it is mostly to average values over relatively few individuals from the past, the loss of which will nevertheless have had repercussions on those unobserved ones remaining in nature today).

As for systematics, exploration of new characters will destabilize clustered taxonomies, while openness to new taxa destabilizes taxa associated by parsimony or related techniques. Here too we might recall the shifts in results that can accompany shifts in outgroup grounding. Brooks and Wiley's (1988) approach shows this will in that the total informational entropy in a cladogram must increase with the addition of new taxa.

The internalist position, then, implying a continuing increase in disorder in the system entails a strong uncertainty principle with respect to the knowledge an included observer can have of the supersystem, the attainment of which knowledge *causes* the continuing increase in total information, H. Much of this increase is stored information, H_i, in other, unobserved systems, S_i, which effectively adds to environmental C_{max}. It is clear that unknown (or known) stored information would be especially large in biological systems, but it is not restricted to them.

So, if we want C to increase in nature (i. e., if we want macroscopic information to act entropically, thereby allowing the construction of a more encompassing science of information and thermodynamics such as proposed by Brillouin, 1956), it must, in an internalist construction, be at the expense of continued observer ignorance and confusion - that is, at the expense of limited knowledge within the global system. This could, of course, be taken as a gain in opportunities as well. From an internalist position, all temporary local decreases in C_i result in increases in H by way of irreversible increases in H_i and in H_o which are not compensated by decreases in C_{max}:

$$H = C_{max} + H_i + H_o + \ldots H_n, \qquad C_{max} \sim k.$$

V. Under What Circumstances Might an Externally-Viewed System Necessarily Possess Entropic Macroscopic Information, H_i?

(1) If it were growing (assuming that no system, having grown, will decrease in size - but we must recall, and reinterpret, e. g., decreases in size during metamorphosis). It must continue to grow without fluctuations *or* we must see it for a long enough time to register enough fluctuations so that we could identify the real trend.

(2) If it were differentiating (assuming, again, that no dedifferentiation is possible - but here we must recall, and reinterpret, limb regeneration, e. g., in amphibians). It might be argued that no system could grow indefinitely without differentiating (e. g., Soodak and Iberall, 1978), in which case growth (either in size, energy throughput, ascendency, or mass-specific entropy production) would really be the primary factor. Whether differentiation can occur in the absence of growth is another question needing empirical work.

(3) If it were fully capable of registering all scars and traces of historical events (but this would require a growing scroll [i. e., (1, above)], otherwise new traces would eventually obliterate the oldest ones. However, there might come to be maintained a maximum amount of historical information in the absence of growth, with no further change after a while.

So, for an externally-viewed system to show an entropic increase in macroscopic information, either that object system must be continually growing or it must be fully capable of being scarred by any perturbation (and, of course, there must *be* perturbations).

It might be argued that any natural dissipative structure will grow during its immaturity and maturity and that they are amply capable of registering historical perturbations - increasingly so in their senescence. They, of course, do exist in fluctuating environments capable of perturbing them. So, just being a dissipative structure might be enough for an external observer to see a system as never losing macroscopic information. And, of course, natural dynamic systems are dissipative structures.

But there is a problem: it is *not* the case that one always sees only complete natural dissipative structures. A kind of mechanical system might be viewed that did not increase or even maintain its stored macroscopic information. Or only a portion of a dissipative structure might be viewed instead of a complete one. Again, there would no longer be any necessarily entropic aspect to its stored information. Or a temporary fluctuation causing a loss in stored information might be all that is observed.

So, only if one always observes a complete natural dissipative structure over a significant period of time will its stored information necessarily be expected to behave entropically.

One could still argue that for theoretical purposes all natural entities are dissipative structures and that we include their entire life histories in our theories of them, including also the average registration of perturbations caused by pseudorandom fluctuations built into the theoretical environment, so that it would not be necessary to have an internalist perspective in order to have necessarily entropic macroscopic information.

But that pulls the assertion too far out of the realm of empirical observations, not a situation congenial to scientists. What are the appropriate dissipative structures to observe, for example, in climatology? This raises the vexed problem of boundaries. We could not always be certain we were observing a fully-expressed dissipative structure. Hence, informational entropy *might* be observed to decrease in an externalist perspective. With this perspective we have to make an implausible assumption of ontic certainty.

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Bibliography and References

Ashby, W. R. 1956, *An Introduction to Cybernetics*. London: Chapman and Hall.

Brillouin, L. 1956. *Science and Information Theory*. New York: Academic Press.

Brooks, D. R., and E. O. Wiley. 1988. *Evolution as Entropy: Toward a Unified Theory of Biology*. Chicago: University of Chicago Press.

Buchler, J. 1966. *Metaphysics of Natural Complexes*. New York: Columbia University Press.

Collier, J. D. 1990. *Intrinsic Information, Information, Language, and Cognition*, ed. P. Hansen. Vancouver: University of British Columbia.

Conrad, M. 1983. *Adaptability: The Significance of Variability From Molecule to Ecosystem*. New York: Plenum.

Dretske, F. I. 1981. *Knowledge and the Flow of Information*. Cambridge, Mass.: MIT Press.

Geertz, C. 1983. *Local Knowledge: Further Essays in Interpretive Anthropology*. New York: Basic Books.

Latour, B. 1987. *Science in Action*. Cambridge, Mass.: Harvard University Press.

Morowitz, H. J. 1968. *Energy Flow in Biology: Biological Organization as a Problem in Thermal Physics*. New York: Academic Press.

Nicolis, J. S. 1986. *Dynamics of Hierarchical Systems: An Evolutionary Approach*. Berlin: Springer-Verlag.

Odling-Smee, F. J. 1988. Niche-constructing phenotypes. In *The Role of Behavior in Evolution*, ed. H.E. Plotkin. Cambridge, Mass.: MIT Press.

Odum, E. P. 1969. The strategy of ecosystem development. *Science* 164: 262-270.

Rosen, R. 1985. *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations*. Oxford: Pergamon.

Salthe, S. N. 1985. *Evolving Hierarchical Systems: Their Structure and Representation*. New York: Columbia University Press.

Salthe, S. N. 1989. Self-organization of/in hierarchically structured systems. *Syst. Res*. 6: 199-208.

Salthe, S. N. In press. *Complexity and Change in Biology: Development and Evolution*. Cambridge, Mass.: MIT Press.

Salthe, S. N. and M. L. Crump. 1977. A Darwinian interpretation of hindlimb variability in frog populations. *Evolution* 31: 737-689.

Singer, B. J. 1983. *Ordinal Naturalism: An Introduction to the Philosophy of Justus Buchler*. Lewisburg: Buchnell University Press.

Soodak, H. and A. Iberall. 1978. Homeokinetics: A Physical Science for Complex Systems. *Science* 201: 579-582.

Uexkull, J. Von. 1926. *Theoretical Biology*. New York: Harcourt, Brace.

Ulanowicz, R. E. 1986. *Growth and Development: Ecosystems Phenomenology*. New York: Springer-Verlag.

Wicken, J. S. 1989. Can the information contents of biological systems be quantified? *Syst. Res*. 6: 133-142.