Infodynamics, a Developmental Framework for Ecology/Economics

S.N Salthe

Introduction

Infodynamics (information dynamics) is a developmental perspective animating information theory by way of thermodynamics (Brooks and Wiley, 1988; Salthe, 1993, 2000; Ulanowicz, 1986, 1997; Weber et al, 1989). A fundamental postulate of infodynamics is that the formal isomorphism between Boltzmann's (1886) statistical interpretation of physical entropy as disorder, and Shannon's formulation of variety as informational entropy (Shannon and Weaver, 1949), signals a deep connection between information generation and entropy production. Because it is so general, the infodynamical perspective -- a non-equilibrial, process type framework -- can be applied to virtually any dynamical material system whatever.

This fact leads us to Figure 1, a generalization of empirical curves taken from biological organisms (see especially Zotin, 1972), ecosystems (see especially Aoki, 2001; Jørgensen, 2001), and several abiotic dissipative structures (Salthe, 1989, 1993). In the spirit of the strategy of confirmation (which must always precede the strategy of testing), I postulate that these curves hold for all natural dissipative structures, biotic and abiotic. I know of no data that fail to corroborate this as yet. There are two major facts about these curves: (a) they begin by increasing, and (b) they sooner or later begin to show a deceleration of the increase. We need to explain both of these phenomena, which together can be taken as Minot's Law (Minot, 1908, Needham, 1964).

The increasing function, when taken over growth in mass and/or growth in energy throughput (or other flows -- see Ulanowicz, 1986, 1997), seems perfectly general, and so calls for some general explanation. Why do dynamical things grow at all? And then, having started, why don't they just keep on growing, or even set off exponentially?

(a) The Burgeoning

Taking the first question first, today we have an answer from cosmology (Frautschi, 1982, 1988; Landsberg, 1984; Layzer, 1976, 1990), which is that things grow because of the universal expansion following the Big Bang. Dissipative structures grow for the same general reason that wave fronts spread and diffusion occurs -- because the universe is way out of equilibrium and getting even moreso all the time. Diffusion and wave front spreading serve the Second Law of thermodynamics by moving local situations toward equilibrium. Dissipative structures do the same, by degrading energy gradients during their growth and repair, and by doing it in such a way as to produce entropy to the extent that they derogate the gradients they feed on as rapidly as possible. That is, the faster a gradient is reduced, the less of its embodied energy can serve as exergy in the interests of its consumers and the more of it will head to the sink as heat (Carnot, 1824; Clausius, 1851). The general point is this: as the universal expansion accelerated beyond a certain rate, matter precipitated from the energy that failed to stay in equilibrium. In its own haphazard search for equilibrium, matter collided, forming clumps, taking the universe even further from equilibrium. The universal solution to this was to use some clumps to destroy others, and this ploy

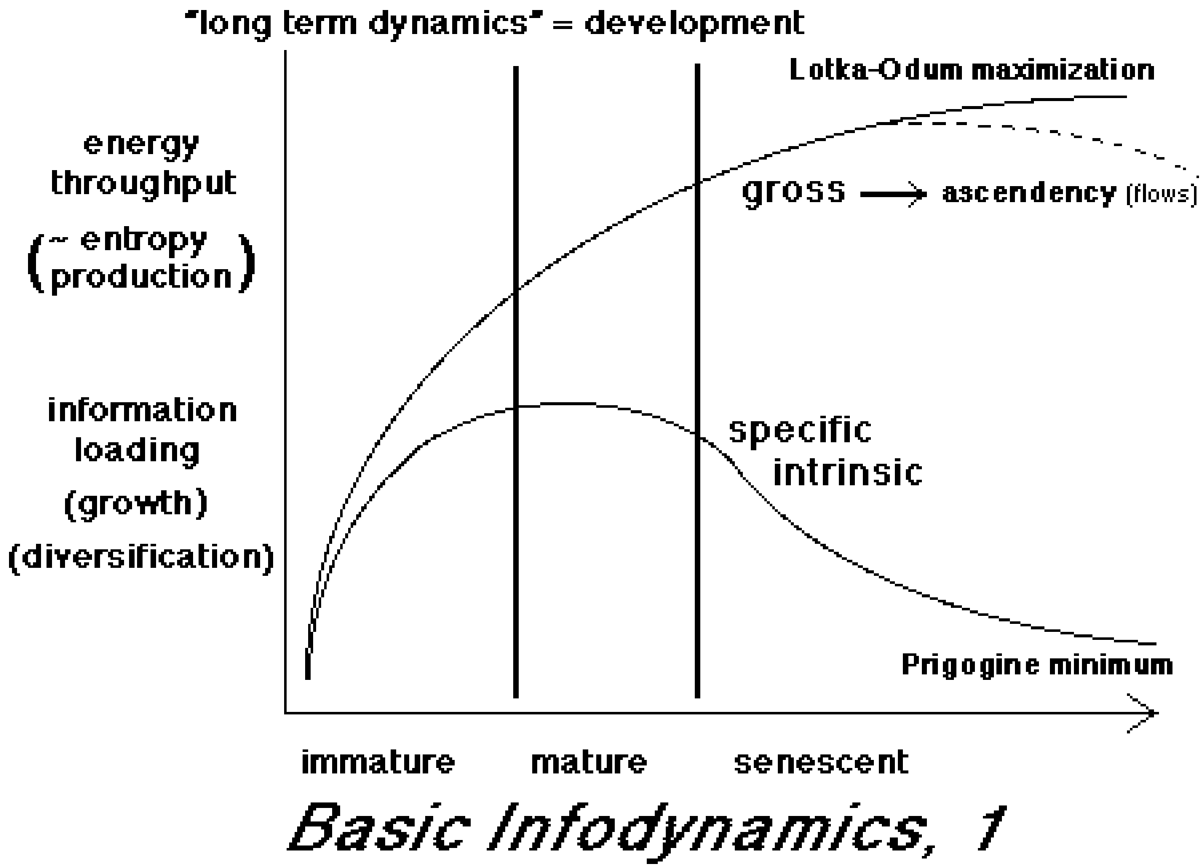

Figure 1

entrained the further evolution of complex structures, all the way to living ones. This tactic works for the universe because more of an energy gradient must always be lost as heat than can become reembodied in its consumers (this is the Second Law sense of dissipation).

So, then, systems grow because they are linked to energy gradients in such a way that some of the energy in those gradients gets transferred to themselves because some of its flow is harnessed by their formation. They grow in order to serve gradient degradation. That is, energy degradation is attracted in the direction of being harnessed by growing systems because that direction allows the fastest overall dissipation of the gradient (however well or poorly it actually serves their growth). This line of thought derives from Swenson (1989a, 1989b, 1997), Schneider and Kay (1994), and Matsuno and Swenson, (1999). Swenson formulated a maximum entropy production principle to the effect that the universe everywhere acts to maximize entropy production, given the local constraints. He and Schneider later amended this to: the universe acts to degrade all gradients as fast as possible. The entropy production view is a global, externalist interpretation, while the gradient destruction version is a local, internalist one (Matsuno and Swenson, 1999).

Systems grow relatively rapidly at first because they have not yet acquired any impediments to growth. Indeed, we may suppose that the rapid growth rates of immature systems represent the universal urgency of equilibration. But then we notice a decline in growth rates in older systems; there seems to be a diminishing returns law for growth. Diversification seems to be self-limiting. I have proposed (Salthe, 1993) that the limit is imposed by information overload, because it is being loaded into a finite locale. (I need to say here that I am defining information as any constraint on entropy production, and so any new twist in any configuration of any kind might in principle function as information. Such constraints are familiarly represented as constants in equations.) Information overload works out as (a) overconnectedness, which leads to functional underconnectedness (lags and delays) and (b) reinforcement of system propensities, which leads to loss of flexibility in responses to fluctuations. Both consequences have negative impact upon energy throughput, as well as upon the requisite variety of the system (Ashby, 1962; Conrad, 1982), which then erodes its adaptability, setting it up for recycling (see more below).

Figure 1 shows that Minot's law has had two well-known descendants -- the Lotka-Odum maximum power principle (Lotka, 1922; Odum and Pinkerton, 1955), and the Prigogine minimum entropy production principle (Prigogine, 1955). The interpretation given here (Salthe, 1993) is that, since the gross rate only levels off despite the intrinsic rates being pulled down, this allows us to hold onto the maximum power principle even in senescence -- in many systems anyway; some ecosystems do show declines, as indicated by the dotted line. Note that the Prigogine principle is being interpreted as a characteristic of senescence (see also Kay, 1984 and Jørgensen, 2001). The experiments that demonstrated it (Prigogine and Wiame, 1946) developed rapidly into this stable condition, which was then maintained by a continuing low level energy input.

<u>Immature systems</u> are characterized as: relatively simple (often relatively small), with a high and even increasing intrinsic energy throughput, growing and self-transforming. They are generated by larger scale systems at trivial energy cost, and need to hook up to significant energy sources in order to continue to develop.

<u>Senescent systems</u> are characterized as becoming increasingly complex even though they are not growing, and as becoming increasingly metastable as their intrinsic energy throughput drops, making it increasingly difficult to maintain themselves.

<u>Mature systems</u> are transitional between the immature and senescent stages. They are in most kinds of systems so transient as to be indiscernible. Indeed, if it were not for the fact that biological systems have gained unusual stability (via genetic information), this stage would not need to be interpolated between the immature and senescent ones. In biological systems this is the stage at which reproduction occurs. Mature systems can be characterized as relatively complex and not growing, maintaining themselves in their less-than-maximum complexity with a high gross energy throughput.

(b) The Decline

Figure 2 shows the informational entropy correlates of development, which are

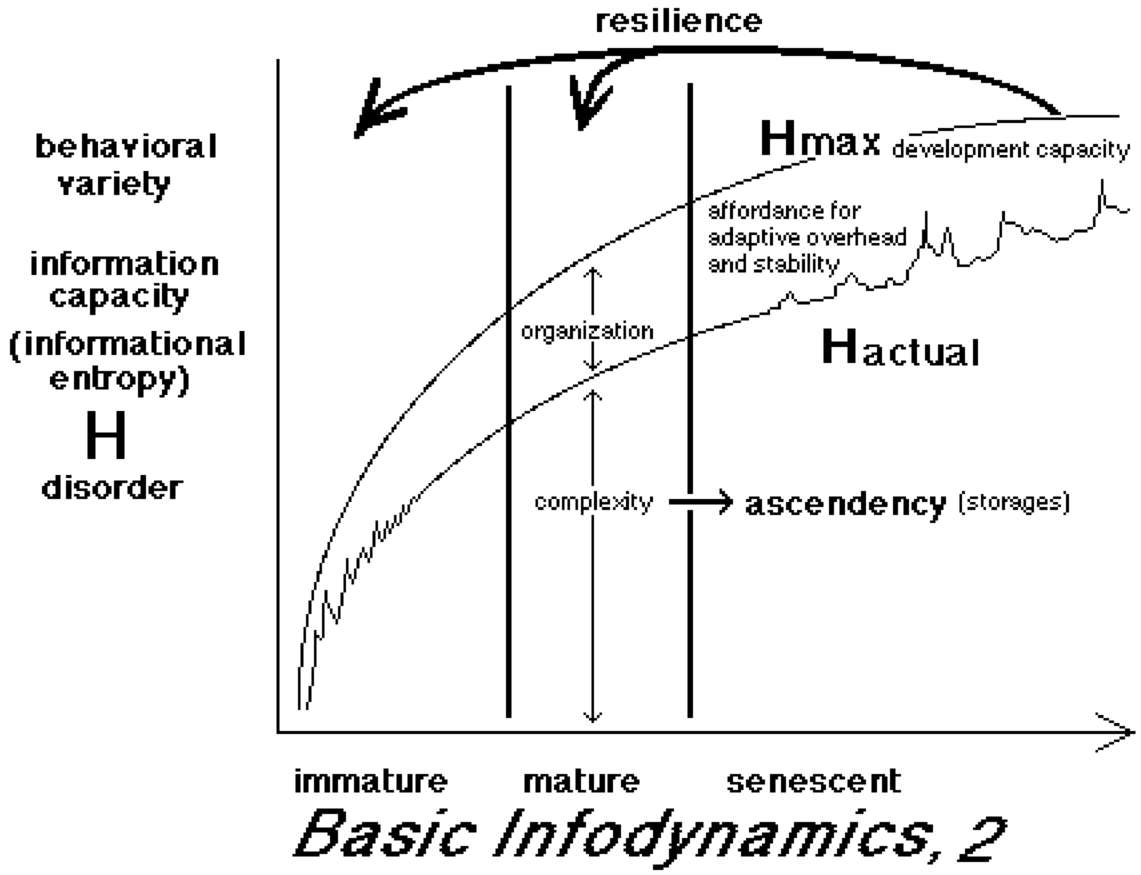

Figure 2

helpful in understanding the second fact about dissipative structures -- that system growth and diversification do not continue indefinitely, but always eventually decline.

Once again, this formulation goes back to the cosmologists (cited above), who wished to explain how it could be that form (order, information) could appear in the world despite the Second Law. The answer they found was that in a system expanding so fast that equilibrium was left behind, order could increase along with entropy. Order (organization in the figure) could be viewed as being just a consequence of a system not being able to reach equilibrium (H_{max} in Figure 2 -- for cosmologists, H would be replaced by S, physical entropy). The amount of order is evaluated as the distance between the curves. Furthermore, order could actually increase if the system continued to expand fast enough to cancel out the effects of equilibration. But its increase would have to be at the expense of yet more entropy requirement, so that the curves in Figure 2 must increasingly diverge as order -- the distance between the curves -- increases (the cosmological version of the figure would just show the two curves smoothly diverging -- see Brooks an Wiley, 1988). So the expanding universe is getting ever further from equilibrium as its burden of forms increases, making the Second Law ever more urgent along with continued complexity increase. For cosmology, complexity would be a label for the hierarchy of material forms, as in [galaxy [solar system [planet [some planetary macroscopic form]]]]. In general, complexity in the figure signifies organized complexity (as in the scale hierarchy), while the distance between the curves would represent disorganized complexity.

Figure 2 has been complexified beyond the original cosmological concept because it can now be proposed that these general relations apply to every individual dissipative structure inasmuch as these grow (which they do) either in size, numbers of components or in throughput. In this context, where we know much more about the details of system behavior, it is more fruitful to replace physical entropy with informational entropy. This can be done because Boltzmann's interpretation of physical entropy as disorder can be mapped to Shannon's interpretation of variety as an entropy. Physical entropy is rooted in microscopic diffusion processes, where disorder increases as randomly moving particles access a greater variety of coordinates. If occupied coordinates could be used as digital tokens in some communication, we have arrived at the Shannon concept, which may be taken as a macroscopic formulation, or even generalization, of the same basic idea. It has been argued that while the formal isomorphism holds, informational entropy need not increase if it changes, and so could not be a bonafide entropy. This view is falsified for any expanding or growing system, and I have argued (Salthe, 1990) that informational entropy must grow as well (if it changes) when systems are modeled as from within.

Next we need to briefly consider the idea of an ecosystem being taken as an individual. I have argued in detail for this view in my book on scalar hierarchies (Salthe, 1985), and so will not dwell on this vexed topic here. The major point was that, if our observations had the same scale relations to an organism as they have with respect to most ecosystems of biome size, we would not suppose an organism to be an individual either. Furthermore there is no argument I know of that establishes individuality as an all or nothing category. In 1989 and 1993 I added to my argument for ecosystem individuality the fact that, when viewed from the very general perspective of infodynamics, there is sufficient evidence of the kind shown in Figure 1 (see also Aoki, 2001; Jørgensen, 2001) to support this viewpoint. This is the perspective -- deriving conceptually from E.P. Odum's 1969 paper in science (see also Schneider, 1988) -- that I will bring to the data being considered below. (Some moral considerations of this view were considered by Salthe and Salthe, 1989.)

Turning again to Figure 2, I note that information capacity would increase merely by way of system growth (increase in locales, in numbers and kinds of components and/or processes, and in possible global states). Growth generates informational constraints (symmetries or degrees of freedom), some of which will become fixed during development as a system differentiates. These will generate an array of possible states that the system could occupy or display. And dynamical systems are active as well, exhibiting behavior globally and locally, both of which increase (other things being equal) as a system acquires more structure. Consider the appropriateness of using the label 'disorder' for macroscopic systems. In a more diverse ecosystem, an individual will face greater uncertainty as to its next encounter than in a more depauperate one. Order signifying regularity, a species-rich system's behavior would seem relatively disorderly, either for an internal player or for a naive external observer.

Why, then, do dissipative structures grow in one way or another? The fundamental reason, noted above, is that they exist within an expanding, non-equilibrial universe. The final cause here is the need to produce entropy, which all growth leads to via derogating energy gradients in its service. But each kind of system has its own material and efficient causes -- its connections to those gradients -- which make up the basis of detailed discourse about each of them. What we can dwell upon here in more general terms are the formal causes, which we suppose apply to all of them.

Given some kind of connection to a gradient, and some configuration susceptible to efficient pushes (a location on the H_{actual} curve determined by the variety of its behavioral repertoire), a dissipative system would be attracted by an array of possible resolutions concerning its next state -- somewhere between its own location and the one above it on the H_{max} curve. This upper curve -- that of the system reaching equilibrium, where it could access any potential behavior and state from any other -- would represent the effective demise of the system, where it would have no more organized complexity. Its current embodiment alone prevents such a dash (or explosion) to instant extinction, restricting its reach to somewhere within its “adjacent possible” (Kauffman, 2000) range. In other words, whatever slight material embodiment an immature system might have provides friction against its changes, which, then are restricted to states that would produce more entropy than it currently can do, rather than totally dissipating its own embodied energy. Swenson (1989a, 1997) would say that a system changes in the direction of maximizing its entropy production; Schneider and Kay (1994) would say that it positions itself so as to maximize the rate of dissipation of its energy sources; Kauffman (2000) would say that it changes in such a way as to increase the size of its work surface; Jørgensen (1992, 2001) would say that it chooses a path that will maximize the amount of energy stored or embodied within itself. All of these have a large intersection that some would call a Fourth Law of thermodynamics. The upshot is that the system moves up on the H_{actual} curve, accessing a somewhat greater range of behavioral variety [and so imposing a greater entropy cost upon any observer (or enemy) engaging it as well].

Ulanowicz (1986) has provided an autocatalytic cycle model for increased complexification of a system of flows that works more closely into the kinetics (as opposed to thermodynamics) of such a process. He constructs a measure -- ascendency - that combines flow rate increases (growth) with increases in the mutual information contained in the internal connections of the system (differentiation, which increases organization) as an overall quantitative measure of development.

Note that in Figure 2 the H_{actual} curve shows considerable uncertainty as to its location in the immature range, which gradually damps out as the system increases its organization. The control by an immature system over its range of behavior is limited on account of its relatively little amount of organization.

Thus far we have the understanding that the H_{actual} curve generates the H_{max} curve, by, we might say, permutations of a system’s controllable or functional behavior, which its embodiment largely restricts to some smaller search space (Brooks and Wiley, 1988) wherein its developmental trajectory would be preserved (that is, as a Darwinian would say, if it survives at all). Simultaneously, we can see that the H_{actual} curve is a material restriction on the H_{max} curve, which is set ultimately by the kind of system in question (a ball bearing would have a much smaller absolute H_{max} than would, say, a nut -- Collier, 1990). That is, H_{actual} is in a sense carved out of H_{max} (Ulanowicz, 1986, 1997). The space between them in this sense represents a reserve of unusual behavioral repertoire to be used in adapting to unusual fluctuations in the system's environment. Such responses are always dangerous because the system moves closer to the H_{max} curve when utilizing this reserve. Put another way (Ulanowicz, 1986, 1997), this range between the curves represents the "overhead" a system must pay as tribute for its continuing existence.

Considering now the problem of why, in individual dissipative structures, the developmental process eventually terminates, we can recall that in connection with Figure 1 I have proposed that this is a result of information overload. We can pursue this here again. The key feature in Figure 2 is the increasing uncertainty of the position of the behavioral uncertainty curve (H_{actual}) in the senescent stage. This signifies that the senescent system is becoming increasingly metastable, being perturbed more often because of its relative rigidity and sluggishness of response, and having as well to reach more deeply into its reserve behavior in order to recover from perturbations. As these fluctuations increase, the H_{actual} curve gradually closes upon H_{max}. Put in Ulanowicz's (1997, pp.86-92) terms, the system is using up its developmental capacity, which, as scaled by system throughput, may actually decline, as shown in Figure 1. Eventually the H_{actual} fluctuations get so close to H_{max} that the system collapses. In highly organized systems like organisms, existence is terminated (note: after reproduction) and its materials get recycled. In more loosely organized systems, like ecosystems, the system collapses back to some more immature condition, as in the figure 8 formulation of Holling (1978, 1986). This system resilience is the ecosystem's tactic whereby it accomplishes its escape from senescence, and is comparable to the organism's tactic of reproduction. In much less organized abiotic systems, like tornadoes, system growth has just dispersed it so far from its focus on its energy gradient that it just falls apart, being dismembered, as it were, into other, more powerful dissipative structures.

Selected Applications

etc.

REFERENCES

Aoki, I., 2001. Entropy and the exergy principles in living systems. Pages 167-190 in Jørgensen, S.E., editor. Thermodynamics and Ecological Modelling. Lewis Pubs., Boca Raton, FL.

Ashby, C.R., 1962. Requisite variety, and its implications for the control of complex systems. General Systems Yearbook 9: 99-105.

Boltzmann, L.,1886/1974. The second law of thermodynamics. In McGuinness, B., editor. Ludwig Boltzmann, Theoretical Physics and Philosophical Problems. D. Reidel, Dordrecht.

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

Carnot, S., 1824 / 1960. Reflections on the motive power of fire, and on machines fitted to develop that power. In Mendoza, E., editor, Reflections on the Motive Power of Fire and Other Papers. New York: Dover Pubs.

Clausius, R., 1851. On the moving force of heat and the laws regarding the nature of heat itself which are deducible therefrom. Philosophical Magazine (Series 4) 2: 1-12.

Collier, J.D. (1990) “Intrinsic information.” In Information, Language, And Cognition. P.P.Hanson (ed.) New York: Oxford University Press.

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

Frautschi, S., 1982. Entropy in an expanding universe. Science 217: 593-599.

Frautschi, S. (1988) “Entropy in an expanding universe.” in B.H. Weber, D.J. Depew and J.D. Smith, eds. Entropy, Information and Evolution. Cambridge, MA: MIT Press.

Holling, C.S.,1973. Resilience and stability of ecological systems. Annual Review of Systematics and Ecology 4: 1-23.

Holling, C.S., 1986. The resilience of terrestrial ecosysems. In W.C. Clark and R.E. Munn (eds.) Sustainable Development of the Biosphere. Cambridge University Press.

Jørgensen, S.E., 1992. Development of models able to account for changes in species composition. Ecological Modelling 62: 195-208.

Jørgensen, S.E., 2001. A tentative fourth law of thermodynamics. Pages 303-348 in Jørgensen, S.E., editor, Thermodynamics and Ecological Modelling. Lewis Pubs., Boca Raton, FL.

Kauffman, S.A., 2000. Investigations. Oxford University Press, New York.

Kay, J.J., 1984. Self-organization in Living Systems. Ph.D. Thesis, University of Waterloo.

Landsberg, P.T., 1984. Can entropy and “order” increase together? Physics Letters 102 A: 171-173.

Layzer, D., 1976. The arrow of time. Scientific American 233: 56-69.

Layzer, D. (1990) Cosmogenesis. New York: Oxford University Press.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proceedings of the National Academy of Science. 8: 147-151.

Matsuno, K. and Swenson, R., 1999. Thermodynamics in the present progressive mode and its role in the context of the origin of life. BioSystems 51: 53-61.

Minot, C.S.,1908. The Problem of Age, Growth and Death. Murray. London.

Needham, A.E., 1964. The Growth Process of Animals. London, Pitman and Sons.

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

Odum, H.T. and Pinkerton, R.C., 1955. Time’s speed regulator, the optimum efficiency for maximum output in physical and biological systems. American Scientist 43: 331-343.

Prigogine, I., 1955. Introduction to Thermodynamics of Irreversible Processes. New York: Interscience Publishers.

Prigogine, I. and J.M. Wiame (1946) “Biologie et thermodynamique des phenomènes irréversible.” Experientia 2, 451-453.

Salthe, S.N., 1989. Self-organization of / in hierarchically structured systems. Systems Research 6: 199-208.

Salthe, S.N., 1990. Sketch of a logical demonstration that the global information capacity of a macroscopic system must behave entropically when viewed internally. Journal of Ideas 1: 51-56.

Salthe, S.N., 1993, a. Development and Evolution: Complexity and Change in Biology. MIT Press, Cambridge, MA.

Salthe, S.N., 2000. Ecology and infodynamics. Journal of Social and Evolutionary Systems 21: 223-231.

Salthe, S.N. and B.M. Salthe, 1989. Ecosystem moral considerability: a reply to Cahen. Environmental Ethics 11: 355-361.

Schneider, E.D., 1988. Thermodynamics, ecological succession and natural selection: a common thread. Pages 107-138 in Weber, B.H., Depew, D.J., and Smith, J.D., editors, Entropy, Information and Evolution: New Perspectives on Physical and Biological Evolution. MIT Press, Cambridge, MA.

Schneider, E.D. and Kay, J.J., 1994. Life as a manifestation of the Second Law of thermodynamics. Mathematical and Computer Modelling 19: 25-48.

Shannon, C.E. and W. Weaver, 1949. The mathematical Theory of Communication. University of Illinois Press.

Swenson, R., 1989, a. Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution. Systems Research 6: 187-198.

Swenson, R., 1989, b. The earth as an incommensurate field at the geo-cosmic interface: fundamentals to a theory of emergent evolution. Proceedings of the First Congress on Geo-cosmic Relations. PUDOC Science Publishers, Amsterdam.

Swenson, R.,1997. Autocatakinetics, evolution, and the law of maximum entropy production. Advances in Human Ecology 6: 1-47.

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

Ulanowicz, R.E., 1997. Ecology, The Ascendent Perspective. Columbia University Press, New York.

Weber, B.H., D.J. Depew, C. Dyke, S.N. Salthe, E.D. Schneider, R.E, Ulanowicz and J.S. Wicken (1989) “Evolution in thermodynamic perspective: an ecological approach.” Biology and Philosophy 4, 373-405.

Zotin, A.I., 1972. Thermodynamic Aspects of Developmental Biology. Basel: S.Karger.