Published in Sven Erik Jørgensen, Felix Müller (eds), Handbook of Ecosystem Theories and Management, CRC Press - Lewis Publishers. pp 135-160, 2000

Ecosystems as Self-organizing Holarchic Open Systems : Narratives and the Second Law of Thermodynamics

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Introduction

A new understanding of complex systems, and in particular ecosystems, is emerging. (Kay (1984), Holling (1986), Kay and Schneider (1994), Kay (1997), Kay, Regier, Boyle and Francis (1999).) The hierarchical nature of these systems requires that they be studied from different types of perspectives and at different scales of examination. There is no correct perspective. Rather a diversity of perspectives is required for understanding. Ecosystems are self-organizing. This means that their dynamics are largely a function of positive and negative feedback loops. This precludes linear causal mechanical explanations of ecosystem dynamics. In addition emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena. Such systems organize about attractors. Even when the environmental situation changes, the system's feedback loops tend to maintain its current state. However, when ecosystem change does occur, it tends to be very rapid and even catastrophic. When precisely the change will occur, and what state the system will change to, are often not predictable. Often, in a given situation, there are several possible ecological states (attractors), that are equivalent. Which state the ecosystem currently occupies is a function of its history. There is not a "correct" preferred state for the ecosystem.

Given this understanding of the self-organizing phenomena exhibited by ecological systems, it has been argued that conventional science approaches of modelling and forecasting are often inappropriate, as are prevailing explanations in terms of linear causality and stochastic properties. (Holling (1986), Kay and Schneider (1994),.Schneider and Kay, 1994a, Kay (1997).) Elsewhere (Kay, Regier, Boyle and Francis (1999)) we have discussed an approach for dealing with these realities of ecosystems in the context of informing resource and land use decision makers and planners. This approach is different from the "traditional" ecosystem approaches which are interdisciplinary in nature but focus on forecasting and a single type of entity such as a watershed or forest community. Rather this approach is in the mode of post normal science and is grounded in complex systems theory. At its heart is the portrayal of ecological systems as Self-organizing Holarchic Open systems (SOHO systems).

In this approach scientists take on the role of narrators. The task of the narrator is to scope out the array of attractors available to the SOHO system, the potential flips between them, and the underlying morphogenetic causal structure of the organization in the domain of the attractors. This is reported as a narrative of possible futures for the SOHO. The role of the scientists is then to inform the decision makers, through the narratives, about the ecological options, the tradeoffs and uncertainties involved, and various strategies for influencing what happens on a landscape.

At the core of these narrative descriptions of ecosystems as self-organizing holarchic open systems is the conceptualization of these systems as dissipative systems. Dissipative system descriptions are in terms of how the system makes use of available energy (and other resources) to self-organize. Such a description is inherently thermodynamic in nature and as such the second law of thermodynamics plays a central role. This paper explores the role of the second law of thermodynamics in building narratives of ecosystem self-organization. This paper begins with an exploration of the second law and its implications for self-organization. This serves as the basis for a discussion of the characterization of ecosystem attractors in terms of the their sources of exergy. This in turn provides the basis for formulating narratives and in particular a conceptual model of ecosystems as self-organizing holarchic open systems.

Thermodynamics and Self-organization.

The dilemma of the random heat death of the universe

At the turn of the century, thermodynamics, as portrayed by Boltzmann, viewed nature as decaying toward a certain death of random disorder in accordance with the second law of thermodynamics. This equilibrium seeking, pessimistic view of the evolution of natural systems is in contrast with the phenomenology of many natural systems. Much of the world is inhabited by coherent systems whose time dependent behavior is a progression away from disorder and equilibrium, into highly organized structures that exist some distance from equilibrium. Boltzmann (1886) recognized the apparent contradiction between the heat death of the universe, and the existence of life in which systems grow, complexify, and evolve. He turned to thermodynamics in an attempt to resolve this issue and suggested that the sun's energy gradient drives the living process and suggested a Darwinian like competition for entropy in living systems.

Erwin Schrödinger addressed this same dilemma in his seminal book *What is Life?* (1944). In *What is Life?* Schrödinger noted that life was comprised of two fundamental processes; one "order from order" and the other "order from disorder". He observed that the gene, with it's soon to be discovered DNA, controlled a process that generated "order from order" in a species, that is the progeny inherited the traits of the parent. This observation, combined with the work of Watson and Crick, provided biology with a research framework for some of the most important findings of the last fifty years.

However, Schrödinger's "order from disorder" observation is equally important but largely ignored (Schneider and Kay, 1995) "Order from disorder" is about the relationship between biology and the fundamental theorems of thermodynamics. He noted that at first glance living systems seem to defy the second law of thermodynamics, as the second law insists that, within closed systems, entropy should be maximized and disorder should reign. Living systems, however, are the antithesis of such disorder. They continually evolve new order from disorder. For example, plants are highly ordered structures, which are synthesized from disordered atoms and molecules found in atmospheric gases and soils. Schrödinger solved this dilemma by turning to nonequilibrium thermodynamics, that is, he recognized that living systems exist in a world of energy and material fluxes. An organism stays alive in its highly organized state by taking energy from outside itself, from a larger encompassing system, and processing it to produce, within itself, a lower entropy, more organized state. At the same time it exports entropy to the larger encompassing system, thus contributing to the larger system's disorder. Schrödinger recognized that living systems are far from equilibrium systems that maintains their local organization, through entropy export, at the expense of the larger system they are part of. He proposed that the investigation of living systems from a nonequilibrium perspective would help reconcile biological self-organization and thermodynamics.

Schneider and Kay (1994a,b) have taken on the research task proposed by Schrödinger and expanded on his thermodynamic view of life. The second law of thermodynamics is not an impediment to the understanding of life but rather is necessary for a complete description of living processes. The second law underlies and determines the direction of many of the processes observed in the development of living systems. The second law mandates behaviour in systems that are a necessary (but not sufficient basis) for life itself. This reexamination of thermodynamics shows that biology is not an exception to physics, we have simply misunderstood the rules of physics.

A fresh look at thermodynamics

Comparatively speaking, thermodynamics is a young science and has been shown to apply to all work and energy systems including the classic temperature-volume-pressure systems, chemical kinetic systems, electromagnetic and quantum systems. The first law of thermodynamics arose from efforts, in the early 1800s, to understand the relation between heat and work. The first law states that energy cannot be created or destroyed and that the total energy within a closed system remains unchanged. This laws deals strictly with the quantity of energy. The second law of thermodynamics requires that if there are any processes underway in a system, the quality of the energy in that system will degrade. The second law is usually stated, as it was in 1860, in terms of the quantitative measure of irreversibility, entropy. For any process the change in entropy is greater than zero, or any real process can only proceed in a direction which results in an entropy increase. This statement of the second law is in terms of what systems cannot do vis a vis entropy change.

In 1908, Carathéodory moved thermodynamics a step forward. He developed a proof that showed that the law of "entropy increase" is not the general statement of the second law Rather the more fundamental observation of the second law is the that all natural phenomena are irreversible. The more encompassing and fundamental statement of the second law of thermodynamics, made by Carathéodory, is that "In the neighborhood of any given state of a closed system, there exists states which are inaccessible along any reversible or irreversible adiabatic paths". This implies that irreversible processes constrain systems so they cannot attain certain states previously accessible. It tells us that certain system states cannot happen spontaneously.

More recently Hatsopoulos & Keenan (1965) and Kestin (1966) have put forward a principle which subsumes Carathéodory's work as well as the 0th, 1st and 2nd Laws: "When an isolated system performs a process after the removal of a series of internal constraints, it will reach a unique state of equilibrium: this state of equilibrium is independent of the order in which the constraints are removed" (Kestin, 1966). This is called the Law of Stable Equilibrium by Hatsopoulos & Keenan and the Unified Principle of Thermodynamics by Kestin.

The importance of the work of Hatsopoulos & Keenan and Kestin is that their statement dictates a direction and an end state for all real processes, equilibrium. All previous formulations of the second law tells us what systems cannot do. This statement tells us what systems will do. They will spontaneously move to equilibrium. Furthermore it is a statement which is in terms of directly measurable quantities, gradients in the system, such as temperature and pressure. At equilibrium differences in these quantities, over space, that is their spatial gradients, are zero. An example of this phenomena are two flasks, connected with a closed stopcock. One flask holds 10,000 molecules of a gas, the other virtually none. Upon removing the constraint (opening the stopcock) the system will spontaneously move to it's equilibrium state of 5,000 molecules in each flask, with no gradient between the flasks. This principle hold for a broad class of thermodynamic systems from chemical kinetic reactions to a hot cup of tea cooling to room temperature.

There are two points to this summary, thermodynamics is a discipline which should be thought of as part of modern physics, contemporary with quantum and relativity theorem, albeit a poor cousin in terms of attention and development. Most of thermodynamic thinking has been about equilibrium or near equilibrium situations and an integrated theory of these phenomena is less than thirty-five years old, very young indeed in terms of scientific maturity.

Nonequilibrium open systems

The same cannot be said for the phenomena of systems that are open to energy and or material flows and reside at quasi stable states some distance from equilibrium. An integrated theory for these situations does not exist. Yet it is understanding precisely these situations that Schrödinger identified as pivotal to the reconciliation of biological self-organization and thermodynamics.

These nonequilibrium situations have been investigated by Prigogine (1955) and his collaborators (Nicolis and Prigogine, 1977, 1989). These systems are open and are moved away from equilibrium by the fluxes of material and energy across their boundary and maintain their form or structure by continuous dissipation of energy and, thus, are known as dissipative structures. This research group, along with many others, showed that nonequilibrium systems, through their exchange of matter and/or energy with the outside world, can maintain themselves for a period of time away from thermodynamic equilibrium in locally produced stable steady-states. This is done at the cost of increasing the entropy of the larger "global" system in which the dissipative structure is imbedded; thus following the second law, that overall entropy, in the global sense, must increase. Non living organized systems (like convection cells, tornadoes and lasers) and living systems (from cells to ecosystems) are dependent on outside energy fluxes to maintain their organization in a locally reduced entropy state. The entropy relationships in dissipative systems were put forward by Denbeigh (1951) and Prigogine (1955).

Unfortunately, Prigogineian descriptions of dissipative structures are formally limited to the neighbourhood of equilibrium. This is because this form of analysis depends on a linear expansion of the entropy function about equilibrium. This is a severe restriction on the application of Prigogineian theory and in particular precludes its formal application to living systems.

To deal with the thermodynamics of nonequilibrium systems, we propose the following corollary that follows from the proof by Kestin of the Unified Principle of Thermodynamics. His proof shows that a system's equilibrium state is a unique stable attractor in the Lyapunov sense. A consequence of Lyapunov stability theory is that there will be a domain of any attractor within which a system will resist being moved from the attractor. Bearing in mind that the equilibrium attractor is unique (in state space), a thermodynamic system will necessarily resist being removed from the equilibrium state (the attractor). The degree to which a system has been moved from equilibrium is measured by the gradients imposed on the system. The thermodynamic principle which governs the behaviour of systems as they are moved away from equilibrium is:

As systems are moved away from equilibrium, they will utilize all available avenues to counter the applied gradients. As systems are moved further from equilibrium, attractors, for (thermodynamic) nonequilibrium organizational steady states, will emerge that allow the system to be organized in a way that reduces or degrades the applied gradients. Hence, as the applied gradients increase, so does the system's ability to oppose further movement from equilibrium. If environmental conditions permit, self organization processes are to be expected. The building of organizational structure and associated processes is such that it degrades the imposed gradient more effectively than if the dynamic and kinetic pathways for those structures were not available.

When moved away from their local (spatially) equilibrium state systems shift their state in a way which opposes the applied gradients and moves the system back towards its local equilibrium attractor. The stronger the applied gradient, the greater the effect of the equilibrium attractor on the system. In simple terms, systems have the propensity to resist being moved from equilibrium and a propensity to return to the equilibrium state when moved from it. We refer to this principle as the "restated second law of thermodynamics".

Le Chatelier's principle is an example of this equilibrium seeking principle. LeChatelier's principle is about the effect of a change in external conditions on the equilibrium of a chemical reaction. "If the external conditions of a thermodynamic system are altered, the equilibrium of the system will tend to move in such a direction as to oppose the change in the external conditions", (Fermi, 1956). Fermi noted that if a chemical reaction were exothermal, i.e. (A+B=C+D+heat) an increase in temperature will shift the chemical equilibrium to the left hand side. Since the reaction from left to right is exothermal, the displacement of the equilibrium towards the left results in the absorption of heat and opposes the rise in temperature. Similarly a change in pressure (at a constant temperature) results in a shift in the chemical equilibrium of reactions which opposes the pressure change. This equilibrium seeking nature in chemical systems is a shared aspect of all dissipative systems.

Exergy degradation

Further discussion requires the introduction of the notion of quality of energy, exergy. Over the past thirty years and particularly in the last decade, *exergy* has emerged as a central concept in the discussion of thermodynamics. (Bejan (1997), Szargut, Morris, Steward, (1988), Wall, G. (1986)). Energy varies in its quality or capacity to do useful work. During any chemical or physical process the quality or capacity of energy to perform work is irretrievably lost. Exergy is a measure of the maximum capacity of the energy content of a system to perform useful work as it proceeds to equilibrium with its surroundings and reflects all the free energies associated with the system. (Brzustowski and Golem, 1978). For example, water at the top of a high cliff is a high quality energy source (high exergy) because its potential energy can be used to perform work. We can use the falling water to turn a turbine and produce high quality energy in the form of electricity. But if the high quality energy in the falling water is not run through a turbine and falls freely to the rocks below, it turns into low quality dispersed heat energy. The exergy content of the water at the top is high, but the same water, at the bottom, with the same energy content, has much less exergy. Exergy is a measure of the quality of energy.

In terms of exergy, the classical second law of thermodynamics can be stated as: during any macroscopic thermodynamic process, the quality or capacity of energy to perform work is irretrievably lost. Energy looses exergy during any real process. A traditional first law energy analysis does not account for differences in energy qualities. A first law efficiency only compares the total amount of energy put into a system to the total amount received out of the system. This realization has, in the discipline of energy system analysis and engineering thermodynamics, as can be seen from examining any introductory text book in the field that postdates 1993 (Moran and Shapiro, 1993), resulted in the recognition that both first law (energy, quantity) and second law (exergy, quality) analysis are necessary for the understanding and development of efficient and effective energy utilization systems. (Bejan (1997), Gaggiolo,. (1980, 1983), Hevert, H.; Hevert, S. (1980), Moran, M.J. (1982), Szargut, Morris, Steward, (1988))

Exergy is a function of the gradients between a system and its environment. It is a summation of the free energies in the situation. It measures the distance between a system and its environment. In effect it measures how far a system is from thermodynamic equilibrium with its environment. Exergy is not a useful concept for discussing equilibrium situations, the domain of classical thermodynamics, as, by definition, it value is zero in such situations. However it is a very powerful tool for nonequilibrium situations. The larger the value of the exergy, the more out of equilibrium the situation is.

The restated second law can be formulated in terms of exergy: A system exposed to a flow of exergy from outside will be displaced from equilibrium. The response of the system will be to organize itself so as to degrade the exergy as thoroughly as circumstances permit, thus limiting the degree to which the system is moved from thermodynamic equilibrium. Furthermore, the further the system is moved from equilibrium, the larger the number of organizational (i.e. dissipative) opportunities which will become accessible to it and consequently, the more effective it will become at exergy degradation. This is the exergy degradation principle for nonequilibrium thermodynamic situations.

Dissipative Structures as Gradient Dissipators and exergy degraders

This section examines the behavior of dissipative structures in light of the exergy degradation principle. Prigogine and others have shown that dissipative structures self-organize through fluctuations and instabilities which lead to bifurcations and new stable system states. Glansdorff and Prigogine (1971) have shown that these thermodynamic systems can be represented by coupled nonlinear relationship i.e. autocatalytic positive feedback cycles, many of which lead to stable macroscopic structures which exist away from the equilibrium state. Convection cells, hurricanes, autocatalytic chemical reactions, and living systems are all examples of nonequilibrium dissipative structures which exhibit coherent behavior.

The formation of Bénard cells is the classic example of emergent coherent organization in response to an external energy input. They occur when a heated fluid makes the transition from conduction to convection as the primary form of heat transfer. In Bénard cell experiments, the lower surface of an experimental fluid filled chamber is heated, the upper surface is kept at a cooler temperature, and thus a temperature gradient is induced across the fluid. The initial heat flow through the fluid is by conduction. Energy transfer is by molecule to molecule interaction. When the heat flux reaches a critical value of the temperature gradient, the system becomes unstable and the molecular action of the fluid becomes coherent and connective overturning emerges. This coherent convective overturn results in hexagonal patterns in the fluids This coherent kinetic structuring increases the rate of heat transfer and exergy degradation by the fluid.

This transition between non-coherent, molecule to molecule, heat transfer, to coherent convection and structure results in excess of 10^{22} molecules acting together in an organized manner. This seemingly improbable occurrence is the direct result of the applied temperature gradient, the dynamics of the system at hand, and is the system's response to attempts to move it away from equilibrium. At higher temperature gradients, there appear to be a number of further transitions at which the hexagonal cells re-organize themselves so that the cost of increasing the temperature gradient escalates even more quickly. Ultimately the system becomes chaotic and dissipation is maximized in this regime. Organization in this system resides in a window between linear near equilibrium processes and the chaos of turbulent flow.

Detailed analysis of Bénard cell experiments in terms of exergy degradation and entropy production have been reported on earlier. (Schneider and Kay, 1994b) Figure 1 shows a graph of exergy degradation rate versus Rayleigh number. (Rayleigh number is linearly proportional to the temperature gradient across the fluid.) As the system is moved further from equilibrium by the increased temperature gradient, the amount of exergy degraded by the system increases. The rate of increase of exergy degradation goes up sharply with the emergence of the Bénard cells. Furthermore for every incremental increase in temperature gradient there is an increase in the incremental increase in the exergy degradation rate. (i.e. the exergy destruction rate increases non-linearly with temperature difference across the fluid.)

Exergy Destruction Rate (Ø) vs Gradient (Ra)

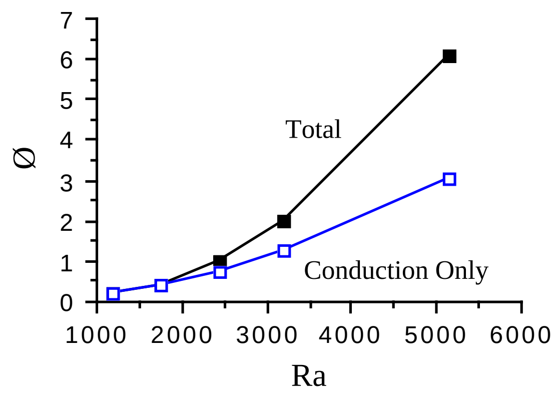


FIGURE 1: EXERGY DEGRADATION IN Bénard Cells

This graph shows exergy destruction during heat transfer across a fluid. In the Bénard cell apparatus the working fluid is heated from below and the top of the apparatus acts as a cold sink. Initially all dissipation through the fluid occurs via conduction and molecule to molecule interaction. When the gradient reaches a critical level (Rayleigh number 1760) the transition to organized convection (Bénard Cells) occurs.

The graph shows the exergy (Kcal/hour) which must be provided from an external source in order to maintain the gradient versus Rayleigh number (the gradient). The bottom curve is the exergy destruction rate without Bénard Cells and the top curve is the exergy destruction rate with the formation of Bénard Cells. The point is that the emergence of the ordered structure (Bénard Cells) degrades more exergy. As the gradient increases a greater amount of work must be done to incrementally increase the gradient. The further the system is moved away from its equilibrium state the more exergy is destroyed, the system produces more entropy, and more work is required to maintain it in it's nonequilibrium state. It becomes more difficult to maintain the gradient as the system becomes more organized.

The point of the Bénard cell example is that in simple physical systems, new structures and processes can spontaneously emerge which better resist the application of an external gradient, in the sense that it gets harder and harder to move the system from equilibrium because the system gets better and better at degrading the external input of exergy. The more a system is moved from equilibrium, the more sophisticated its processes for resisting being moved from equilibrium. This behavior is not sensible

Table 1: Properties of Dissipative Systems

- **Open** to material and energy flows.
- **Nonequilibrium**: Exist in quasi-steady states some distance from equilibrium.
- Maintained by energy **gradients** (exergy) across their boundaries. The gradients are **irreversibly** degraded in order to build and maintain organization. These systems maintain their organized state by exporting entropy to other hierarchical levels.
- Exhibit material or energy **cycling**: Cycling and especially autocatalytic cycling is intrinsic to the nature of dissipative systems. The very process of cycling leads to organization. **Autocatalysis** (positive feedback) is a powerful organizational and selective process.
- Exhibit **chaotic** and **catastrophic** behavior. Will undergo dramatic and sudden changes in **discontinuous** and **unpredictable** ways.
- As dissipative systems are moved away from equilibrium they become organized:
  - they use more exergy
  - they build more structure
  - this happens in spurts as new attractors become accessible.
  - it becomes harder to move them further away from equilibrium

from a classical second law perspective, but is what is expected given the exergy degradation principle. No longer is the emergence of coherent self-organizing structures a surprise, but rather it is an expected response of a system as it attempts to resist and dissipate externally applied gradients which would move the system away from equilibrium. The term dissipative structure takes on new meaning. No longer does it mean just increasing dissipation of matter and energy, but dissipation of gradients as well.

The literature is replete with similar phenomena in dynamical chemical systems. Chemical gradients result in dissipative autocatalytic reactions, examples of which are found in simple inorganic chemical systems, in protein synthesis reactions, or phosphorylation, polymerization and hydrolysis autocatalytic reactions. Autocatalytic reaction systems are a form of positive feedback where the activity of the system or reaction augments itself in the form of self-reinforcing reactions. In autocatalysis, the activity of any element in the cycle engenders greater activity in all the other elements, thus stimulating the aggregate activity of the whole cycle. Such self-reinforcing catalytic activity is in itself self-organizing, is an important way of increasing the dissipative capacity of the system and can act as an active selection process between competing elements in the cycle (Ulanowicz, 1996). Cycling and or autocatalysis are fundamental aspects of dissipative systems and represent not only the building of structure but is the source of complexity in nonequilibrium systems. Table 1 outlines some of the common behavior or properties of dissipative systems.

Living Systems as nonequilibrium dissipative systems

As discussed earlier, Schrödinger and Boltzmann, recognized the apparent contradiction between the thermodynamically predicted randomized cold death of the universe and the existence of processes (i.e. life) in nature by which systems grow, complexify, and evolve. Life does not decay into its composite parts but grows and complexifies. This apparent contradiction is resolved, as Schrödinger suggested, by considering living systems as nonequilibrium dissipative systems. Given the exergy degradation principle and the right conditions, the emergence of living systems should be expected as a means of furthering the mandate of exergy degradation.

If we view the earth as an open thermodynamic system with a large exergy flow impressed on it by the sun, physical and chemical processes will emerge to degrade the incoming exergy. Energy shifts, (conversion of short wave radiation to longer wave infrared), absorption, meteorological and oceanographic circulation will degrade much of the incoming solar exergy. However there will still be exergy available for degradation. It has been argued elsewhere that life is another means of degrading this exergy (Kay, 1984, Kay and Schneider, 1992, Schneider and Kay, 1994ab).

The origin of prebiotic life is the development of yet another route for the degradation of exergy. Most theories on the origin of life start with a chemical homogeneous soup. External sources of exergy (sun light, thermal or chemical gradients (e.g. deep sea vents)) can drive the system from equilibrium. Chemical or hydrophobic potentials probably developed phase transitions favoring self assembly of various molecules. A stepwise progression of stages can be recognized in the emergence of prebiotic organized structures; formation of simple molecules, the formation of biomonomers (amino acids, sugars), the formation of biopolymers (polypeptides, nucleic acids), the aggregation of bipolymers onto microspheres and the emergence of protocells as functional relationships develop among microspheres (Wicken, 1987). Life should be viewed as the sophisticated end in the continuum of development of natural dissipative structures from physical, to chemical autocatalytic, to living systems.

Life with its requisite ability to reproduce, insures that these dissipative pathways continue and has evolved strategies to maintain these dissipative structures in the face of a fluctuating physical environment. Living systems are essentially dynamic dissipative processes with encoded memories. The gene with its DNA, allows the dissipative process to continue without having to restart new dissipative pathways via stochastic events. Wicken (1987) noted that living systems are a unique example of dissipative structures, because they are self creating, rather than a product of only impressed forces. Life is a self-replicating system, operating through informed pathways of autocatalytic thermodynamic dissipation. The origin of life should not be seen as an isolated event but as a holistic process that represents the emergence of yet another class of processes whose goal is the dissipation of thermodynamic gradients, the degradation of exergy.

The dilemma which faced Schrödinger and Boltzmann is resolved in that aspects of growth, development, and evolution are the response to the thermodynamic imperative of exergy degradation. Biologic growth occurs when the system adds more of the same types of pathways for degrading exergy. Biologic development occurs when new types of pathways for degrading exergy emerge in the system. The larger the living system, i.e., the larger the system flow activity, the more reactions and pathways (both in number and type) are available for exergy destruction. This observation, derived from considering the principle of exergy degradation, provides a criteria for evaluating growth and development in living systems. All else being equal, the more effective exergy degradation pathway is preferred.

Ecosystems as exergy degraders

Following this line of logic ecosystems can be viewed as the biotic, physical, and chemical components of nature acting together as nonequilibrium dissipative processes. As ecosystems develop or mature they should develop more complex structures and processes with greater diversity, more cycling and more hierarchical levels all to abet exergy degradation. Species which survive in ecosystems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total exergy degradation of the ecosystem. In short, ecosystems develop in a way which systematically increases their ability to degrade the incoming solar exergy. (Kay, 1984, Kay and Schneider, 1992, Schneider and Kay, 1994ab)

Keeping in mind that the more processes or reactions of material and energy that there are within a system, (i.e. metabolism, cycling, building higher trophic levels) the more the possibility for exergy degradation, Schneider (1988) and Kay and Schneider (1992) showed that most, if not all, of Odum's (1969) phenomenological attributes of maturing ecosystems can be explained by ecosystems behaving in such a manner as to degrade as much of the incoming exergy as possible

The energetics of terrestrial ecosystems provides an excellent example of the thesis that ecosystems will develop so as to degrade exergy more effectively. The exergy drop (i.e. degradation) across an ecosystem is a function of the difference in black body temperature between the captured solar energy and the energy reradiated by the ecosystem. (This is discussed in detail in Fraser and Kay, 2000) Thus if a group of ecosystems are bathed by the same amount of incoming energy, the most mature ecosystem should reradiate its energy at the lowest exergy level, that is the ecosystem would have the coldest black body temperature. The black body temperature is determined by the surface temperature of the canopy of the ecosystem.

Consider the fate of solar energy impinging on five different surfaces, a mirror, a flat black surface, a piece of false grass carpet (i.e. Astroturf), a natural grass lawn and a rain forest. The perfect mirror would reflect all the incoming energy back toward space with the same exergy content as the incoming radiation. The black surface will reradiate the energy outward at a lower quality than the incoming energy, because much of the high quality ultraviolet exergy is converted to lower quality infra-red sensible heat. The green carpet will reradiate it's energy similar to the black surface but will differ because of it's surface quality and different emissivity. The natural grass surface will degrade the incoming radiation more completely than the green carpet surface, because processes associated with life, (i.e. growth, metabolism and transpiration) degrade exergy. (Ulanowicz, and Hannon, 1987). The rain forest should degrade the incoming exergy most effectively because of the many pathways (i.e. more species, canopy construction) available for degradation.

In previous papers (Schneider and Kay 1994, a, b) have discussed the work of Luvall and Holbo (1989, 1991) and Luvall et al. (1990) who conducted experiments in which they overflew terrestrial ecosystems and measured surface temperatures using a Thermal Infrared Multispectral Scanner (TIMS). Their technique allows assessments of energy budgets of terrestrial landscapes, integrating attributes of the overflown ecosystems, including vegetation, leaf and canopy morphology, biomass, species composition and canopy water status. Luvall and his co-workers have documented ecosystem energy budgets, including tropical forests, mid-latitude varied ecosystems, and semiarid ecosystems. Their data shows one unmistakable trend, that when other variables are constant the more developed the ecosystem, the colder its surface temperature and the more degraded it's reradiated energy.

Work by Akbari, Murphy, Swanton and Kay on agricultural plots showed a similar trend. A lawn (single species of grass) had the warmest surface temperature, a undisturbed hay field was cooler, and a field which has been naturally regenerating for 20 years was coldest. These trends were confirmed over three years of observation. Also another field, which was regenerating for 20 years was disturbed by mowing. Its surface temperature immediately rose significantly, but very quickly returned to its cooler pre-disturbance value. Very recently Allen and Norman have performed a set of experiments to explore the relationship between development and surface temperature in plant communities. So far their experimental results demonstrate that the surface temperature of plant communities tend to warm when they are removed from their normal conditions. That is plant communities are coldest (degrading the most exergy) when they are in the normal conditions which they are adapted to.

Clearly there is much to be gained from examining ecosystems through the lens of exergy degradation. A number of ecosystem phenomena can be explained and hypotheses concerning ecosystem development can be generated and tested. But there is more to the story. Most ecosystems will have many different options for exergy degradation available to them. Some will have different sources of exergy available. Different combinations of exergy sources and degradation possibilities may be equivalent from a exergy degradation perspective. So the number of possible variations on ecosystem organization, which are thermodynamically equivalent, may be significant. This quickly leads to a complicated set of possible organizational pathways and which is actually manifested may very well be a reflection of a collection of accidents of history.

The imperative of thermodynamics and exergy degradation is not the only one acting on living systems. Of equal importance is survival, an imperative which may not be consistent with maximum exergy degradation. Inevitably tradeoffs will have to be made and ecosystems as they exist on the ground will reflect these tradeoffs. (Kay, 1984) There will not be single best solutions to the imperatives of exergy degradation and survival. Just solutions that work longer than others. Furthermore, to add to the complexity and uncertainty, Dempster (1998) and Kay have shown that such systems must, by necessity, be recursively nested autopoietic and synpoietic systems. Together these factors and others, summarized in Table 2, mean that the consideration of ecosystems as self-organizing systems must confront the issues of complexity and uncertainty head on. Conventional scientific approaches simply are not adequate for

Table 2: Properties of *complex systems* to bear in mind when thinking about ecosystems.

•**NON-LINEAR:** Behave as a whole, *a system*. Cannot be understood by simply decomposing into pieces which are added or multiplied together.

•**HIERARCHICAL:** Are *holarchically nested.* The system is nested within a system and is made up of systems. The "control" exercised by a holon of a specific level always involves a balance of internal or self-control and external, shared, reciprocating controls involving other holons in a mutual causal way that transcends the old selfish-altruistic polarizing designations. Such nestings cannot be understood by focusing on one hierarchical level (holon) alone. Understanding comes from the multiple perspectives of different *types* and *scale*.

•**INTERNAL CAUSALITY:** non-Newtonian, not a mechanism, but rather is *self-organizing*. Characterized by: goals, positive and negative feedback, autocatalysis, emergent properties and surprise.

•**WINDOW OF VITALITY:** Must have enough complexity but not too much. There is a range within which self-organization can occur. Complex systems strive for *optimum*, not minimum or maximum.

•**DYNAMICALLY STABLE?:** There may not exist equilibrium points for the system.

•**MULTIPLE STEADY STATES:** There is **not** necessarily a unique preferred system state in a given situation. *Multiple attractors* can be possible in a given situation and the current system state may be as much a function of historical accidents as anything else.

•**CATASTROPHIC BEHAVIOUR:** The norm
Bifurcations: moments of unpredictable behaviour
Flips: sudden discontinuities, rapid change
Holling four box cycle Shifting steady state mosaic

•**CHAOTIC BEHAVIOUR:** our ability to forecast and predict is always limited, for example to between five and ten days for weather forecasts, regardless of how sophisticated our computers are and how much information we have.

this task. (Kay and Schneider, 1994, Kay, Regier, Boyle and Francis (1999)) In the next section an alternative way to describe ecosystems, which is rooted in their nature as adaptive self-organizing complex dissipative systems, is presented.

The Self-organizing Holarchic Open Systems portrayal of ecological systems

Complex systems thinking and SOHO system descriptions

The issue of complexity has attracted much attention in the past decade. This issue emerged in the wake of the new sciences which became prominent in the 1970's; catastrophe theory, chaos theory, non-equilibrium thermodynamics and self-organization theory, Jaynesian information theory, complexity theory etc. A number of authors have focused specifically on self-organizing systems (di Castri, 1987, Casti,1994, Jantsch, 1980, Kay 1984, Nicolis and Prigogine, 1977, 1989, Peacocke, 1983, Wicken, 1987.) The term *complex systems thinking* is being used to refer to the body of knowledge that deals with complexity. Complex systems thinking has its origins in von Bertalanffy's general systems theory.

Maruyama (M.T. Caley and D. Sawada. 1994) was one of the first to examine the issues of complexity. In his "second cybernetics" of the mid 1960s, he identified a class of systems which require explanation in terms of morphogenetic causal models, that is explanations that involve both positive and negative feedback loops and autocatalysis, mutual causality. He demonstrated how probabilistic or deterministic loops of mutual causality can increase a system's pattern of heterogeneity towards higher levels of organized complexity. He showed that traditional explanations in terms of linear causality, that is in terms of a clear cause and effect relationship, were not possible for the phenomena exhibited by this class of systems. The problem is that when feedback loops dominate a system, the effect becomes part of the cause. So the cause is not independent of the effect as is required by linear cause and effect explanations. The new fields of (first) cybernetics and general systems theory were also incapable of providing an explanation of these phenomena as they focused on systems where negative feedback leads to homeostasis. His conclusion was that a new mode of explanation, quite different from traditional scientific approaches, was needed for this class of systems.

Koestler (Koestler & Smythies 1969, Koestler 1978) focused on self-organizing, holarchic and open (SOHO) attributes of systemic phenomena of the kind identified by Maruyama. A holarchy is a generalized version of a traditional hierarchy (not to be confused with Allen's notion of hierarchy, Allen and Starr, 1982, Allen and Hoekstra, 1992), with reciprocal power relationships between levels rather than a preponderance of power exerted from the top downwards. A particular system of this type Koestler termed a “holon” because it occurs in a contextually nested or holarchic reality with mutual causality guiding reciprocal interactions between a holon and proximate contiguous holons of different scales – inside, outside and lateral to the holon of interest. The term holon or SOHO system is used herein to refer to the self-organizing entity that is the subject of our inquiry.

Ulanowicz (1996, 1997) developed further some proposals by K. R. Popper (Popper, 1990) to extend a perception of indeterminacy in the quantum realm to other scales of phenomena by generalizing the usual Newtonian concept of force to obtain a notion of systemic dynamical cohesion which Popper called a “propensity”. A propensity is always contextual (as are Maruyama’s morphogenetic system and Koestler’s SOHO holon) rather than universalistic as in the Newtonian sense of “force”. Ulanowicz (1995) proposed that a mutual-causal kind of autocatalysis plays a self-organizing role in Popper’s propensity, perhaps in generating dynamical cohesion through forces that act asymmetrically, and not symmetrically as in the Newtonian sense. Ulanowicz also implied that “dynamical cohesion” tends to be attenuated in a step-wise manner at the interfaces of interacting holons, both with respect to nested and non-nested kinds of relationships and these attenuations may be perceived as boundary like.

It has been argued (Kay, Regier, Boyle and Francis (1999)) that ecosystems fall into the class of systems that Maruyama identified and which Koestler called SOHO systems. The dynamics of such systems are described by narratives. A central question to be addressed by the narrative description of a SOHO system is an elaboration of its propensities. The elaboration delineates the mutual causality of the feedback loops and autocatalytic process which give the system its coherence as an entity. This set of propensities, which define a holon, is referred to as its "canon".

The remainder of this section sketches the elements of a Self-organizing Holarchic Open Systems description of an ecological system with particular emphasis on the application of the exergy degradation principle as part of a complex systems thinking approach to understanding ecosystems.

Hierarchy

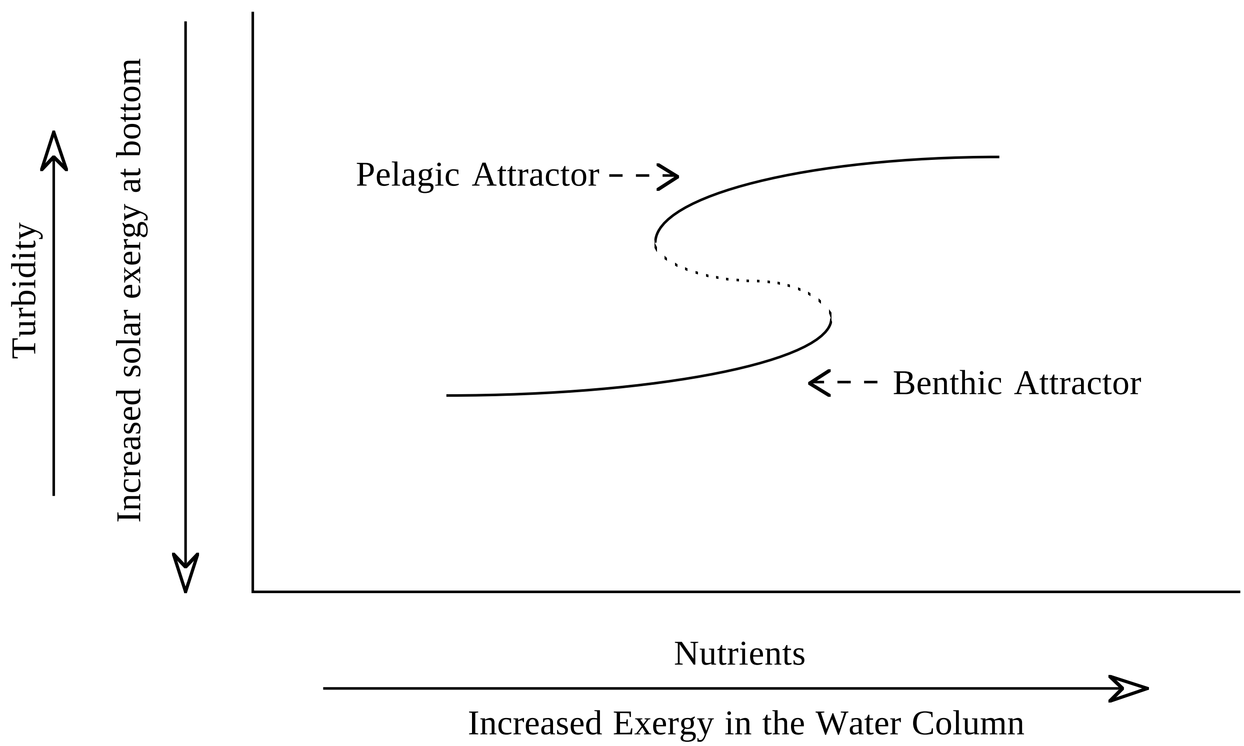
The consideration of a SOHO system must begin with a hierarchical description. The first step is to define the holons, that is self-organizing entities of interest. Careful attention must be paid to the issues of scale and type. (Allen and Starr, 1982, Allen and Hoekstra, 1992, Allen, Bandurski, and King 1993, King, 1993, Günther and Folke, 1993.) The narrator must decide if the focus is a watershed, or perhaps a community, or the home range of a species, etc. A delineation of the important processes which make up the holon and their interconnection is required. (Are we talking about reproduction?, energetics?, spatial interconnection..., and of what?). Key relationships between holons must be established. Most importantly, the context for the holon must be explored. This requires investigating the constraints on the holon dictated by the upper level holon of which it is a part (i.e. the implications for a lake of its watershed). The hierarchical description of a SOHO system will encompass several levels of holons (different scales: watersheds, drainage basins, sub watersheds, ...) and several holarchies (different types: a description as a watershed, as a landscape, as habitat etc.) Prior experience helps to inform how many levels and types of descriptions are sufficient to understand the SOHO system, as the array of such descriptions is only limited by the narrator's imagination.

Figure 2: Benthic and Pelagic Attractors in shallow lakes

Two different attractors for shallow lakes have been identified. In the **benthic** state, a high water clarity bottom vegetation ecosystem exists. As nutrient loading increases the turbidity in the water, the ecosystem hits a catastrophe threshold and flips into a hypertrophic, turbid, phytoplankton **pelagic** ecosystem. The relationship of these two attractors, from a thermodynamic perspective, is as follows:

Let us assume that the benthic attractor is dominant and that the rate at which phosphorus is being added to the water is increasing. The benthic system has means of deactivating phosphorus. However the amount of active phosphorus will increase, albeit slowly, effectively increasing the exergy in the water column. As this exergy increases a critical threshold is passed which allows the pelagic system to self-organize to coherence. Once this occurs the exergy at bottom decreases rapidly due to shading (turbidity) thus catastrophically de-energizing the benthic system. This results in the eventual re-activation of the phosphorus in the bottom muds which the benthic system had previously deactivated, thus strengthening the pelagic attractor even more.

Assuming the pelagic attractor is dominant and if the level of active phosphorus in the water column decreases, a critical threshold is again reached below which it is no longer possible to capture enough solar energy to energize the pelagic system. In effect, the exergy in the water column decreases below the minimum level for the window of vitality of the pelagic system. As this occurs the exergy at the bottom increases thus re-energizing the benthic system. And so the aquatic system flips back and forth between the pelagic and the benthic regime depending on where in the water column the sunlight's exergy is available to energize the system.



Attractors

Having defined the SOHO system of interest, the next aspect to explore is its self-organizing behaviour. A SOHO system exhibits a set of behaviours which are coherent and organized, within limits. The nexus of this organization at any given time is referred to as an attractor. The term "attractor" comes from the state space description of the behaviour. The system has a propensity to remain in a limited domain of state space (for example a gravity well). It behaves as if it were "attracted" toward this domain and hence the term "attractor". As SOHO systems evolve they shift between attractors within the SOHO system's overall state space. The re-organization that these shifts entail is not smooth and continuous but rather is step-wise. The system flips its organizational state in often dramatic ways. (Recall the emergence of Bénard Cells discussed earlier.)

Ecosystems have multiple possible operating states or attractors, and may shift or diverge suddenly from any one of them (See Figure 2). The notion of alternate stable states (attractors) in ecosystems is not well known in the ecological community, but it is also not new. Kay (1984), Holling (1986), Kay (1991), and Kay and Schneider (1994), Kay (1997), Ludwig et al. (1997) examine, in general, the notion of alternate stable states in ecosystems and their implications. Yet the importance of this notion for explaining ecosystem phenomena remains largely unexplored.

For example, a portion of a natural area[1] in Southern Canada is a **closed soft maple swamp** in a wetland community. However, the amount and duration of the flows of water can radically alter this operating state. Drying events, such as an extended drought, could change the operating state to an **upland forest community or grassland** with associated vegetation structure. If there are extended periods of flooding causing high water levels, the operating state would be that of a **marsh ecosystem**. This is because red and silver maple are tolerant to flooded conditions within 30% to 40% of the growing season. If flooding events are greater than this threshold, the forest trees will die, giving way to more water tolerant herbaceous marsh vegetation. The feedback mechanism which maintains the swamp state is evapotranspiration (i.e. water pumping) by the trees. Too much water overwhelms the pumping capability of the trees and not enough shuts it down. The point of this example is that the current ecosystem state is a function of its physical environment and the accidents of its history. A single dry or wet season can change what is on the landscape for decades.

The task of the narrator is to scope out the array of attractors available to the SOHO system, the potential flips between them, and the underlying morphogenetic causal structure of the organization in the domain of the attractors.

[1] More detail about this case study, The Huron Natural Area can be found on its WWW site: www.fes.uwaterloo.ca/u/jjkay/HNA/

The Thermodynamics of Self-organization

A key question about attractors is what characterizes them. This is equivalent to asking what gives rise to the propensities which animate the particular canon associated with a given attractor. As discussed earlier, Prigogine showed that, when dealing with open systems with an enduring (not necessarily constant) flow of exergy, spontaneous emergence of coherent behaviour and organization can occur (Nicolis and Prigogine, 1977, 1989). Prigogine showed that this occurs because the system reaches a catastrophe threshold and flips into a new coherent behavioural state. (This is evident for example in the vortex which spontaneously appears when draining water from a bathtub.)

In examining the energetics of open systems, Kay and Schneider (Schneider and Kay, 1994a,b) noted that as an open system with exergy pumped into it is moved away from equilibrium. But nature resists movement away from equilibrium. So in such a situation a system will organize itself so as to degrade the exergy as thoroughly as circumstances permit, thus limiting the degree to which the system is moved from thermodynamic equilibrium. When the input of the exergy and material pushes the system beyond a critical distance from equilibrium, the open system responds with the spontaneous emergence of new organized behaviour that uses the exergy to build, organize and maintain its structure. This dissipates the ability of the exergy to move the system further away from equilibrium. As more exergy is pumped into a system, more organization emerges, in a step-wise way, to degrade the exergy. Furthermore these systems tend to get better and better at "grabbing" resources and utilizing them to build more structure, thus enhancing their dissipating capability. There is however, in principle, an upper limit to this organizational response. Beyond a critical distance from equilibrium, the organizational capacity of the system is overwhelmed and the system's behaviour leaves the domain of self-organization and becomes chaotic. As noted by Ulanowicz there is a "window of vitality", that is a minimum and maximum level in between which self-organization can occur.

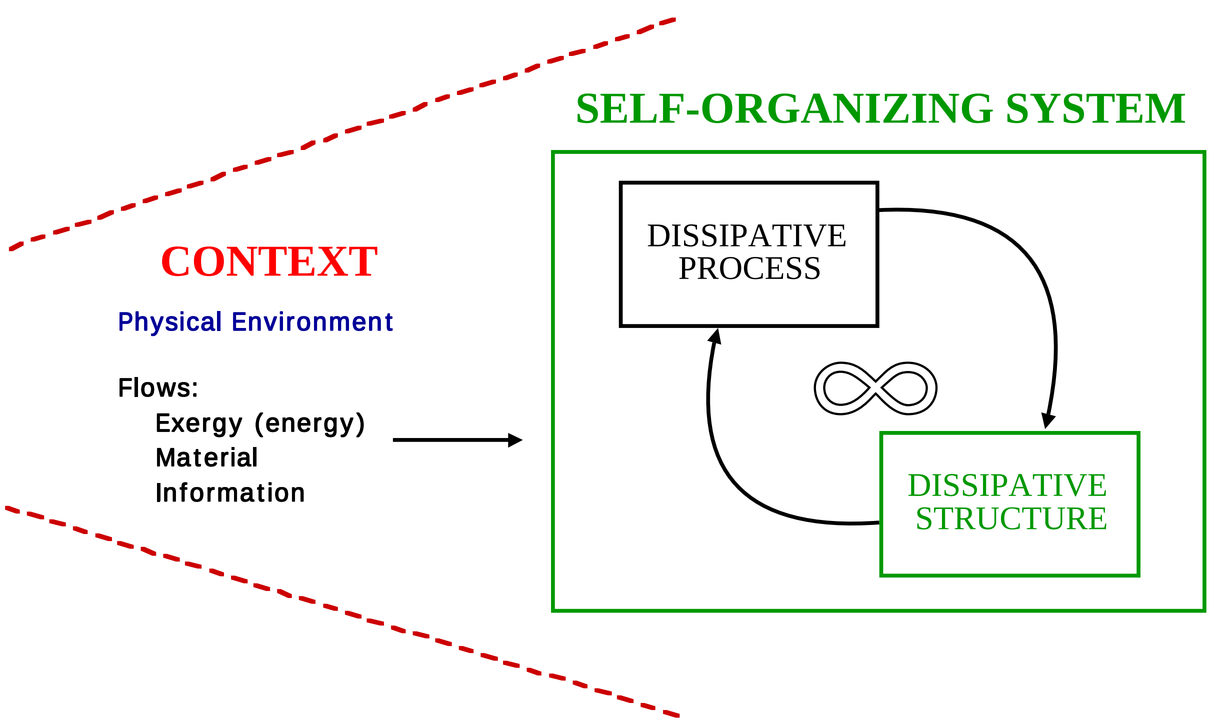
The theory of non-equilibrium thermodynamics suggests that the self-organization process in ecosystems proceeds in a way that: a) captures more resources (exergy and material); b) makes more effective use of the resources; c) builds more structure; d) enhances survivability (Kay, 1984, Kay and Schneider, 1992, Schneider and Kay, 1994a,b). These seem to be the kernel of the propensities of self-organization in ecosystems. How these propensities manifest themselves as morphogenetic causal loops is a function of the given environment (context) in which the ecosystem finds itself imbedded as well as the available materials, exergy and information.

SOHO Systems as Dissipative Systems: A conceptual Model

The conceptualization of self-organization, as a dissipative system, is presented in Figure 3. Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. This expectation is a consequence of the exergy degradation principle. Dissipative processes restructure the available raw materials in order to degrade the exergy. Through catalyse, the information present enables and promotes some processes to the disadvantage of others. The physical environment will favour certain processes. Therefore which specific processes emerge depends on the raw materials and exergy available to operate them, the information present to catalyse the processes, and the physical environment. The interplay of these factors defines the context for (i.e. constrains) the set of processes which may emerge. (Generally speaking, which specific processes emerge from the available set are uncertain.) Once a dissipative process emerges and becomes established it manifests itself as a structure.

(In the case of a vortex in the bathtub water, the exergy is the potential energy of the

Figure 3: A conceptual model for self-organizing systems as dissipative structures. Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. Dissipative processes restructure the available raw materials in order to dissipate the exergy. Through catalyse, the information present enables and promotes some processes to the disadvantage of others . The physical environment will favour certain processes. The interplay of these factors defines the context for (i.e. constrains) the set of processes which may emerge. Once a dissipative process emerges and becomes established it manifests itself as a structure. These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment. The canon of the SOHO system is the complex nested interplay and relationships of the processes and structures, and their propensities, that give rise to coherent self-perpetuating behaviours, that define the attractor.



water, the raw material is the water and there is no information, the dissipative process is water draining, the dissipative structure is the vortex. The vortex will not form until enough height of water is in the bathtub, and if too much height of water is present, laminar flow occurs instead of a vortex.)

These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment. The canon of the SOHO system is the complex nested interplay and relationships of the processes and structures, and their propensities, that give rise to coherent self-perpetuating behaviours that define the attractor.

In an ecological setting, examples of the structures are the individuals of species, breeding populations, forests etc. The processes are reproduction, metabolism, evapotranspiration etc. The context is the available set of nutrients and exergy sources in a physical environment. The information includes the biodiversity (See Kay & Schneider 1994). The general propensities of the ecological systems were stated above.

Narratives I: Exergy, canons, and attractors

The task of characterizing the attractors and canon of ecosystems then becomes one of describing how the local context of exergy, materials and information and biophysical environment, and the global propensities of capturing more resources (exergy and material), making more effective use of the resources; building more structure, and enhancing survivability, give rise to the emergence of the nested structures and processes which constitute a self-organizing holarchic open system. This characterization takes the form of a narrative[2], literally a story of how the system might unfold over time. The narrative is qualitative, multi threaded (multiple threads of explanation) and multi pathed (that is portrays a number of possible pathways for development or storylines). Following are two overly brief examples of how narratives can be used to discuss ecosystem organization.

A narrative of Lake Erie

Consider the case of shallow lakes, such as Lake Erie in North America. Regier and Kay (1996) interrelated empirical generalizations from aquatic ecology by R. Margalef, R. A. Vollenweider and others, together with notions from complex system theory to propose a two-attractor catastrophe cusp model (Figure 4) as a way of integrating much empirical information of how aquatic systems might transform under powerful, careless human interventions. Two different attractors for shallow lakes have been identified. (Scheffer(1990), Blindow et al. (1993), Scheffer et al. (1993), Regier and Kay (1996), and Carpenter and Cottingham (1997) Scheffer (1998), Kay and Regier (1999).) In the oligotrophic/pelagic state, a high water clarity bottom vegetation ecosystem exists. As

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[2] Thanks to David Waltner-Toews for suggesting this term.

nutrient loading increases the turbidity in the water, the ecosystem hits a catastrophe threshold and flips into a hypertrophic, turbid, phytoplankton oligotrophic/benthic ecosystem. Each has its own canon. Different locations in a lake will be organized about one of these attractors depending on the holarchic context for the specific portion of the lake. Lakes which flip between these attractors on a regular basis have been found. (Lake Erie appears to be currently in the midst of such a flip, from pelagic to benthic.) At least three quite different descriptions of such a lake will be needed, one for the pelagic state, one for the benthic, and one for the intermediate stage as the system flips between attractors.

The essence of the canon of the benthic system is that it depends on solar energy reaching the bottom for the exergy necessary to energize the system. The solar exergy is captured by the green matter on the bottom and is transformed into forms appropriate to power the benthic processes. These include predation and grazing of the pelagic system, thus suppressing it. Various means emerge to maintain the ecosystem at the benthic attractor. Notable of these are means for keeping the water clear so solar energy will reach the bottom and means for keeping the water column free of sufficient exergy which would empower the pelagic attractor.

The pelagic system, on the other hand, depends on exergy in the water column to energize it. Solar energy may be in the water column. However, unless the materials necessary for the existence of dissipative processes, which can utilize the solar energy, are present in the water column, nothing can be done with the solar energy, so it has no exergy. For example, in many lakes, available phosphorus in the water column limits the level of photosynthesis by phytoplankton. Beyond a critical level of available phosphorus in the water column, there is enough availability of solar energy (i.e. sunlight exergy) to support the phytoplankton bloom necessary for the activation of the pelagic attractor. Once this occurs, the solar energy capture happens near the surface water instead of at the bottom and means emerge for promoting and maintaining the pelagic attractor. Of course by its very presence the pelagic system shades the benthic from irradiation by the sun, thus decreasing the exergy at the bottom.

The relationship of these two attractors, from a thermodynamic perspective, is shown in Figure 2. This thermodynamic relationship is based on the nutrient-turbidity relationship reported by Scheffer et al (1993) for shallow lakes and generalized to deeper systems (Regier and Kay, 1996) and in particular for Lake Erie (Kay and Regier, 1999). Let us assume that the benthic attractor is dominant and that the rate at which phosphorus is being added to the water is increasing. The benthic system has means of deactivating phosphorus, as discussed in Kay and Regier (1999). However the amount of active phosphorus will increase, albeit slowly, effectively increasing the exergy in the water column. As this exergy increases a critical threshold is passed which allows the pelagic system to self-organize to coherence. Once this occurs the exergy at bottom decreases rapidly due to shading (turbidity) thus catastrophically de-energizing the benthic system. This results in the eventual re-activation of the phosphorus in the bottom muds which the benthic system had previously deactivated, thus strengthening the pelagic attractor even more.

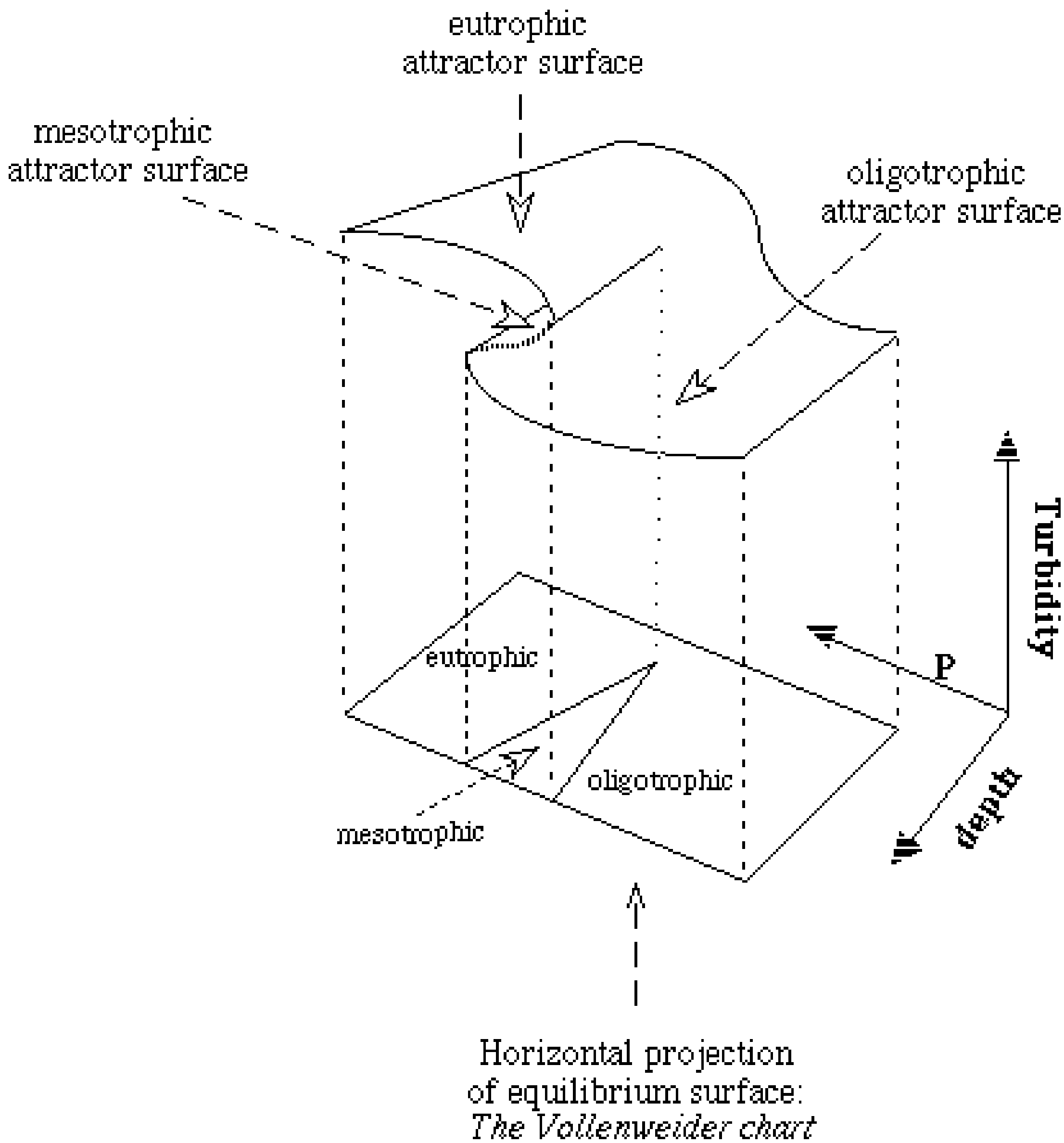


Figure 4: A catastrophe model for aquatic ecosystems: One attractor, associated with high loading of phosphates into relatively shallow waters with high residence time, relates to an eutrophic state. The other attractor associated with low loadings into deep waters of low residence time, is associated with an oligotrophic state. The narrow zone of mesotrophic conditions may be related to the unstable overlapping part of the catastrophe fold. The horizontal projection of the surface (control space) is the so called "Vollenweider chart". The vertical projection gives a fold catastrophe surface similar to that presented in Scheffer et al. (1993). The axis labeled **P**, the phosphorous loading in the lake (or other nutrient loading), corresponds to the Y axis is the Vollenweider chart and Scheffer fold catastrophe diagram. **Depth** is the mean depth of the lake as in the X axis in the Vollenweider chart. **Turbidity** is the z-axis and corresponds to the x-axis in the Scheffer fold catastrophe diagram.

Assuming the pelagic attractor is dominant and if the level of active phosphorus in the water column decreases, a critical threshold is again reached below which it is no longer possible to capture enough solar energy to energize the pelagic system. In effect, the exergy in the water column decreases below the minimum level for the window of vitality of the pelagic system. As this occurs the exergy at the bottom increases[3] thus re-energizing the benthic system. And so the aquatic system flips back and forth between the pelagic and the benthic regime depending on where in the water column the sunlight's exergy is available to energize the system.

In the numerous shallow parts of the Great Lakes it appears that the phosphate rich runoff from human activities, usually in combination with other cultural stresses, empowered the pelagic attractor decades ago. Sewage treatment plants, agricultural management practices and other remediative measures, now seem to have reduced the phosphate content of the runoff sufficiently that the benthic attractor is reasserting itself.

A narrative of the Holling four box

Another example (see figure 5) of the notion of canon and attractor and the ability to characterize them in terms of the form of exergy utilized is Holling's four-box model of the dynamics of terrestrial ecosystems. (See Holling 1986, 1992). All living systems exhibit a birth-renewal-growth-death cycle and it is this characteristic which makes life more sophisticated than non living dissipative systems (Wicken, 1987). We are all familiar with the death and reproduction at the cellular level and the birth-growth and death of individuals, but it is only recently that Holling has made us aware that this cycle occurs at many temporal and spatial scales, including ecosystems. (Holling, 1992). The idea of a forever stable climax stage of succession has been abandoned. Fire, pests, new species and other disturbances produce a shifting mosaic pattern of ecosystem succession on the landscape.

Using the restated second law of thermodynamics and in particular the exergy degradation principle as a basis, the dynamics of the Holling four box model can be described to proceed as follows:

Referring to figure 5, the horizontal axis can be taken as "stored exergy". This is the amount of exergy stored in biomass and is related to the amount of nutrients bound in the biomass. The vertical axis is the "exergy consumption". This is the rate at which exergy is utilized by the system, that is the rate at which the incoming exergy is degraded.

Starting at **exploitation**, if there is sufficient materials and biological information available, then dissipative processes will emerge which utilize the exergy in the solar energy. In other words, some organisms will take advantage of the available resources. The thermodynamic direction of all self-organizing processes is to increase the rate of exergy degradation. Thus the exergy consumption rate will increase as the ecosystem proceeds to develop towards **conservation.** In this case (as noted by Jørgensen, Meijer, 1978, Jørgensen, 1992) this developmental pathway also involves increasing

[3] As trhe pelagic system unravels the shading of the bottom decreases.

biomass and hence stored exergy. The more exergy stored, the bigger the structure, the better able it is to utilize exergy, the bigger it gets, … This is the direction of the **first thermodynamic branch[4].** The exergy source is solar energy.

However there is a fundamental contradiction inherent in this developmental pathway. The more exergy that is stored in the system, the more likely (according to the restated second law of thermodynamics) that some dissipative process will emerge to take advantage of it. So fire, pest outbreaks etc., occur that take advantage of all the exergy stored in the biomass. The paradox is that the more effective the ecosystem is at consuming exergy, that is the more organized it is, the more exergy it contains and hence the more likely it is to be consumed by another self-organizing process (i.e. fire, pest outbreaks etc.). So **conservation** represents a point of maximum thermodynamic organization in the sense that the system is utilizing the available exergy as fully as possible. But it also represents a point of maximum thermodynamic risk as it as far out of equilibrium as is possible. (Recall that distance from thermodynamic equilibrium is measured by exergy content of a system.)

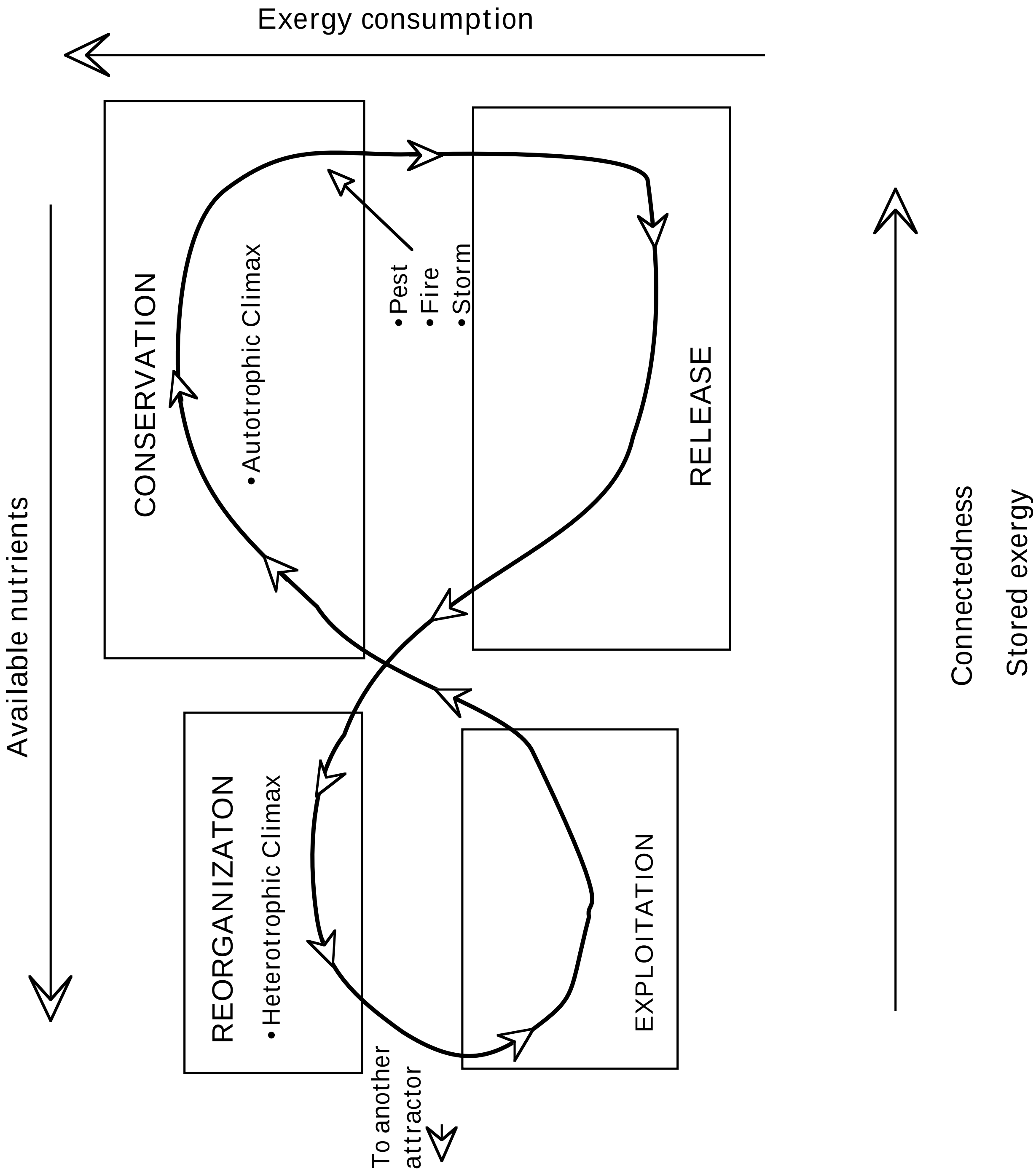
In the language of attractors, there are two attractors, the attractor of maximum exergy consumption and the attractor of local thermodynamic equilibrium. For this particular thermodynamic branch the attractor of maximum exergy consumption is moving in opposition to the local equilibrium attractor. The **conservation** point is the place where the two attractors are in balance. For some systems this balance is precarious for others less so, but in the end the local equilibrium attractor is always dominant

Figure 5: Holling's four box model as a dual thermodynamic branch system.

The first trajectory is the "exploitation" to "conservation" thermodynamic branch which culminates in the "climax" community. The biological attractor is the autotrophic system (i.e. a forest). The canon is expressed, for example, as the growth of a forest to maturity and this is energized by solar energy. However in the process of increasing the utilization of solar energy and hence building more structure, much exergy is stored in the biomass. This has the effect of moving the system further and further from thermodynamic equilibrium as it develops.

When, as Holling puts it, the inevitable accident (fire, windstorm, or pest outbreaks) happens, suddenly much exergy is available in the form of dead biomass. This exergy energizes a new biological attractor, the heterotrophic or decomposer system. This is the thermodynamic branch which runs from "release" to "re-organization". As the system progresses along this path it releases the stored nutrients while using the stored exergy. Eventually the stored exergy runs out and the heterotrophic system collapses. However in the process it has released the nutrients necessary for the re-emergence of the solar energy-powered system. This interplay between two biological attractors, which are organized around different forms of exergy, materials, and information is played out giving rise to the landscape we see.

[4] Thermodynamic branch: the developmental path taken by a self-organizing system as it develops


Exergy consumption
CONSERVATION
•Autotrophic Climax
•Pest
•Fire
•Storm
RELEASE
REORGANIZATON
•Heterotrophic Climax
EXPLOITATION
To another attractor
Available nutrients
Connectedness
Stored exergy

Once the inescapable happens, that is **release,** a new source of exergy is available for use, that is the exergy in the stored biomass. Again it inevitable that this new exergy source will be utilized. As always, the self-organizing process unfolds in a direction of increasing exergy utilization, except that the processes involved are fundamentally different and instead of storing biomass and hence exergy, they release the exergy in the stored biomass and at the same time release the stored nutrients. This is the direction of the **second thermodynamic branch**. The exergy source is stored energy.

Eventually the **reorganization** point is reached, that is point where the stored exergy runs out. But now the raw materials are available to start along the first type of thermodynamic branch again. Which specific branch is followed is a function of the biological information, nutrients and current environmental conditions. (And this is the point where biodiversity is so crucial, as this is the point where resiliency matters.)

To summarize:

The **exploitation point** is one of minimum exergy use and storage. The **conservation point** is one of maximum exergy use and storage. The **release point** is one of minimum exergy use and maximum storage. The **reorganization point** is one of maximum exergy use and minimum storage.

There are two thermodynamic branches, that is self-organizing pathways that are followed. One (from **exploitation** to **conservation**) is driven by the exergy in solar energy and involves increasing biomass and hence stored exergy. The other (from **release** to **reorganization**) is driven by stored exergy and involves the release of the stored exergy and hence biomass. The direction of both is increased exergy consumption. The ecosystem alternates between these two sources of exergy and hence follows two qualitatively different pathways of self-organization. The specifics are determined by the environmental conditions, available resources and biological information, the latter usually being the determining factor.

The first branch has been traditionally referred to as succession, or growth and development and culminates in the "climax" community of Clementsian succession theory. Biologically it is the attractor for the autotrophic system (i.e. a forest). The canon is expressed, for example, as the growth of a forest to maturity and this is energized by solar energy. The second branch is about creative destruction, that is decomposition. Biologically it is the attractor for the heterotrophic system, a system whose canon is the decomposition of organic material. The interplay between these two biological attractors, which are organized around different forms of exergy, materials, and information is played out giving rise to the landscape we see.

These two examples demonstrate the role of thermodynamics, particularly the dissipative system conceptual model, and the restated second law in generating a narrative description of ecological systems as SOHO systems.

Narratives II: Morphogenetic Causal Loops

Having discussed the hierarchical structure of the SOHO system, it's attractors, flips, propensities and canons in terms of the dissipative system conceptual model, as above, there is still the matter of describing the internal causal schemes which maintain the attractor and which make up the canon of the ecosystem. The description of these causal schemes explains the local propensities of the ecosystem and are the kernel of the narrative. Their description is in terms of morphogenetic causal loops which are made up of positive and negative feedback loops, some of which generate autocatalysis. Ulanowicz (1997) discusses the importance of these morphogenetic causal loops to the understanding of ecosystems. DeAngelis (DeAngelis et al, 1986, DeAngelis, 1995) has written extensively about these feedback loops and has given many ecological examples. Two simple examples, taken from DeAngelis (1986), are presented here to illustrate narration in terms of morphogenetic causal loops.

Consider forests in dry mountainous areas of the world. Often, as moisture laden clouds pass over bare mountains, they will not drop rain because of the heat reflected from the bare rocks. However as a forest develops on a mountain the re-radiated heat decreases. (Schneider and Kay, 1994b). As the re-radiated heat decreases more rain falls, which promotes more forest growth, which promotes more rain fall....

In southeastern Australia the dominant trees are sclerophyllous eucalypts, but the undergrowth consists of lush mesophytic vegetation. Normally these circumstances would give rise to a temperate rain forest. However these systems are subject to frequent fire, which would not occur if the mesophytic vegetation dominated. Fire increases soil leaching and sclerophylls are better adapted to poorer soils than mesophylls. Thus the dominance by sclerophyllous forest depends on fire and the occurrence of fire depends on the dominance by sclerophyllous forest. The morphogenetic causal loop of sclerophyllous dominant forest, fire, and soil infertility obstructs the development of temperate rain forests.

Another important aspect of SOHO systems to be scrutinized is the role of morphogenetic causal loops in maintaining the canon of a system in spite of a changing context (Rapport and Regier, 1985, 1995). Consider for example the acidification of lakes. The acidity in the precipitation did not suddenly change, but rather incrementally changed over the years. In our terms the context (pH of precipitation) of the SOHO system changed substantially over time. However the pH of the lake water did not change substantially, relatively speaking, over the same period. (Stigliani, 1988) The lake maintained the canon through a series of feedback loops that largely buffered the lake from the environmental change. Eventually the runoff reached a level of acidity which exceeded the compensatory capacity of these loops. Once this happened, the effectiveness of the SOHO system decreased, which in turn decreased the capacity of the loops to compensate, which decreased the effectiveness of the SOHO system.... and then quickly the canon unraveled and the SOHO system flipped to another attractor, in this case a "dead" lake. The narrative description of a SOHO system must not only delineate the morphogenetic causal loops, but also the contextual circumstances in which the loops can and cannot operate. Doing this in effect defines the domains of the attractors, the resiliency of the canon, its window of vitality.

Elsewhere (Kay and Regier, 1999) a more detailed partial narrative sketch of Lake Erie as a SOHO system is presented. It suggests that some issues are not as important as is currently thought and that others of importance have not been examined at all. This narrative of Lake Erie weaves together the themes of organism, species, ecosystem, landscape and biome in the context of physical environment, climate and human habitation and the changes therein. Some of the crucial morphogenetic causal loops, particularly those involving phosphorus, and their relationships to the canon of the pelagic and benthic attractors are outlined. The narrative takes the form of a multilayered account of the ecosystem's operation from different perspectives and scales. While some individual elements of the narrative consist of traditional scientific models and descriptions, the synthesise of these elements together into a narrative transcends normal scientific descriptions.

In this narrative of Lake Erie, the feedback loops, which buffer the system from changes in external influences, are of particular importance. The benthic attractor has elaborate feedback schemes, operating at different spatial and temporal scales, for limiting the phosphorous in the water column[5]. The pelagic attractor has elaborate schemes to accomplish just the opposite. The way in which changes in context enable and disable these feedback loops, and their associated canons, thus re-enforcing attractors or triggering flips between them, has received little attention from the scientific community whether it be for this example or for ecosystems in general.

Yet our work would suggest that it is precisely these issues (that is describing the "flip" from one attractor to another through accounting for how environmental influences (context), acting at different spatial and temporal scales, disable one feedback system while enabling another) that we must understand, if we are to comprehend the relationships between human activities and changes in the ecology of our planet. Understanding about attractors and flips is a necessary prerequisite for sustainability. It is the capability to address these issues which is at the core of the utility of the SOHO ecosystem description. This paper has argued that thermodynamics and in particular, the revised second law, plays a central role in discussing ecosystem self-organization and building SOHO descriptions. The concept of exergy is the focal point for the construction of narratives of the possible futures of ecosystems on this planet.

Acknowledgements:

This paper represents a synthesis of much of what I have thought about over the past twenty years. As such it is important to acknowledge that this paper reports on the results of extensive collaborations with several individual whose ideas are so intertwined with my own that it is not possible to tease them apart. The section on Thermodynamics and Self-organization draws heavily on my collaboration with Eric Schneider. The section on SOHO models owes much to my collaboration with Henry Regier and Michelle Boyle. I have also depended heavily on Roydon Fraser for discussions about exergy as a thermodynamic concept. Many conversations over the past twenty years with Bob Ulanowicz and Tim Allen have helped to shape my thinking about complex systems. More recently members of the Dirk Gently gang have also contributed much to my thinking. (Silvio Funtowicz, Jerry Ravetz, Mario Giampietro, Martin O'Connor, David Waltner-Toews, Tamsyn Murray and Gilberto Gallopin). I thank my grad students, Nina-Marie Lister, Kate Oxley, Richard Martell, and Beth Dempster (UW) and Charlotte Sunde (Massey University, N.Z.) for keeping me honest. Finally on

[5] Kay and Regier (1999)

this day of his retirement (1 August, 1999) I wish to acknowledge the inspiration throughout my career of the work of Buzz Holling and I dedicate this paper to him.

References

Allen, T.F.H.; Bandurski, B.L.; King, A.W. The Ecosystem Approach: theory and ecosystem integrity: International Joint Commission; 1993 (Report to the Great Lakes Science Advisory Board).

Allen, T. F. H.; Hoekstra, T.W. Toward a Unified Ecology. New York: Columbia University Press; 1992.

Allen, T. F. H.; Starr, T. B. Hierarchy: Perspectives for Ecological Complexity: University of Chicago Press; 1982.

Akbari, M., Murphy, S., Kay, J.J., Swanton, C., 1999. "Energy-Bases Indicators of (Agro)Ecosystem Health", in D. Quattrochi and J. Luvall (eds) *Thermal Remote sensing in Land Surface Processes* Ann Arbor Press

Bejan, A. (1997) **Advanced Engineering Thermodynamics**. New York: John Wiley and sons.

Blindow, I.; Andersson, G.; Hargeby, A., and Johansson, S. Long-term pattern of alternative stable states in two shallow eutrophic lakes. Freshwater Biology. 1993; 30:159-167.

Boltzmann, L. (1886). *The Second Law of Thermodynamics*. in McGinness, B. (1974). Ed. *Ludwig Boltzmann, Theoretical Physics and Philosophical Problems*. New York: D. Reidel.

Brzustowski, T.A., and P.J. Golem (1978) **Second Law Analysis of Energy Processes Part 1: Exergy-An Introduction.** Transactions of the Canadian Society of Mechanical Engineers. 4:209-218.

Caley M.T. and D. Sawada (eds.). 1994. Mindscapes: the Epistemology of Magoroh Maruyama. Gordon and Breach Science Publishers, Langhorne, Pennsylvania. xxiii + 206 pp.

Carathéodory, C. Investigations into the foundations of thermodynamics. in Kestin, J.(1976), Ed. *The Second Law of Thermodynamics:* (Benchmark Papers on Energy; v. 5). New York: Dowden, Hutchinson, and Ross. 229-256.

Carpenter, S. R., & K. L. Cottingham. 1997. Resilience and restoration of lakes. Conservation Ecology 1 (1): Article 2.

Casti, J. L. Complexification: Explaining a Paradoxical World Through the Science of Surprise. NY: Harper Collins; 1994.

DeAngelis, D. L.; Post, W. M.; Travis, C. C. Positive Feedback in Natural Systems. Berlin: Springer-Verlag; 1986

Dempster, M.L. "A Self-Organizing Systems Perspective on Planning for Sustainability", Masters Thesis, School of Planning, University of Waterloo, 1998.

Denbeigh, K. G. (1951). *The Thermodynamics of the Steady State*. London: Methuen LTD.

di Castri, F. The Evolution of Terrestrial Ecosystems. in Ravera, O., Ed. Ecological Assessment of Environmental Degradation, Pollution and Recovery. : Elsevier Science; 1987: pp.1-30

Fraser, R., Kay, J.J. "Surface temperature and Solar exergy" in D. Quattrochi and J. Luvall (eds) *Thermal Remote sensing in Land Surface Processes* Ann Arbor Press

Fermi, E. (1956; c1933.) *Thermodynamics*. London: Dover Publications.

Gaggiolo, Richard A. (1980) **Thermodynamics: Second Law Analysis:** American Chemical Society.

Gaggioli, Richard A., Ed. **Efficiency and Costing; Second Law Analysis** of Processes. Washington, D.C.: American Chemical Society; 1983.

Glansdorff, P.and I. Prigogine (1971). *Thermodynamic Theory of Structure, Stability, and Fluctuations*. New York:Wiley-Interscience.

Günther, F., Folke, C. Characteristics of Nested Living Systems. *Biological Systems*; 1993; 1(3): 257-274.

Hatsopoulos, G. and J. Keenan. (1965). *Principles of General Thermodynamics.* New York:John Wiley.

Hevert, H.; Hevert, S. **Second Law analysis: An alternative indicator of system efficiency.** Energy-The International Journal; 1980; 5(8-9): 865-873.

Holling, C.S. , "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change, *Sustainable Development in the Biosphere,* W.M.. Clark and R.E.. Munn, eds. (Cambridge: Cambridge University Press, 1986), pp. 292-320;

Holling, C.S. "Cross-scale Morphology, Geometry, and Dynamics of Ecosystems," *Ecological Monographs,* 62:4 , pp. 447-502.(1992)

Jantsch, Erich. The self-organizing universe : scientific and human implications of the emerging paradigm of evolution. Pergamon Press, 1980.

Jørgensen, S.E. and H. Mejer (1979). A holistic approach to ecological modeling. *Ecol. Modeling* ; 7:169:189.

Jørgensen, S. 1992. Integration of Ecosystem Theories: a Pattern. Elsever Publishing, London, U.K. 383 pp.

Kay, J.J. 1984. Self-organization in living systems. Ph.D. thesis. Systems Design Engineering, University of Waterloo, Waterloo, Ontario. 458 pp.

Kay, J.J. 1991. A nonequilibrium thermodynamic framework for discussing ecosystem integrity. Environmental Management 15(4): 483-495.

Kay, J.J., Schneider, E.D., 1992. "Thermodynamics and Measures of Ecosystem Integrity" in *Ecological Indicators*, Volume 1, D.H. McKenzie, D.E. Hyatt, V.J. Mc Donald (eds.), *Proceedings of the International Symposium on Ecological Indicators*, Fort Lauderdale, Florida, Elsevier, pp.159-182.

Kay, J.J. and E. Schneider. 1994. Embracing complexity, the challenge of the ecosystem approach. Alternatives 20(3): 32-39.

Kay, J.J.. 1997. Some notes on: The Ecosystem Approach, Ecosystems as Complex Systems. In: T. Murray, & G. Gallopin (eds.) *Integrated Conceptual Framework for Tropical Agroecosystem Research Based on Complex Systems Theories*;, pp. 69-98. Cali, Colombia. Centro Internacional de Agricultura Tropical, Working Document No. 167.

Kay. J., Regier, H., Boyle, M. and Francis, G. 1999. " An Ecosystem Approach for Sustainability: Addressing the Challenge of Complexity" *Futures* Vol 31, #7, Sept. 1999, pp.721-742

Kay. J., Regier, H.., 1999. "An Ecosystem Approach to Erie's Ecology" in M. Munawar, T.Edsall, S.Nepszy, G. Sprules & B. Shute (eds), *International Symposium. The State of Lake Erie (SOLE) - Past, Present and Future. A tribute to Drs. Joe Leach & HenryRegier* Backhuys Academic Publishers, Netherlands, pp.

Kestin, J. (1968). *A Course in Thermodynamics.* New York: Hemisphere Press.

King, A.W. Considerations of Scale and Hierarchy. Woodley, S.; Kay, J. ; Francis, G., (eds). Ecological Integrity and the Management of Ecosystems: St. Lucie Press; 1993: 19-46.

Koestler, A. and Smythies, J. R., eds. Beyond Reductionism. London: Hutchinson; 1969.

Koestler, A. 1978. Janus: a Summing Up. Hutchinson, London, U.K. vii + 354 pp.

Ludwig, D., B. Walker, B & Holling, C. S., 1997. Sustainability, stability, and resilience. Conservation Ecology. 1(1): Article 7.

J. C. Luvall, and H. R. Holbo, 'Measurements of short term thermal responses of coniferous forest canopies using thermal scanner data', *Remote Sens. Environ.,* 27, 1989, pages 1-10.

J. C Luvall, et.al., 'Estimation of tropical forest canopy temperatures, thermal response numbers, and evapotranspiration using an aircraft-based thermal sensor', *Photogrammetric Engineering and Remote Sensing*, 56, 10, 1990, pages 1393-1401.

J. C. Luvall, and H. R. Holbo, 'Thermal Remote Sensing Methods in Landscape Ecology', in M. Turner, and R.H. Gardner, *Quantitative Methods in Landscape Ecology,* Ch.6, (New York: Springer-Verlag, 1991).

Moran, M.J. (1982) **Availabilty Analysis: A Guide to Effecient Energy Use.** : Prentice-Hall

Moran, M. and Shapiro, H. Fundamentals of Engineering Thermodynamics. New York: John Wiley and sons; 1993.

Nicolis, G., Prigogine, I.; "Self-Organization in Non-Equilibrium Systems"; Wiley-Interscience, 1977.

Nicolis, G., Prigogine, I.; "Exploring Complexity"; Freeman, 1989.

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

Peacocke, A. R. The Physical Chemistry of Biological Processes. : Oxford University Press; 1983;

Prigogine, I. (1955). *Thermodynamics of Irreversible Processes*. New York: John Wiley.

Popper, K.R. 1990. A World of Propensities. Thoemmes, Brussels.

Rapport, D.J., H.A. Regier and T.C. Hutchinson. 1985. Ecosystem behavior under stress. American Naturalist 125: 617-640.

Rapport, D.J. and H.A. Regier. 1995. Disturbance and stress effects on ecological systems. Pp. 397-414 in S.E. Jorgensen and B.C. Patten (eds.) Complex Ecology: the Organization, Feedback and Stability. Prentice-Hall, New York.

Regier, H.A. and J.J. Kay. 1996. An heuristic model of transformations of the aquatic ecosystems of the Great Lakes - St. Lawrence River Basin. Journal of Aquatic Ecosystem Health 5: 3-21. Kluwer Academic Publishers.

Scheffer, M. 1990. Multiplicity Of Stable States In Freshwater Systems. Hydrobiologia 200/201: 475-486.

Scheffer, M. Ecology of Shallow Lakes. London: Chapman and Hall; 1998.

Scheffer, M. S.H. Hosper, M.L. Meijer, B. Moss and E. Jeppesen. 1993. Alternative equilibria in shallow lakes. TREE 8(8): 275-279.

Schneider, E. D. (1988). Thermodynamics, information, and evolution: new perspectives on physical and biological evolution. In Weber, B.H.; Depew, D.J.; and J.D. Smith, J. D., (ed.) *Entropy, Information, and Evolution: New Perspectives on Physical and Biological Evolution*. Boston: MIT Press, 108-138.

Schneider, E.D, Kay, J.J., 1994a "Complexity and Thermodynamics:Towards a New Ecology", *Futures* **24** (6) pp.626-647, August 1994

Schneider, E.D, Kay, J.J., 1994b, "Life as a Manifestation of the Second Law of Thermodynamics", *Mathematical and Computer Modelling*, Vol 19, No. 6-8, pp.25-48.

Schneider, E.D, Kay, J.J., 1995, "Order from Disorder: The Thermodynamics of Complexity in Biology", in Michael P. Murphy, Luke A.J. O'Neill (ed), *"What is Life: The Next Fifty Years. Reflections on the Future of Biology",* Cambridge University Press,pp. 161-172

Schrödinger, E. (1944.). *What is Life?:* Cambridge University Press.

Stigliani, W.M. Changes in valued "capacities" of soils and sediments as indicators of non-linear and time-delayed environmental effects. Int. J. Env. Mon. and Assess.; 1988; 10: 95-103

Szargut, J.; Morris, D. R.; Steward, F. R. **Exergy Analysis of Thermal, Chemical, and Metallurgical Processes:** Springer-Verlag; 1988.

Ulanowicz, R.E. 1995. Ecosystem integrity: a causal necessity. Pp. 77-87 in L. Westra and J. Lemons (eds.) Perspectives on Ecological Integrity, Kluwer Academic Publishers, Dordrecht, The Netherlands, vii + 279 pp.

Ulanowicz, R.E. 1996. The propensities of evolving systems. Pp. 217- 233 In: E.L. Khalil and K.E. Boulding (Eds.) Evolution, Order and Complexity. Routledge, London. 276p.

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

Ulanowicz, R. E. 1997. Limitations on the Connectivity of Ecosystem Flow Networks. IN: A. Rinaldo, & A. A. Marani (eds), *Biological Models: Proceedings of the 1992 Summer School on Environmental Dynamics*., pp.125- 143. Venice, Istituto Veneto di Scienze, Lettere ed Arti, Venice.

Wall, G. 1986. Exergy- A Useful Concept. Goteborg, Sweden: Physical Resource Theory Group, Chalmers University of Technology.

Wicken, J. S. Evolution, Thermodynamics, and Information: Extending the Dawinian Program. : Oxford University Press; 1987.