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Self-Organizing Systems and Environmental Management

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ABSTRACT / The characteristics of self-organizing systems are described and their implications for environmental management are discussed. It is concluded that the aim of management should be to enhance the capacity of the system for self-management, with active intervention being used only to steer it away from large discontinuities. Environmental managers must view ecosystems and themselves as parts of a larger sociobiophysical system, cultivate the capacity of environmental systems for self-management, and learn to live with change and uncertainty. Practical consequences of this approach for plans, policies, programs, and institutions are discussed.

Many environmentalists argue that environmental management must be based on a philosophy in which we cease to see ourselves as separate from a mechanistic natural world. Instead, we must believe ourselves to be integral parts of a unified whole in which all things are related (e.g., Fox 1984, Devall and Sessions 1985). The roots of this "deep ecology" lie in various spiritual and religious traditions, but advances in the understanding of self-organizing systems now provide scientific support for such a philosophy. This article introduces the main characteristics of self-organizing systems and then explores their practical implications. It concludes by outlining a strategy for environmental management.

Characteristics of Self-Organizing Systems

The Nature of Self-Organizing Systems

A self-organizing system produces complex organization from randomness without external intervention. In the words of Prigogine and Stengers (1984), it creates "order out of chaos." The simplest self-organizing systems are certain chemical reactions that produce spatial patterns of concentrations or oscillating "chemical clocks" (Prigogine and Stengers 1984). However, perhaps the best introduction is provided by the behavior of the computer game known as "Life," versions of which abound (Poundstone 1985).

"Life" is played on a grid in which "live" cells are black and "dead" cells are white. The game starts with a pattern of black and white cells, and the distribution for the next generation is calculated using four rules.

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A live cell with: 0 or 1 adjacent live cells dies of isolation; 2 or 3 adjacent live cells survives; 4–8 adjacent live cells dies of crowding. Finally, if a dead cell has three live neighbours it results in a birth. Two generations of a simple pattern known as an R-pentomino are shown in Figure 1.

When iterated over many generations, these simple rules can produce the most startlingly complex results. For example, the R-pentomino grows for 1103 generations before reaching a stable pattern that fits a rectangle of 51 × 109 cells plus six distant patterns known as gliders, which steadily move away (Poundstone 1985). Further, an initially random distribution of live cells gradually becomes organized into a stable pattern. A small disturbance to this pattern may cause only a slight change, or the pattern may be transformed as the mutation is amplified and spreads before a new equilibrium is reached. It has even proved possible to design patterns that reproduce themselves (Poundstone 1985).

Over a decade ago, James Lovelock (1979) hypothesized that the planet earth, or Gaia, is a self-organizing system in which conditions for life have been created and maintained over billions of years by life itself. Among the evidence adduced is the fact that planetary temperatures have remained more or less stable over a period when solar radiation has increased about 30%. Lovelock developed a simple computer model, "Daisyworld," to explain how this might happen.

Daisyworld is a planet like earth, with steadily increasing solar energy input, so that the temperature would rise gradually without regulation. Two types of daisy grow on the planet—one dark and one pale. Neither can grow if the temperature is too low or too high, and both grow best at an intermediate tempera-

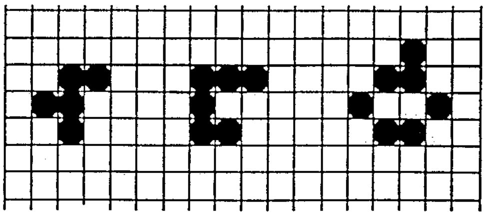

Figure 1. Two generations of the R-pentomino.

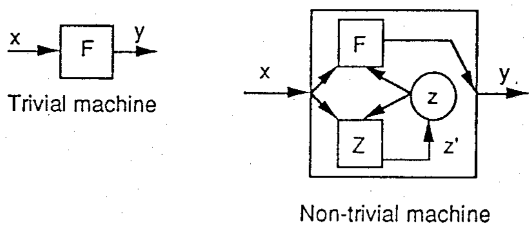

Figure 2. Trivial and nontrivial machines.

ture. The dark daisy absorbs more energy than the pale one or bare ground, and hence is warmed and warms its environment. Similarly, the pale daisy has a cooling effect.

As the sun gets hotter, there comes a time when the planet is just warm enough for daisies to grow. The dark one grows better because it is warmed to a more favorable temperature, and hence it spreads, and warms the planet, Eventually, as solar input increases, the temperature rises above the optimum. The pale daisy is now favored, and hence spreads and becomes dominmant until even it cannot survive. Experiments with this model showed that the two daisies are a very stable regulator of planetary temperature (Lovelock 1988).

Five characteristics are essential for a system to the self-organizing.

- It must be far from thermodynamic equilibrium.
- It must be governed by recursive application of internal rules. In other words, its state in the next time interval must be determined by the application of fixed rules to its state now. This is the basis for computer simulations of dynamic processes.
- At least some of its rules must be nonlinear.
- It must have positive feedback loops so that there is the potential for small changes to be amplified.
- It must be able to exchange energy with its surroundings in order to maintain its structure against the natural increase of entropy.

Finally, it must be emphasized that there is no need to invoke some higher purpose or goal-seeking behavior to explain self-organization.

Properties of Self-Organizing Systems

Self-organizing systems display a range of properties, which are summarized in this section.

The whole is greater than the sum of the parts. The behavior of a self-organizing system cannot be deduced from that of its constituent parts and the rules by which they interact. It can be determined only by operating the system or a model of it. Thus, no one has found a way of predicting the evolution of patterns in "Life" without running the program. Similarly, the properties of organic molecules cannot be predicted from those of carbon, hydrogen, and oxygen; the properties of a living cell cannot be predicted from those of organic molecules; and so on at larger scales.

Von Foerster (1984) illustrated this unpredictability by reference to trivial and nontrivial machines. A trivial machine is a system in which the input, x, is transformed by a driving function, F, to produce the output, y (Figure 2). Its behavior is totally predictable and is independent of its history. Further, the form of F may be deduced by observing the machine's behavior. By contrast, the output of a nontrivial machine is also dependent on its internal state, z, as shown in Figure 2. The new internal state, z', is determined in turn by x, z, and the state function, Z.

The nontrivial machine is synthetically deterministic in the sense that it is composed of deterministic components. However, the presence of this simple internal process makes its behavior unpredictable and dependent on its history. Further, it is not possible to deduce the internal structure by observing input and output values. For example, if there are four possible input states and two possible output states, von Foerster estimated that there are as many possible nontrivial machines as elementary particles in the universe!

Many natural systems display characteristics of nontrivial machines. For example, phytoplankton may be regarded as systems for transforming light and other inputs into oxygen. However, the relationship between input and output is dependent on the organism's history of light exposure, or its internal state.

They are self-controlled within larger-scale constraints. The term holon is used to describe certain types of systems. A holon is an independent, autonomous entity when viewed from the perspective of its constituent subsystems, such as an animal from the viewpoint of an organ. However, the same holon viewed from a larger scale appears as simply a component of the larger system, e.g., an animal in an ecosystem. Thus, large systems form a hierarchy of holons, potentially ranging in scale from the whole universe to subatomic particles. Within a system, the behavior of the smaller scale holons is constrained by the larger scales, as, for example, the nature and functions of a cell are controlled by the organism of which it is a part.

Within the constraints imposed by larger scales, the behavior of self-organizing systems is dominated by internal processes. Perhaps the best example of this is the human brain, whose structure and function is determined by the total human organism, but which has several orders of magnitude more internal connections than external sensors, so that the former dominate its behavior (Segal 1986). This means that external influences may produce little more than perturbations and be unable to exert control. For example, the internal temperature of mammals is maintained constant over a wide range of environmental temperatures.

They evolve. A self-organizing system evolves in the sense that the system's structure and relationships change with time so that its behavior changes irreversibly. Evolution is caused by random fluctuations originating in the environment or internally. Most such fluctuations are damped out, but if they are large enough or have the right characteristics, they may be amplified until they permanently modify the system. For example, in natural evolution most genetic mutations are disadvantageous and die out, but some are successful and lead to new species. Once such a species has evolved, the process cannot be reversed.

Evolutionary change is marked by bifurcation points at which two or more alternative paths are available. The path taken is very sensitive to random perturbations near the bifurcation point, and hence prediction is impossible. This is similar to the "butterfly effect" in chaos theory, where, at least in principle, the fluttering of a butterfly's wings in Beijing could affect the weather in Washington some time later. The difference is that in a self-organizing system it is the system itself that may be changed, and not simply its behavior. In the case of the atmosphere, such evolutionary change might take the form of a shift to a different global circulation pattern in response to altered energy fluxes resulting from small changes to its chemical composition.

Self-organizing systems may be stable for long periods, during which they behave deterministically or stochastically. However, eventually a fluctuation will occur that triggers evolutionary change. The further the system is from equilibrium, the smaller the fluctuations that can cause structural change, and the smaller the system discontinuity that occurs. Thus, far from equilibrium, change can be relatively smooth. Close to equilibrium, however, change may be less frequent but more radical. The speed of communication within the system and between the system and its environment is also important. The faster the communication, the larger the fluctuation that can be damped.

Self-Organizing Systems in Environmental Management

Most of the systems involved in environmental management are self-organizing, and two examples are discussed briefly in this section to illustrate the point. However, it should be noted that some relevant systems do not appear to be self-organizing. These include groundwater aquifers, and man-made systems such as pollution-control equipment.

Ecosystems

It is intuitively obvious that ecosystems are self-organizing, but nevertheless, it is worth demonstrating that they fulfill the formal criteria. They are clearly far from thermodynamic equilibrium, and use natural energy flows to maintain themselves. They are governed by recursive rules, many of which are nonlinear, as shown by the typical structure of ecosystem models. Examples of positive feedback are not hard to identify. For instance, in many parts of Australia, death or removal of native vegetation from an area may result in increased soil and water salinity and the death of further vegetation.

Ecosystem behavior cannot be deduced from that of component parts, as evidenced by the need for simulation models. Moreover, it is significantly determined by internal processes within regional climatic and geological constraints. System evolution occurs due to both human and natural disturbances. "We used to think that a forest was basically a group of species that had evolved together or been together for a very long time. Now what we find is that a forest community is a group of species that may have recently migrated together and then, in the future, might migrate in separate directions" (Oliver, cited by Dayton 1990). "The only constant factor in our forest ecosystems is change" (Shea and Underwood 1990).

The Economic System

Ecosystems and environmental managers may be regarded as holons within the larger sociobiophysical system. For example, future demand for natural resources from an ecosystem is determined by the type and rate of economic growth and the level of resource efficiency. Similarly, the nature and location of urban and industrial waste streams is determined by market forces, within legal and political constraints. Thus, the behavior of the economy is a central concern of environmental planners and managers.

Modern economies are maintained far from thermodynamic equilibrium by massive energy flows. Economic models rely on the recursive application of rules, and positive feedback is common. For example, in times of recession, workers are laid off, thus reducing their purchasing power and exacerbating the recession. The division of the discipline into macro- and microeconomics indicates that total system behavior cannot be understood from that of component parts. Furthermore, national and regional economies are clearly self-controlled to a significant extent, within constraints applied by the global economy and sociocultural factors. Finally, economic systems evolve with time and display quite frequent instability.

Self-organization in economic systems has been demonstrated by Allen (1981), who modified a classic supply-and-demand model to incorporate the effects of product quality. He showed that in this case there are many potential market equilibria, with the actual outcome depending on the precise timing and scale of a new product launch and the profit strategy of each company: ". . . our analysis shows us that for the same population, having the same 'value system,' for the same technology and the same products, the flow of goods in a given market can be both qualitatively and quantitatively different depending only on the 'history' of the system" (Allen 1981).

Allen (1981) extended this analysis to modeling the spatial evolution of cities in response to economic and other forces. "The structure that emerges depends on the timing and location of . . . each economic function, and is therefore merely one of many 'possible' structures . . . the spatial organization . . . does not result uniquely and necessarily from the 'economic and social laws' enshrined in the equations, but also represents a 'memory' of . . . deviations from average behaviour." These findings have major implications for urban land planning and other fields of environmental management.

Implications for Environmental Management

There is a rich literature on the implications of self-organization for economics, technological innovation, and management, among other fields. In this section, an attempt is made to summarize the key issues for environmental management.

Sustainability and the Evolutionary Paradigm

Over the last 50–100 years, social, economic, and technological systems have changed dramatically. Less obvious are the significant changes in natural and physical systems, mainly due to human interference. These changes are qualitative, and not simply quantitative, in the sense that the structures of the systems have changed so that models that were relevant in the past are no longer applicable. There is no reason to suppose that change will be any less rapid or profound over the next 50–100 years, and good reason to expect it to be more so.

Despite this, much of the thinking about the sustainability of environmental management embodies a "static" view of the world. For example, Brown and others (1987) identified the following common themes in definitions of sustainability:

- Continued support of human life on earth;
- Maintenance of biological and agricultural systems;
- Stable human populations;
- Limited growth economics;
- An emphasis on small scale and self-reliance; and
- Preservation of environmental quality.

These themes are pervaded by a sense of limited resources, an absence of opportunities, and the risks of change. Although many of the definitions recognize the reality of change, nevertheless a paradigm of evolution appropriate to self-organizing systems is missing. By contrast, Slocombe (1990) proposed a more dynamic vision of sustainability as "avoiding catastrophic change at the systemic and subsystemic level while retaining the capacity for creative self-organizing evolution without affecting the capacity of other similar, external, systems for the same persistence and evolution."

This failure to come to terms with evolutionary change is hardly surprising given that the Newtonian paradigm still dominates our thinking. This views the world as made up of interconnected components with a fixed structure and organization, and is concerned with how this machine works. By contrast, an evolutionary paradigm must be concerned primarily with how the system came into being, how its structure is maintained, and the processes of structural change. The challenge here can be illustrated by considering traditional approaches to system modeling (Allen 1988).

In order to think about reality, we are forced to reduce its complexity by grouping objects into classes and by aggregating properties and processes. No matter how good the choice of variables, parameters, and relationships may be, they are averages that smooth out much spatial diversity and short-term variability. Such a model can simulate the functioning of a static "average" system, but cannot evolve by changing its own structure as in real self-organizing systems. Indeed, despite the insights from chaos theory, instability in a computer model is still often regarded as a symptom of bugs in the model, rather than a potential reflection of real system behavior.

Including natural fluctuations in models can capture some of the richness of real system behavior. For example, Allen (1988) developed a model of a coastal fishing industry that included natural variations in the production of young fish. He found that these short-term events were amplified into long-term (order 20 year) cycles of boom and bust in the industry, which compared quite favourably with actual experience. However, such models are still an imperfect tool for exploring system evolution because there is no means other than hindsight by which variables or processes that are neglected as insignificant can be introduced if they become significant. Holling (1978) suggested that a range of alternative models should be developed and tested against historical data. He argued that the "chance exists that other models will meet these historical tests equally well but give very different predictions of future impacts. . ." If this proved to be the case, we would no longer have a single prediction of the future, but two or more alternative explorations of how the future might evolve.

Even this approach has limitations because all models are inevitably rooted in current paradigms, and none of them may capture some aspect of the system that later proves to be important. "There are many different 'facts' that are relevant . . . and any selection process . . . is bound to the moral and philosophical assumptions of the individual or organization. . ." (Grzybowski and Slocombe 1988). More fundamentally, self-organizing systems are inherently unpredictable, except for short time periods and small departures from the status quo, because of their sensitivity to small random perturbations. Thus, a basic premise of an evolutionary paradigm must be an acceptance that the future is unknowable.

Allen (1988) took the idea of an evolutionary approach to sustainability a step further. He described models of species competition in ecosystems that included the effect of random mutations, most of which were disadvantageous. This negative drift in population performance was balanced by a positive drift due to natural selection. Populations with mutations and variability were more successful than those with perfect reproduction. Allen extrapolated these ideas to social systems and concluded that what is important in an evolving world is not optimal performance so much as the ability to learn and create new solutions through exploration and error. He argued that people who weigh information carefully and seek to optimize their behavior provide stability and efficiency in society, but that it is the smaller number who behave randomly, ignoring conventional rationality, who enable the system to adapt creatively to new challenges.

Unpredictability, Planning, and Control

If the future is inherently unknowable, then technocratic control in the sense of management based on objective, scientific prediction of system behavior in response to alternative management inputs is impossible. "He who thinks that he is managing the evolution of a complex system is likely only managing the microscopic fluctuations, the incremental changes—optimizing the details and neglecting to anticipate possible qualitative changes. Then comes the surprise: a staggering realization that the old order no longer works" (Grzybowski and Slocombe 1988).

It also can be argued that attempts at technocratic control may be counterproductive in the long term. For example, human management of natural systems is generally aimed at reducing fluctuations in order to achieve more consistent and higher yields or to reduce disruptions to socioeconomic systems. Such management moves the system towards equilibrium, and away from evolutionary bifurcation points, with the result that larger perturbations are needed to trigger change in the system structure. The effect in the long-term may be infrequent but large system discontinuities rather than more frequent small adjustments. Examples include the crash of some managed fisheries, spruce budworm outbreaks (Holling 1978), depressions in managed economies, and increasing flood damages as a result of flood control works.

Few water resource systems are as controlled as those of California. For decades, the deserts have bloomed and huge cities have grown on assured supplies of cheap water harnessed at the expense of massive subsidies and extensive environmental damage. However, after five years of drought, the state was forced to cut off water supplies to farmers and to cut urban supplies by half. Federal authorities cut irrigation supplies by three quarters. Estimated losses in the rural economy ranged up to $4 billion, with the state paying farmers not to plant their land (Chatterjee 1991). It may yet be shown that decades of development and stability were bought at the price of major longer-term dislocations. If a less controlling and smaller-scale approach to water resources had been taken, limits would have been apparent sooner, constraining unsustainable urban growth and rural development, encouraging water efficiency, and minimizing environmental impacts. Dislocation now might have been avoided at the expense of less economic growth and affluence in the past.

While technocratic management may not be possible, self-organizing systems can be influenced by deliberate introduction of perturbations such as effluent standards. The problem is that we cannot be sure what the effect of a particular perturbation will be on the whole socioeconomic system in the long term, even if we have a fairly good understanding of the effect of effluent standards on local industrial subsystems in the short term. Hence management must be significantly experimental. However, we can reduce the potential for long-term surprise by adopting appropriate planning and management processes.

Grzybowski and Slocombe (1988) and Slocombe (1990) developed a qualitative process for management of regional sociobiophysical systems such as river basins. They sought to understand the historical dynamics of component subsystems at a range of spatial and temporal scales, and to identify critical variables and processes that had lead to discontinuities in the past or might lead to system transformations in the future. They focused on periods of instability and macroscopic change, rather than on periods of stability. They did not seek to predict the future, but rather to understand the processes of change "in the expectation that this will improve the ability to monitor and manage complex . . . systems." The approach has similarities to certain studies of technological change (e.g., Freeman and Perez 1988) and futures research methods (e.g., Tydeman 1987, Naisbitt 1982).

One consequence of focusing on processes of change is the need to monitor trends in key variables and processes in order to detect when major discontinuities may be about to occur. Once again, however, selection of parameters to monitor is dependent on current paradigms, and there will continue to be a risk of surprise due to failure to correctly identify the key factors.

"In contrast to a widely held belief, planning in an evolutionary spirit . . . does not result in the reduction of uncertainty and complexity, but in their increase. Uncertainty increases because the spectrum of options is deliberately widened; imagination comes into play. Instead of doing the obvious, the not-so-obvious is also deliberately sought out and taken into consideration. Complexity increases because the immediate domain of the organization in question . . . is transcended and relations within the larger system of society, culture or the world at large move into the foreground. Reality IS complex and evolution manifests in the increase of this complexity." (Jantsch 1980)

Management Structures and Roles

Given that the future is unknowable and that periodic surprises are inevitable, management must be flexible and adaptable. However, hierarchical command structures, such as bureaucracies, tend to protect existing institutions and values, thus reducing openness to change. By comparison, "heterarchy" is both more flexible and better able to cope with complex situations (von Foerster 1984). The difference may be illustrated by the contrast between a ship's crew (hierarchy) in which the crew act only in response to explicit orders from the captain, and a football team (heterarchy) in which each player takes responsibility for his actions within general guidelines set by the captain.

Heterarchy works well because, like the market economy, it can process more information and mutually adjust more relationships than hierarchy (Malik and Probst 1984). Similarly, research shows that hierarchical communication and power structures work well when the task is simple, but fail completely when it is complex. By contrast, democratic groups with no power hierarchy and free interchange of information perform well (von Foerster 1984, Burke and Heaney 1975). An example of heterarchy in practice is the battle of Midway in the Second World War in which the US flagship was sunk at the start. The fleet organized itself by the captain of each vessel taking command of the whole fleet whenever he was in a position to know best what to do, resulting in a resounding victory (von Foerster 1984).

Self-organization also has major implications for the role of management (Jantsch 1980). Managers are holons within the larger socioeconomic and natural systems and hence are parts of the systems they seek to manage. As von Foerster (1984) expressed it, a world of separate organizers and organizations is a world of "thou shalt. . .," but a world where organization and organizer merge is a world of "I shall. . . ." One consequence of this perception and the fact that system evolution depends on small perturbations is that each participant in the system is also a manager of it. Further, goals can do no more than point the direction to start, and senior management become managers of change, dealing with the exceptional cases where self-organization fails (Ulrich 1984). Thus, "as managers we have to . . . learn to be what we really are: not doers and commanders, but catalysts and cultivators of a self-organising system in an evolving context" (von Foerster 1984). "Management's task consists above all in providing social systems with a capability for self-control" (Ulrich 1984).

Conclusion: Towards a New Strategy for Environmental Management

The concepts of self-organization reveal new ways of understanding the world that demand new strategies for environmental management. Elements of such a strategy are summarized below.

The aim of planning and management should be to enhance the capacity of the system for self-management. Active intervention should be used only to steer the system away from large discontinuities, not to achieve or maintain an optimal equilibrium state. The distinction being made here may be illustrated imperfectly by reference to management of national economies. The communist ideal of a planned "command and control" economy has been discredited, and capitalist "free market" theories are in the ascendancy, but even the most extreme free-marketeers do not eschew all interventions. Rather than impose direct controls, however, they seek indirect means of influencing the market in order to avoid problems such as recession, and they try to stimulate the market's self-organizing ability by providing incentives and removing government constraints. This should not be taken as a blanket endorsement of free-market ideology or of the market approach to environmental management. However, it does demonstrate the essential difference in management philosophy being suggested.

In order to foster self-organization, environmental managers must:

- View ecosystems as part of a larger sociobiophysical system which may be the source of external stimuli with the capacity to trigger major system changes;
- View themselves as parts of the system they manage, and other participants in the system as managers as well;
- Recognize and cultivate the capacity of the systems they manage for self-organization rather than trying to control them;
- Learn to live with change and uncertainty, ready "to engage with full ambition and without any reserve in the structure of the present, and yet to let go and flow into a new structure when the right time has come" (Jantsch 1980).

More pragmatically, managers should:

- Seek to understand the processes of change, and identify key variables and processes that may amplify fluctuations;
- Explore possible alternative futures rather than seek to predict the future;
- Monitor key variables and processes in order to detect potential discontinuities;
- Maximize the flexibility of plans, programs, infrastructure systems, and organizations;
- Maximize the number of options available at all times;
- Prolong processes which seem to run in creative directions, stop those which appear unpromising, and eliminate those deemed uncreative;
- Make frequent incremental adjustments to the system rather than major changes;
- Use technologies that harmonize with the surrounding natural and social systems rather than being imposed on them.

This approach also has implications for institutions and technologies. The needs for flexibility, creativity, and a broad, systemic view are more likely to be met within relatively small, interdisciplinary groups with a heterarchical structure than within traditional sectoral agencies. Such decentralization, coupled with the perception that all citizens are managers of the system, necessitates effective and widespread communication of all relevant information. Similarly, the need for flexible and adaptable management systems that harmonize with the environment implies a move towards smaller, more diverse, and decentralized technologies (Clark 1990).

It is intriguing that the elements of this strategy derived from the literature on self-organizing systems are similar in many respects to those proposed by "deep ecologists" and advocates of "green politics."

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