

Panarchy
*Understanding Transformations in
Human and Natural Systems*

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Risk
Uncertainty
Degradation
Collapse
Biodiversity
~~Extinction~~

Top-down
Bottom-up
System
Variables

Evolution
History

Scale
Surprise
Novelty
Crisis

Cross-scale
CPR

Governance
Stakeholders
Management

Adaptation
Discipline-EEIF

Slow-moving variables (slow variables)

Efficiency
Productivity
Optimization
Evolutionary Stable State

Myths of Nature

Nature Flat = high modernism

Nature Bland = US4 + Carrying capacity

Efficiency vs. Resilience
Lock-in

Diversity

Genetic

Species

Functional

Patch/Landscape

CHAPTER 1

IN QUEST OF A THEORY OF ADAPTIVE CHANGE

C. S. Holling, Lance H. Gunderson, and Donald Ludwig

In all things, the supreme excellence is simplicity.

—Henry Wadsworth Longfellow

In the last decades of the twentieth century, cascades of changes occurred on a global scale. Collapse of the former Soviet Union and its continuing struggle for stability and for ways to restructure have propagated international reverberations far beyond its borders. Increases in connectivity through the Internet are stimulating a flowering of novel experiments that are affecting commerce, science, and international community. Migrations of people, some forced by political upheaval and some initiated as a search for new opportunity, are both threatening and enriching the international order. There have been dramatic changes in global environmental systems—from climate change that is already upon us, to the thinning of the stratospheric ozone layer. Novel diseases have emerged in socially and ecologically disturbed areas of the world and have spread globally, through the increased mobility of people. The tragedy of AIDS, and its origins, transformation, and dispersion because of land-use and social changes, is a signal of deep and broad changes that will yield further surprises and crises. More and more evidence indicates that global climate change has already produced an increase in severe weather that, combined with inappropriate coastal development, has caused dramatic rises in insurance claims and human loss of life. Still other more subtle changes linking ecological, economic, and social forces are occurring on a global scale, such as the typical example described in Box 1-1, regarding the collapse of fisheries.

These examples of global environmental change signal that the stresses on the planet have achieved a new level because of the intensity and scale of human activities. Are these activities leading to a world with impoverished

Box 1-1. Fishing down the Food Web

D. Ludwig

Although total catch levels for marine fisheries have been relatively stable in recent decades, analysis of the data shows that landings from global fisheries have shifted from large piscivorous fishes toward smaller invertebrates and planktivores (Pauly et al. 1998). This shift can be quantified through assignment of a fractional trophic level to each species, depending on the composition of the diet. The values of these trophic levels range from 1 for primary producers to over 4.6 for a few top predators such as a tuna in open water and groupers and snappers among bottom fishes. For data aggregated over all marine areas, the trend over the past forty-five years has been a decline of the mean trophic level from over 3.3 to less than 3.1. In the Northwest Atlantic, the mean trophic level is now below 2.9. There is not much room for further decreases, since most fish have trophic levels between 3 and 4. Indeed, many fisheries now rely on invertebrates, which tend to have low trophic levels.

Global trends appear to show a decline of 0.1 trophic level per decade. This is an underestimate of the actual change, since data from many areas, especially in the tropical developing countries, are lumped into categories such as "mixed fishes" that do not reflect changes in trophic level. Moreover, the analyses performed so far did not consider the decline in trophic level that occurs within species due to the increased removal of older fishes, which tend to have higher trophic levels than the young of the same species. It is likely that a continuation of present trends will lead to widespread fisheries collapses. These trends cast doubt on the idea of estimating future catches by extrapolation of present trends.

The costs of this devastation are difficult to observe since the massive exploitation of stocks is often associated with a displacement of small-scale traditional fisheries by large industrial ones. The small fishers are then jobless, and they move to cities. The costs of this conversion of members of society from being productive to being unproductive are borne by the society as a whole and are not ascribed to displacement from the fishery.

mate collapse of civil society? Or is that too easy a conclusion? Contradicting projections of collapse is the possibility that human foresight and innovation can reverse those trends and develop paths that sustain natural diversity and

We do not intend to evaluate the degradation and potential for collapse of human and natural systems in this book. That has been done as well and as objectively as can be expected elsewhere (McNeill 2000). Even raising the question triggers controversy that is not particularly well founded on objective fact or adequate theory.

Instead, our purpose is to develop an integrative theory to help us understand the changes occurring globally. We seek to understand the source and role of change in systems—particularly the kinds of changes that are transforming, in systems that are adaptive. Such changes are economic, ecological, social, and evolutionary. They concern rapidly unfolding processes and slowly changing ones—gradual change and episodic change, local and global changes.

The theory that we develop must of necessity transcend boundaries of scale and discipline. It must be capable of organizing our understanding of economic, ecological, and institutional systems. And it must explain situations where all three types of systems interact. The cross-scale, interdisciplinary, and dynamic nature of the theory has led us to coin the term *panarchy* for it. Its essential focus is to rationalize the interplay between change and persistence, between the predictable and unpredictable. Thus, we drew upon the Greek god Pan to capture an image of unpredictable change and upon notions of hierarchies across scales to represent structures that sustain experiments, test results, and allow adaptive evolution.

We start the search for sufficient theory by turning to examples where there is adequate history—examples of interactions between people and nature at regional scales. There we see patterns of change that are similar to the more recent global ones—but examples where there has been more history of response. These include dramatic changes in the ecosystems and landscapes of ecosystems, with subsequent changes for society and economic conditions. There have been spasms of biodiversity loss as a consequence of the intersection of climate extremes, poor land use, and global economic pressures. In places, such as in some nations in southeast Africa, these exacerbate political instability. The results are not only erosion of the natural world but also erosion of trust in the institutions of governance. But in other places there has been notable learning. Degraded systems have been restored, organizations restructured, and management revitalized.

How do we begin to track down the cause of the failures and explain the occasional successes? Consider some recent resource management failures:

- Some fisheries have collapsed in spite of widespread public support for sustaining them and the existence of a highly developed theory of fisheries management.
- Moderate stocking of cattle in semiarid rangelands has increased vulnerability to drought.

• Drought has created pest outbreaks that become chronic

- Flood control and irrigation developments have created large ecological and economic costs and increasing vulnerability.

A number of cases point to a common cause behind such examples of failure of management of renewable resources (Holling 1986; Gunderson et al. 1995a). In each case, a target variable (fish stock, meat production, pest control, or water level) is identified and successfully controlled. Uncertainty in nature is presumed to be replaced by certainty of human control. Social systems initially flourish from this ecological stabilization and resulting economic opportunity. But that success creates its own failure.

We now know that the stabilization of target variables like these leads to slow changes in other ecological, social, and cultural components—changes that can ultimately lead to the collapse of the entire system. A pattern of events emerges: at the extreme, the ecological system fails, the economic system reconfigures, and the social structures collapse or move on. Moderate, stabilized grazing by cattle reduces the diversity of the rangeland grasses, which eventually leads to fewer drought-resistant species, less permeable soils, and poor water retention. Pest control leads to more luxuriant growth of the host plants and hence creates more favorable conditions for survival and reproduction of the pest. Effective flood control leads to higher human settlement densities in the fertile valleys and a large investment in vulnerable infrastructure. When a large flood eventually overwhelms the dams and dikes, the result is often a dramatic reconfiguration of the social and economic landscape along the river. And, as described in Box 1-1, the initial success of fisheries leads to an increase in investment and overexploitation of the resource. When the fish stock shows signs of distress, management agencies become paralyzed, the public loses trust in governance, and human institutions are unable to make the required adjustments.

The pattern common to these examples leads to the first of two paradoxes that complicate any quick and easy predictions of collapse and disaster:

- **Paradox 1. The Pathology of Regional Resource and Ecosystem Management**

Observation: New policies and development usually succeed initially, but they lead to agencies that gradually become rigid and myopic, economic sectors that become slavishly dependent, ecosystems that are more fragile, and a public that loses trust in governance.

The Paradox: If that is as common as it appears, why are we still here? Why has there not been a profound collapse of exploited renewable resources and the ecological services upon which human survival and development depend?

The observed pattern of failure can be analyzed from an economic

sources are appropriated by powerful minorities able to influence public policy in ways that benefit them. Hence inappropriate measures such as perverse subsidies are implemented that deplete resources and create inefficiencies (Magee, Brock, and Young 1989). A fundamental cause of the failures is the political inability to deal with the needs and desires of people and with rent seeking by powerful minorities.

But as part of the fundamental political causes of failure, there are, as well, contributing causes in the way many, including scientists and analysts, study and perceive the natural world. Their results can provide unintended ammunition for political manipulation. Some of this ammunition comes from the very disciplines that should provide deeper and more integrative understanding, primarily economics, ecology, and institutional analysis. That leads to the second paradox: the trap of the expert. So much of our expertise loses a sense of the whole in the effort to understand the parts.

- **Paradox 2. The Trap of the Expert**

Observation: In every example of crisis and regional development we have studied, both the natural system and the economic components can be explained by a small set of variables and critical processes. The great complexity, diversity, and opportunity in complex regional systems emerge from a handful of critical variables and processes that operate over distinctly different scales in space and time.

The Paradox: If that is the case, why does expert advice so often create crisis and contribute to political gridlock? Why, in many places, does science have a bad name?

We begin unraveling these paradoxes with an examination of the obstacles that arise not just from multiple, competing scientific perspectives but also from disciplinary hubris. The complex issues connected with the notion of sustainable development are not just ecological problems, or economic, or social ones. They are a combination of all three. Actions to integrate all three typically shortchange one or more. Sustainable designs driven by conservation interests can ignore the need for a kind of economic development that emphasizes synergy, human ingenuity, enterprise, and flexibility. Those driven by economic and industrial interests can act as if the uncertainty of nature can be replaced with human engineering and management controls, or can be ignored altogether in deference to Adam Smith's "invisible hand" of the perfect market. Those driven by social interests often presume that nature or a larger world presents no limits to the imagination and initiative of local groups

Compromises among those viewpoints can be arrived at through the political process. However, mediation among stakeholders is irrelevant if it is based on ignorance of the integrated character of nature and people. The results may be momentarily satisfying to the participants but ultimately reveal themselves as based upon unrealistic expectations about the behavior of natural systems and the behavior of people. As investments fail, the policies of government, private foundations, international agencies, and nongovernmental organizations flop from emphasizing one kind of partial solution to another. Over the last three decades, such policies have flopped from large investment schemes to narrow conservation ones to, at present, equally narrow community development ones.

Each approach is built upon a particular worldview or theoretical abstraction, though many would deny anything but the most pragmatic and nontheoretical foundations. The conservationists depend on concepts rooted in ecology and evolution, the developers on variants of free-market models, the community activists on precepts of community and social organization. All these views are correct, in the sense of being partially tested and credible representations of one part of reality. The problem is that they are partial. They are too simple and lack an integrative framework that bridges disciplines and scales.

Partial Truths and Bad Decisions

The fields of economics, ecology, and organizational or institutional analysis have developed tested insights. Yet there is growing evidence that the partial perspectives from these disciplines generate actions that are unsustainable. One way to generate more robust foundations for sustainable decision making is to search for integrative theories that combine disciplinary strengths while filling disciplinary gaps. But before we can begin such a task, we should examine the partial constructs that characterize these fields.

Economics

Modern neoclassical economics has gone far in discovering the process whereby millions of decisions made by individuals give rise to emergent features of communities and societies (e.g., the rate of inflation, productivity gains, the level of national income, prices, stocks of various types of capital, cultural values, and social norms). Two factors make economic theory particularly difficult. First, individual decisions at any moment are themselves influenced by these emergent features and by past decisions. Learning, practice, and habit influence the moment as much as present prices do. Second, the emergent features that can be well handled by standard neoclassical economic theory and policy concern only fast-moving variables that define present conditions. The more slowly emergent properties that affect attitudes, culture, and institutional arrangements are recognized but are rarely

incorporated. The high discounting commonly employed in applications of neoclassical economic theories does not allow the possibilities beyond a decade or two in the future to influence present decisions.

Economists know that success in achieving financial return from fast dynamics leads to slowly emergent, nearly hidden, changes in deeper and slower structures, changes that ultimately trigger sudden crisis and surprise. But the complexities that arise are such that many modern economists are frustrated in their attempts to understand the interactions between fast- and slow-moving variables that create emergent dynamics (Stiglitz 1998). Chapters 7, 8 and 10 begin to expose the consequences and solutions.

Ecology

Ecosystem ecologists, on the other hand, have made it plain for a long while that some of the most telling properties of ecological systems emerge from the interactions between slow-moving and fast-moving processes and between processes that have large spatial reach and processes that are relatively localized. Those interactions are not only nonlinear; they generate alternating stable states and normal journeys of biotic and abiotic variables through those states. Those journeys—measured in decades and centuries—maintain the diversity of species, spatial patterns, and genetic attributes. They maintain the resilience of ecological systems.

Variability in ecosystems is not merely an inconvenient characteristic of these productive, dynamic systems. It is essential for their maintenance. Ecologists are beginning to understand the way that variability and diversity are created by and sustain ecosystems because of interactions among slow and fast processes, large and small. Both Chapters 2 and 3 review and expand that understanding. Reducing variability and diversity produces conditions that cause a system to flip into an irreversible (typically degraded) state controlled by unfamiliar processes.

But ecologists limit their understanding and propose inadequate actions by largely ignoring the realities of human behavior, organizational structures, and institutional arrangements that mediate the relationships between people and nature.

Institutions and Organizations

Institutional and organizational theory and analysis do consider such features but in a largely static sense. They often stop short of the required integration of the three fields of inquiry. Institutional and organizational theory currently provides a fascinating understanding of the variety of arrangements and rules that have evolved in different societies to harmonize the relation between people and nature. Social scientists have gone far in describing the way people store, maintain, and use knowledge in stable circumstances. But they have not attended to the processes that control and

maintain these institutions dynamically, the kind of dynamic causation that is present in economics and ecology.

In order to plan for sustainability, we need to know, and we need to integrate, how information is evaluated and counterproductive information rejected. How is new “knowledge” created from competing information sources and incorporated with useful existing knowledge? Which processes create novelty, which smother innovation, which foster it? Those questions are explored in Chapters 4, 5, and 13. Neither ecology, nor economics, nor institutional theory now deals well with these fundamental questions of innovation, emergence, and opportunity. That is what evolutionary theory is about.

Evolution and Complex Systems

The emergence of novelty that creates unpredictable opportunity is at the heart of sustainable development (Holling 1994b). Biological evolutionary theory—which can be expanded to include cultural evolution—deals with just this process. The new field of complexity studies sees ecological, economic, and social systems as being similar to biological processes that generate variability and expose the patterns that result to selective forces. But, like each of the other fields, the representations are partial. They are detached from deep knowledge of the key natural and human processes, and from convincing tests of the adequacy and credibility of the results.

In this book we argue that the process of developing policies and investments for sustainability requires a worldview that integrates ecological with economic with institutional with evolutionary theory—that overcomes disconnects due to limitations of each field. But as compelling and easy as it is to criticize disciplinary gaps, they are clearly not the only reason for unsustainable practices. There are other, deeper limitations that arise from worldviews that people hold. These worldviews are also partial representations of reality: representations that are valuable because they provide temporary certitude to allow action, but whose partial nature ultimately exposes their inadequacy. They are caricatures of aspects of reality.

Caricatures of Nature

Although some of the failures of complex resource systems are due to limitations in disciplinary theories and experience, others can be traced to differences among the worldviews or myths that people hold. In this section we identify at least five such caricatures that underlie explanations of how nature works and the implications of those assumptions on subsequent policies and actions (Figure 1-1). Each of these caricatures, or myths, leads to different assumptions about stability, different perceptions of the processes that affect that stability, and different policies that are deemed appropriate (Table 1-1). We begin with the most static view: that of a nature lacking stabilizing forces. “Nature Flat”

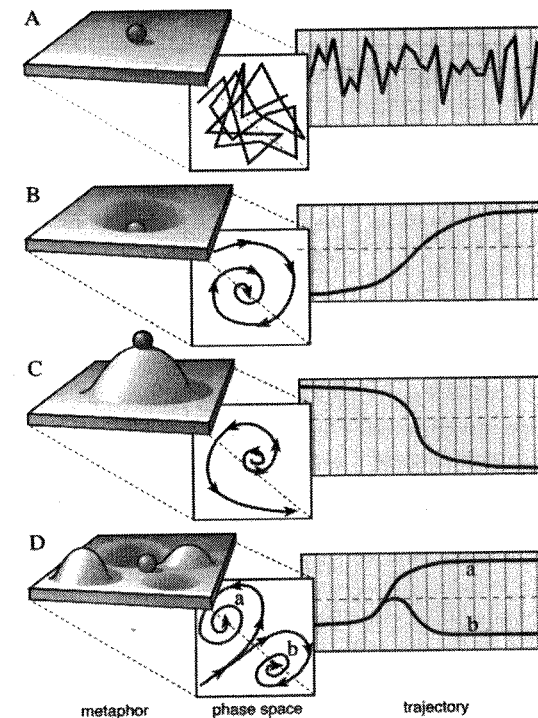


Figure 1-1. Depictions of four myths of nature: (A) Nature Flat, (B) Nature Balanced, (C) Nature Anarchic, and (D) Nature Resilient. Each myth has three representations or metaphors: as stability landscape (left), phase diagram (center), and time-course chart or trajectory of key system variables over time (right).

Nature Flat. In this view, “flat” is used to describe a system in which there are few or no forces affecting stability. There are therefore few limitations on the ability of humans to change nature. There are no feedbacks or consequences from nature of human actions. It is much like rolling a ball around on a cookie sheet (Figure 1-1 A). The processes that affect the position of the ball—i.e., state of nature—are random or stochastic. In such a view of nature, policies and politics are random as well, often described as “garbage can” politics (March and Olsen 1989; Warglien and Masuch 1996). It is a nature that is infinitely malleable and amenable to human control and domination if only the “right” values and the “right” timing are chosen. The issues of resource use, development, and control are identified as issues that are exclusively of human action, issues that can be resolved by community activism or stakeholder control. Alternatively, it can be a view of cornucopian nature where human ingenuity and knowledge surmount all obstacles to produce exponential growth. Such a “flat worlder” view is not wrong, just incomplete. There are indeed strong stochastic elements; the timing of

Table 1-1. Characteristics of Alternative Views or Myths of Nature

	Stability	Processes	Policies	Consequence
Nature Flat	none	stochastic	random	trial and error
Nature Balanced	globally stable	negative feedback	optimize or return to equilibrium	pathology of surprise
Nature Anarchic	globally unstable	positive feedback	precautionary principle	status quo
Nature Resilient	multiple stable states	exogenous input and internal feedback	maintain variability	recovery at local scales or adaptation; structural surprise
Nature Evolving	shifting stability landscape	multiple scales and discontinuous structures	flexible and actively adaptive, probing	active learning and new institutions

Nature Balanced. The second myth is a view of nature existing at or near an equilibrium condition (Figure 1-1 B). That equilibrium can be a static one or a dynamic one. Hence if nature is disturbed, it will return to an equilibrium through (in systems terms) negative feedback. Nature appears to be infinitely forgiving. It is the myth of maximum sustainable yield and of achieving fixed carrying capacities for animals and humanity. It imposes a static goal on a dynamic system. This view of nature underpins prescriptions for logistic growth, where the issue is how to navigate a looming and turbulent transition—demographic, economic, social, and environmental—to a sustained plateau. This is the view of several organizations with a mandate for reforming global resource and environmental policy—of the Brundtland Commission, the World Resources Institute, the International Institute of Applied Systems Analysis, and the International Institute for Sustainable Development. Many individuals in these and similar institutions are contributing skillful scholarship and policy innovation. They are among some of the most effective forces for change, but the static assumptions can create the

also not wrong—just incomplete. There are indeed, forces of balance in the world, forces that can become overwhelmed.

Nature Anarchic. If the previous myth is one where the system stability could be defined as a ball at the bottom of a cup, this myth is one of a ball at the top of a hill (Figure 1-1 C). It is globally unstable. It is a view dominated by hyperbolic processes of growth and collapse, where increase is inevitably followed by decrease. It is a view of fundamental instability, where persistence is possible only in a decentralized system where there are minimal demands on nature. It is the view of Schumacher (1973) and some environmentalists. If the Nature Flat view assumes that infinitely ingenious humans do not need to learn anything different, this view assumes that humans are incapable of learning. This is implicit in the writings of Tenner (1996), where he argues that all technology that is unleashed will eventually “bite back.” This view presumes that small is beautiful, because the inevitable catastrophe of any policy must be kept localized. It is a view where the precautionary principle of policy dominates, and social activity is focused on maintenance of the status quo. The “anarchist worlder” view is also not wrong—just incomplete. There are indeed destabilizing forces, and there is a value in diversity of the small and local.

Nature Resilient. The fourth is a view of multistable states, some of which become irreversible traps, while others become natural alternating states that are experienced as part of the internal dynamics (Figure 1-1 D). Those dynamics result from cycles organized by fundamentally discontinuous events and nonlinear processes. There are periods of exponential change, periods of growing stasis and brittleness, periods of readjustment or collapse, and periods of reorganization for renewal. Instabilities organize the behaviors as much as stabilities do. That was the view of Schumpeter’s (1950) economics, and it has more recently been the focus of fruitful scholarship in a wide range of fields—ecological, social, economic, and technical. These dynamics are the ones argued for ecosystems (Holling 1986). They have similarities in Harvey Brooks’s view of technology (1986); recent views of the economics of innovation and competition (Arthur, Durlauf, and Lane, 1997); Mary Douglas’s (1978) and Mike Thompson’s (1983) view of cultures; Don Michael’s view of human psychology (1984); and Barbara Tuchman’s (1978) and William McNeill’s (1979) view of history. It is a view of multiple stable states in ecosystems, economies, and societies and of policies and management approaches that are adaptive. But this view presumes a stationary stability landscape—stationary underlying forces that shape events. In this case, our cookie sheet has been molded and curved in three dimensions, but its basic contours are fixed over time (Figure 1-1 D). This “resilient worlder” view is also not wrong—just incomplete. There are, indeed, cycles of change that can move variables among stability domains, but those very movements contribute to the apparent fixed nature of the contours. Constrain those movements through policy actions, and the contours shift, as slow variables

sequence of successful but myopic policy. Many of the examples of the pathology of resource management and regional development are just those kinds of structural surprises.

Nature Evolving. The emerging fifth view is evolutionary and adaptive. It has been given recent impetus by the paradoxes that have emerged in successfully applying the previous more limited views. Complex systems behavior, discontinuous change, chaos and order, self-organization, nonlinear system behavior, and adaptive evolving systems are all code words characterizing the more recent activities. They are leading to integrative studies that combine insights and people from developmental biology and genetics, evolutionary biology, physics, economics, ecology, and computer science. Profound innovations have been created and led by John Holland in his applications of genetic algorithms and development of complex adaptive system theory. His more recent work on a simple, highly visual model that illustrates the creation of complex structures by natural selection (Holland 1995) presents a way to explore the generation and selection of novelty in mathematical, economic, and social systems. In economics, some examples of early developments are in Anderson, Arrow, and Pines (1988). A nice review of later work is Sargent (1993), and a current collection of articles is presented in Arthur, Durlauf, and Lane (1997). Marco Janssen extends and applies those approaches to explore changing perspectives on future behavior in Chapter 9. It is a view of an actively shifting stability landscape with self-organization (the stability landscape affects behavior of the variables, and the variables, plus exogenous events, affect the stability landscape). Levin's recent book, *Fragile Dominion* (1999), gives an accessible and effective treatment of present adaptive, complex systems views for ecology.

Nature Evolving is a view of abrupt and transforming change. It is a view that exposes a need for understanding unpredictable dynamics in ecosystems and a corollary focus on institutional and political flexibility. We cannot, at this stage, invent a simple diagram to add this myth to those shown in Figure 1-1. In a sense, that is the purpose of the book—to develop a sufficiently deep understanding of Nature Evolving that its essential behavior and the relevant policies can be captured in a few paragraphs, a few simple models of real situations and a simple set of suggestive diagrams. Subsequent chapters provide the understanding to do just that using the theoretical framework of panarchy.

Many of the examples of successful resource exploitation followed by collapse are based on the above-mentioned myths of nature. The concepts of stability and resilience embedded in these caricatures can be given meaning in the metaphor of raft described in Box 1-2. These myths are useful underpinnings for understanding and action. Yet they reveal a paradox that goes back hundreds of years in thought. That is, if human exploitation leads to resource collapse, why haven't all ecological systems collapsed, and why are we humans still here? We discuss that paradox in the following section.

Why Has the World Not Collapsed?

Part of the answer to this paradox is that natural ecological systems have the resilience to experience wide change and still maintain the integrity of their functions. The other part of the answer lies in human behavior and creativity. People do learn, however spasmodically. Change and extreme transformations have been part of humanity's evolutionary history. People's adaptive capabilities have made it possible not only to persist passively, but to create and innovate when limits are reached.

The reason for the astonishing resilience of natural ecosystems can be found in examining the scales at which processes (including human-dominated ones) operate to control the system. In most terrestrial systems, geophysical controls dominate at scales larger than tens of kilometers. At scales smaller than this, biotic processes, interacting with abiotic ones, can control structure and variability. They produce volumes and patterns of vegetation and soil, for example, that moderate external extremes of temperature, conserve moisture and nutrients, and even affect regional climate and the timing of seasons. These are also the scale ranges where human land use transformations occur so that the arena where plant- and animal-controlling interactions unfold is the same arena where human activities interact with the landscape. That is why human population growth and development are so inexorably interconnected with terrestrial ecosystem resilience.

The controls determined by each set of biotic structuring processes within terrestrial ecosystems are remarkably robust, and the behaviors resulting are remarkably resilient. That robustness comes from functional diversity and spatial heterogeneity in the species and physical variables that mediate the key processes that structure and organize patterns in ecosystems and landscapes. The stability domains that define the type of system (e.g., forest, savanna, grassland, or shrub steppe) are so large that external disturbances have to be extreme and/or persistent before the system flips irreversibly into another state. Except under extreme climatic conditions, Mother Nature is not basically in a state of delicate balance. If she were, the world would indeed have collapsed long ago.

The myths of Nature Balanced and Nature Anarchic therefore have to be expanded to include Nature Resilient. So long as we accept only the axiom that there is a balance between exponential growth and environmental/ecological limits, then we are drawn to an inexorable Malthusian determinism. The only behavior of interest is that near equilibrium and a goal to control the system to remain near that equilibrium. In contrast, when we perceive only external physical variability and passively adapting biota, then Nature Anarchic is the logical image, and spatial heterogeneity emerges as the critical ingredient for persistence in a world of locally unstable equilibria.

When, however, we perceive a structuring and controlling role for key clusters of biota at small- and fast-scale ranges; for zootic and abiotic

Box 1-2. The Raft—A Metaphor of Stability and Resilience

D. Ludwig

The concept of stability refers to the tendency of a system to return to a position of equilibrium when disturbed. For example, if a weight is added suddenly to a raft floating on water, the usual response is for the weighted raft to oscillate, but the oscillations gradually decrease in amplitude as the energy is dissipated in waves and eventually in heat. The weighted raft will come to rest in a different position than the unweighted raft would have, but we think of the new configuration as essentially the same as the old one. The system is stable.

If we gradually increase the weight on the raft, the configuration will eventually change. If the weight is hung below the raft, the raft will sink deeper and deeper into the water as more and more displacement is required to balance the higher gravitational force. Eventually, the buoyant force cannot balance the gravitational force and the whole configuration sinks: the system is no longer stable. On the other hand, if the weight is placed on top of the raft, the raft may flip over suddenly and lose the weight and its other contents long before the point at which the system as a whole would sink. This sudden loss of stability may be more dangerous than the gradual sinking because there may be little warning or opportunity to prepare for it. We may think of the raft system as losing its resilience as more weight is placed on top of it.

Is the raft likely to experience a gradual loss of stability or a sudden one? In order to decide whether a system is stable or not, we must first specify what we mean by a change in configuration or loss of integrity. If we don't care whether the raft flips over when weighted, then there is no problem of sudden loss of stability for the floating raft. We must also specify the types and quantities of disturbances that may affect the system. Suppose that a fixed weight is placed on top of an occupied raft. If the occupants of the raft move about, the raft may float at a slightly different angle, but if they move too far or all at once, the raft may tip. The range of possible movements of the occupants that do not lead to tipping is called the domain of stability or domain of attraction of the upright state. If the amount of the fixed weight is gradually increased, the balance becomes more precarious, and hence the domain of attraction will

shrink. Eventually, the weight becomes large enough so that there is no domain of stability.

The preceding example makes a distinction between the weight loading the raft and the positions of the occupants. If the amount of the weight changes very slowly or not at all, we may think of the "system" as consisting of the raft and weight. If the occupants change position relatively quickly, those changes may be thought of as disturbances of the system. On the other hand, we may more comprehensively view the raft, the weight, and the occupants as a single system. If the occupants organize themselves to anticipate and correct for external disturbances, then the system may be able to maintain its integrity long enough for them to achieve their objectives. Another possible response to disturbance might be to restructure the raft itself. If it were constructed of several loosely coupled subunits, then excessive weighting or a strong disturbance might flip one part of the system but leave the rest intact. Such a structure might not require as much vigilance to maintain as the single-system raft.

The resilience of the raft cannot be determined outside of its social and institutional context. The occupants of the raft might have differing rights and objectives. Those who stand to benefit most from heavy loading may tend to minimize the risks of tipping under load. Those who have the most to lose from a loss of stability may favor a very cautious approach. How will decisions be made about the loading and configuration of the raft? Who are the stakeholders—i.e., whose interests must be taken into account when alternative policies are considered? Does the raft have an owner? How do his rights and obligations compare with the rights and obligations of the occupants? Is there a government agency in charge of regulating rafts? Are there interest groups who would prefer that rafts not be allowed on the waterways? The eventual fate of the raft will depend on the physical characteristics of the raft, the environment in which it is deployed, and the social and political structure in which it is embedded.

intermediate scale ranges; and for geophysical processes at large-scale ranges, then the image of Nature Resilient emerges. Such an image incorporates the principles of negative feedback regulation of Nature Balanced and of the stochastic physical variation of Nature Anarchic but adds the principles of biotically induced variation and self-organization. At scales from leaf to landscape, the biota can create conditions that support the very biotic

In the view of Nature Resilient, behaviors near equilibrium and the traditional mathematical tools for local stability analysis are irrelevant. Populations assume trajectories that are dynamically unstable. The critical focus then becomes the conditions at the boundaries of stability domains, the size of those domains, and the forces that maintain those domains. The paper that originally introduced this contrast between systems resilience and equilibrium stability (Holling 1973b) was written as an antidote to the narrow view of fixed, equilibrium behavior and of resistance of populations to local perturbation. Those narrow, essentially static notions have provided the foundations for the now discredited goals of maximum sustained yields of fish populations or of fixed carrying capacity for terrestrial animal populations. The success of achieving such goals squeezes out variability and resilience is lost. Periodic crises result.

Thus part of the answer to the question of why the world has not collapsed is that natural ecological systems have the resilience to experience wide change and still maintain the integrity of their functions.

But the other part of the answer lies in human behavior and creativity. Change and extreme transformations have been part of humanity's evolutionary history. People's adaptive capabilities have made it possible not only to persist passively, but also to create and innovate when limits are reached. At their extreme, these attributes underlie the economists' presumptions of people's unlimited capacity to substitute for scarce materials and to develop successful remedial policies incrementally once the need is apparent. The themes of human creativity and novelty are developed in subsequent chapters of this volume.

Partial Theories and Partial Explanation

We search for explanations that are simple and general. Can complex adaptive systems help us understand ecological, economic, and social systems separately and as they interact? By "understand" we mean distinguish that which is predictable (even if uncertain) from that which is emergent and inherently unpredictable. The test of understanding is whether we can identify the processes that control the specific properties of many, qualitatively different, specific examples. Can we define adaptive responses and policies that benefit from and perhaps even create useful unpredictability? That is what adaptive policy is about.

There are not too few theories for these systems. There are too many. They are all correct or mostly correct but incomplete. For example, in ecology the notion of Clementsian succession was a typical equilibrium theory that saw ecosystem succession proceeding from establishment of pioneer species that withstand extremes of microclimate, to climax species whose tight competitive relationships precluded other species. The theory was not wrong but incomplete, since empirical tests of that theory exposed a

to microclimate and soils, the existence of a number of different end states, and the role of disturbance as part of ecosystem renewal.

In economics, the pure market model is an equilibrium theory in which demand and supply reach stable equilibrium prices when marginal changes just balance. It is not wrong, but we know that market imperfections occur when the simplifying assumptions are violated. Those violations become more pronounced as the scale of human impacts on the environment increase in extent and intensity (Arrow et al. 1995). That view of the market is not too different from the theory of island biogeography in ecology, in which the equilibrium number of species on islands is seen as the balance between species immigration and extinction. The theory is not wrong but incomplete, because empirical checks demonstrate that the theory can be a poor predictor. The list could go on—density-dependent regulation in population dynamics, competition in community ecology, field theory in economics, garbage-can models in decision theory.

These theories are partial truths. Once proposed, they stimulate fruitful inquiry. As a consequence, their partial nature is exposed, and extension and expansion of theory proceed. Parental affection for theory by those who form them and the psychology of adherents makes those extensions contentious. Critics become extreme; straw-man caricatures are established and roundly defeated. The best of the defenders resist throwing the baby out with the bathwater and are affronted by the often inappropriate attacks when the leading edge of theory formation has often been there earlier. That is where we see the present debates about economics from environmental perspectives. We have learned that economists have often been there before their critics. We hope that we can clarify and open fruitful inquiries through the kind cooperation of ecologists, economists, and social scientists displayed in this book.

In our quest, we would like to discover ways to integrate and extend existing theory to achieve a requisite level of simplicity, just complex enough to capture and explain the behaviors we see. Those include explanations of discontinuous patterns in space, time, and structure and explanations for how novelty emerges, is suppressed, or is entrained. For prescriptive purposes we also seek adaptive ways to deal with surprise and the unpredictable. We concentrate on adaptive approaches that do not smother opportunity, in contrast to control approaches that presume that knowledge is sufficient and that consequences of policy implementation are predictable.

So—requisite simplicity, but generality? What is the context within which the theory is functional? Generality is desired—but also to be feared. It is to be feared because once a theory is formed, once it seems to resolve paradoxes, and once it passes some empirical tests, proponents are sorely tempted to extend its application beyond its natural context. That is particularly true if the theory emerges in the natural sciences and is applied to humans. The history of science is replete with such examples—some disas-

evolutionary psychology), and still others wonderfully overambitious (complexity theory?). It is not always so bad to reach beyond the theory's real grasp because the science-based efforts at least have a process, however lurching and inefficient, to test them. But caution and sharp questioning are essential.

We encountered this issue when faced with the temptation to extend a theory of adaptive cycles developed for ecosystems dynamics and renewal (Chapter 2) to other systems, particularly organizational ones (Gunderson et al. 1995a), business ones (Hurst 1995), and more generally, social and political ones (Holling and Sanderson 1996).

That led to an expansion that recognized that the adaptive cycles were nested in a hierarchy across time and space (Gunderson et al. 1995a). That expansion seemed to explain how adaptive systems can, for brief moments, generate novel recombinations that are tested during longer periods of capital accumulation and storage. These windows of experimentation open briefly, but the results do not trigger cascading instabilities of the whole because of the stabilizing nature of nested hierarchies. In essence, larger and slower components of the hierarchy provide the memory of the past and of the distant to allow recovery of smaller and faster adaptive cycles. In ecosystems, for example, seed banks in soil, biotic heritages, and distant pioneer species are all critical accumulations from the past that are available for present renewal.

That expansion did not help us avoid the pitfall of overstretched generality, however; rather, it made it worse. That was the motive that initiated this book. The expansion seemed to explain everything. It applied to theories of non-living systems, such as plate tectonics. The sequence of phases in the cycle were all there: the establishment of the plates from magma extruding at the mid-Atlantic ridge, slow movement of the plates encountering continental edges, material subducting back to be melted, and the elements resorted in new episodes of mineral formation in mountain building. In addition, too many other systems seemed equally to fit the heuristic model of change: cell development, meiotic reproduction, ecosystem formation, evolution, organizational stasis and transformation, political and social processes. If a theory explains everything, it explains nothing.

What are needed are alternative hypotheses and specific predictions that can be tested empirically. That is possible for the natural science components systems but much less so for social components. But we can continually ask where the emerging theory encounters observations that are not consistent with the theory. Why living systems are not like nonliving ones. Why ecosystems are not like organisms. Why social systems are not like ecosystems. And why linked ecological, social, and economic systems are not like any of the above.

Seeking Simplicity in Quest of a Theory of Adaptive Change

Our goal for this book was to develop and test theories that explain transformational change in systems of humans and nature, theories that are inherently integrative.

We identified two targets for integration. One is to integrate the dynamics of change across space from local to regional to global and over time from months to millennia. Traditions of science have tended to simplify by focusing on one scale. However, growing human impacts on the planet's atmosphere and on international economic patterns have stimulated efforts over the last decade to explore cross-scale influences (Levin 1992, 1999). Examples are impacts of climate change on regional ecosystems and on local human health, or of economic globalization on regional employment and the environment, or of emergence of new diseases, like AIDS, and their spread internationally.

An economist might say that the world's local and regional ecological, economic, and social systems are increasingly influenced by externalities (Arrow et al. 1995; Levin, Barrett et al. 1998). An ecologist might say that they have become increasingly coupled, so that fast and slow processes, local and distant ones cannot be treated separately (O'Neill et al. 1998). Increasingly, local problems of the moment can have part of their cause located half a planet away and have causes whose source is from slow changes accumulated over centuries.

The processes that drive or mediate the spatial intensification range from fast processes of vegetative growth in ecosystems and of economic production in economies, to slow processes of geomorphological change and of human cultural and political development. The processes we need to understand, and in some way integrate, literally cover months to millennia, meters to tens of thousands of kilometers.

This integration builds on prior work (Gunderson et al. 1995a) that identified the linkages between system dynamics and scale—the roots of the term *panarchy*. The term was coined as an antithesis to the word *hierarchy* (literally, sacred rules). Our view is that panarchy is a framework of nature's rules, hinted at by the name of the Greek god of nature, Pan. Chapters 2 and 3 focus on this integration, on developing theories of cross-scale dynamics and, in Chapters 4, 5, and 6, on using it to explore specific examples of ecological, social, and organizational change.

The second target for integration was to integrate across disciplines to better understand systems of linked ecological, economic, and institutional processes. Again, the expanding influence of human activity intensifies the coupling between people and systems of nature so that neither can be understood in isolation (Vitousek 1997; Holling 1994b).

This second goal of interdisciplinary integration—of how linked systems of nature, economies, and institutions function—is a major focus of Chapters 7, 8, 9, and 10, where mathematical representations of these integrated systems are explored. Chapters 11 and 12 use the emerging theories to analyze policies and practices in two specific examples of regional systems, and Chapter 13 describes the challenges that management of resources presents to individuals. Chapter 14 raises broad questions of sustainability and equity that come from experiences in the developing world, questions that emerge when efforts are made to identify alternative paths for development. Finally, Chapter 15 summarizes our conclusions in Table 15-1, and Chapter 16 presents the synthesis we sought at the outset of the work.

We hope that our approach in the remainder of this volume embodies the major elements of a heuristic theory. It draws on theories of adaptive change in biological and ecological systems, of self-organization in complex systems, of rational actor models in economics, and of cultural evolution. We are promulgating regional tests of our approach; we have posed the test questions; we are building a network of test takers—of practitioners, scientists, and policy decision makers who wish to contribute to a sustainable future for regions and for the planet (www.resalliance.org). It is a future that encourages innovative opportunity for people to learn and prosper, that incorporates responsibility to maintain and restore the diversity of nature, and that is based on a just and civil society. We hope this volume contributes to such a future.

Part II

Theories of Change

CHAPTER 2

RESILIENCE AND ADAPTIVE CYCLES

C. S. Holling and Lance H. Gunderson

Make things as simple as possible, but no simpler.

—Albert Einstein

The purpose of this chapter, and the succeeding one, is to deepen understanding of the fifth of the worldviews described in Chapter 1—that of Nature Evolving. It is another step in the effort to develop theories for sustainable futures.

What follows in this chapter is an initial comparison of the structure and dynamics of ecological and social systems from the perspective of ecosystem ecologists. We draw on ecological examples and theory and on lessons from examples of regional ecosystem management in order to develop new concepts to explain the organization and dynamics of complex adaptive systems. We only hint at similarities in social and economic systems—just enough that, in later chapters, they can be the source for discovering the limits of the theory.

We begin by abstracting key elements of our understanding regarding how ecosystems are organized and operate. We then use examples of different ecosystems to develop several variants of a heuristic model of change that involves four phases: exploitation, conservation, creative destruction, and renewal, which constitute an adaptive cycle. We end with questions emerging from puzzles and paradoxes not well treated by the model presented, especially in terms of cross-scale dynamics.

Key Features of Ecosystems

The accumulated body of empirical evidence concerning natural, disturbed, and managed ecosystems identifies key features of ecosystem structure and

- Change is neither continuous and gradual nor consistently chaotic. Rather it is episodic, with periods of slow accumulation of natural capital such as biomass, physical structures, and nutrients, punctuated by sudden releases and reorganization of those biotic legacies (Franklin and MacMahon 2000) as the result of internal or external natural disturbances or human-imposed catastrophes. Rare events, such as hurricanes or the arrival of invading species, can unpredictably shape structure at critical times or at locations of increased vulnerability. The results of these rare events represent “frozen accidents” whose influence can shape the future for long periods. Irreversible or slowly reversible states can exist; once the system flips into such a state, only explicit management intervention can return its previous self-sustaining state, and even then recovery is not assured (D. Ludwig et al. 1997).

Critical processes function at radically different rates that span several orders of magnitude, but these rates cluster around a few dominant frequencies. Episodic behavior is caused by interactions between fast and slow variables.

- Spatial attributes are neither uniform nor scale invariant over all scales. Rather, productivity and textures are patchy and discontinuous at all scales, from the leaf to the landscape to the planet. There are several different ranges of scales, each with different attributes of architectural patchiness and texture and each controlled by a specific set of abiotic and biotic processes. They make attributes of the natural world lumpy, rather than continuous (Holling 1992), thereby concentrating resources and opportunities at particular scales.

Therefore, scaling up from small to large cannot be a process of simple aggregation: nonlinear processes organize the shift from one range of scales to another.

- Ecosystems do not have a single equilibrium with homeostatic controls to remain near it. Rather, multiple equilibria commonly define functionally different states. Normal movements of variables between states maintain structure, diversity, and resilience. Nonlinear features of processes of predation, reproduction, competition, and nutrient dynamics create the multiple equilibria. Stochastic forces and interactions between fast variables and slow ones mediate the movements of variables among those equilibria (Carpenter 2000).

On the one hand, destabilizing forces are important in maintaining diversity, resilience, and opportunity. On the other hand, stabilizing forces

- Policies and management that apply fixed rules for achieving constant yields (e.g., fixed carrying capacity of cattle or wildlife, or fixed sustainable yield of fish or wood), independent of scale, lead to systems that increasingly lose resilience—i.e., to systems that suddenly break down in the face of disturbances that previously could be absorbed (Holling 1986, 1995).

Ecosystems are moving targets, with multiple futures that are uncertain and unpredictable. Therefore, management has to be flexible, adaptive, and experimental at scales compatible with the scales of critical ecosystem functions (Walters 1986; Gunderson et al. 1995b).

Those key features provide the minimal set of strategic criteria that need to be satisfied by any theory of adaptive change appropriate for ecosystems. They lead to a view of ecosystems that can make sense only if it is compatible with some version of both Nature Resilient and Nature Evolving. We propose, moreover, that the same criteria, with several additions unique to human systems, are equally necessary for models of human institutions, organizations, and society. To set the stage we need to define what we mean by stability, variability, and resilience of a system.

Two Ways of Looking at Stability

Resilience has been defined in two very different ways in the ecological literature. These differences in definition reflect which of two different aspects of stability is emphasized. The consequences of those different aspects for ecological systems were first emphasized by Holling (1973b) in order to draw attention to the tension created between efficiency on the one hand and persistence on the other, or between constancy and change, or between predictability and unpredictability. One definition focuses on efficiency, control, constancy, and predictability—all attributes at the core of desires for fail-safe design and optimal performance. Those desires are appropriate for systems where uncertainty is low, but they can be counterproductive for dynamic, evolving systems where variability and novelty result in high uncertainty. The other definition focuses on persistence, adaptiveness, variability, and unpredictability—all attributes embraced and celebrated by those with an evolutionary or developmental perspective. The latter attributes are at the heart of understanding and designing for sustainability.

The first definition, and the more traditional, concentrates on stability near an equilibrium steady state, where resistance to disturbance and speed of return to the equilibrium are used to measure the property (Pimm 1984; Tilman and Downing 1994). We term this *engineering resilience* (Holling 1995; Holling and Meffe 1996).

The second definition emphasizes conditions far from any equilibrium steady state, where instabilities can flip a system into another regime of be-

resilience is measured by the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior. This we term *ecosystem resilience*.

These studies and examples increasingly suggest that effective and sustainable development of technology, resources, and ecosystems requires ways to deal not only with near-equilibrium efficiency but also with the reality of more than one equilibrium.

These two aspects of a system's stability have very different consequences for evaluating, understanding, and managing complexity and change. We argue here that sustainable relationships between people and nature require an emphasis on the second definition of resilience, i.e., as the amount of disturbance that can be sustained before a change in system control and structure occurs—ecosystem resilience. That shifts the management and policy emphasis from micro, command-and-control approaches to ones that set overall conditions to allow adaptive enterprises (Holling and Meffe 1996). That interplay between stabilizing and destabilizing properties is at the heart of present issues of development and the environment—global change, biodiversity loss, ecosystem restoration, and sustainable development.

Exclusive emphasis on the first definition of resilience, engineering resilience, reinforces the dangerous myth that the variability of natural systems can be effectively controlled, that the consequences are predictable, and that sustained maximum production is an attainable and sustainable goal. Gunderson, Holling, and Light (1995a) present examples showing why that leads to the pathology of resource management (Chapter 1). The very success of limiting variability of a target leads to the unperceived shrinkage of stability domains. As ecosystem resilience is lost, the system becomes more vulnerable to external shocks that previously could be absorbed.

These are two contrasting aspects of stability. One focuses on maintaining *efficiency* of function (engineering resilience); the other focuses on maintaining *existence* of function (ecosystem resilience). Those contrasts are so fundamental that they can become alternative paradigms whose devotees reflect traditions of a discipline or of an attitude more than of a reality of nature.

Those who emphasize the near-equilibrium definition of engineering resilience, for example, draw predominantly from traditions of deductive mathematical theory (Pimm 1984) where simplified, untouched ecological systems are imagined. Another example arises from experimental manipulation of organisms where the scale is limited to small enclosures or field quadrats (Tilman and Downing 1994). Yet another example is from traditions of engineering, where the motive is to design systems with a single operating objective (Waide and Webster 1976; De Angelis et al. 1980). Such partial representations make the mathematics more tractable, the experiments more controllable, and the designs more functionally optimal. There is an implicit assumption of global stability—i.e., there is only one equilibrium steady state

guards, so that the variables are maintained near the “best” equilibrium, well away from a dangerous break point. There are also the assumptions that it is sufficient to represent or manipulate only fast, local variables and that slowly changing, extensive variables and their interactions can be ignored.

Those who emphasize the stability domain definition of resilience (i.e., ecosystem resilience), on the other hand, come from traditions of applied mathematics and applied resource ecology at the scale of ecosystems and of landscapes. Examples are the dynamics and management of freshwater systems (Fiering 1982); of forests (Holling et al. 1976a); of fisheries (Walters 1986); of semiarid grasslands (Walker 1981); of lakes (Scheffer 1998; Carpenter, Ludwig, and Brock 1999; Janssen and Carpenter 1999); and of interacting populations in nature (Sinclair et al. 1990; Dublin et al. 1990). Because these studies are rooted in inductive rather than deductive theory formation and in experience with the impacts of management disturbances at multiple scales, the reality of flips from one operating state to another cannot be avoided. Clear lakes can turn into turbid, anoxic pools, grasslands into shrub-deserts, and forests into grasslands. D. Ludwig et al. (1997) provide a fine exploration of the mathematical underpinnings to these different views of resilience with examples from natural and managed systems. Scheffer (1999) provides a lucid and accessible example of multistable behavior in European lakes and the management strategies for dealing with them.

In ecology, the causes and conditions of multiple equilibria were challenged by Sousa and Connell (1985), who analyzed time series data of animal populations. This is an example of a laudably skeptical effort to invalidate a novel proposition. It came to an erroneous conclusion because the data systems used to test the proposition were defined too simply. They did not have the level of requisite complexity needed. They lacked the minimally essential features for answering the question. The example is instructive for other issues: of, for example, the detection and use of pattern in analyzing any long time series—ecological, paleoecological, climatic, or financial—or of spatial or geometric patterns. Causation was ignored and the relevant duration of data was defined by the assumption that fast variables alone defined multistable properties.

For example, Sousa and Connell (1985) presumed that 40 years of available data covering forty generations of the forest insect, the spruce budworm, was sufficient to test for multistable states in the budworm/forest system. It certainly seems long enough to data-starved ecologists! However, slow variables, like the foliage accumulation of the maturing forest, set by a generation time of 80–120 years for the trees, slowly change the stability conditions for fast ones (Box 2-1). The minimal need is for a time series that covers three generations of the trees (at least 300 years). It is no wonder that moving multiple lines of evidence, understanding of causation, and recognition of requisite levels of simplicity has been the only way to establish the reality and importance of multistable states. That is what Carpenter (2000)

twenty-five years to establish that multistable states are, in fact, common in ecosystems, common enough that management dare not ignore them, because of the potential high cost of doing so.

Box 2-1. Spruce-Fir Forests and Insect Outbreaks

C. S. Holling

One classic example of the adaptive cycle shown in Figure 2-1 is the dynamics of the spruce-fir forest of eastern North America. The patterns produced depend on the nonlinear processes that trigger and organize the release and reorganization phase. One of the primary triggers for release in the eastern balsam fir forest of North America is an insect outbreak species, the spruce budworm. Two principal stability states exist. One is with low budworm populations and young, growing trees. The other is with high budworm populations and mature trees. The latter condition is associated with so much defoliation that the trees die over extensive areas. Prior to harvesting and management, up to 80 percent of the balsam fir trees in central eastern Canada and the United States would die from budworm attacks at intervals of from 40 to 130 years. It is an entirely natural phenomenon, part of forest renewal, and is an example of alternating stable states.

The release phase occurs because the maturing forest accumulates a volume of foliage that eventually dilutes the effectiveness of the search by insectivorous birds for budworm. So long as predation by birds is high, as it is in younger stands, it is sufficient, with other mortality agents, to control budworm populations at low densities. Essentially, a lower equilibrium density for budworm is set by a "predator pit" (Clark et al. 1979; Holling 1988) in a stability landscape during the phase of slow regrowth of the forest. This stability pit eventually collapses as the trees mature, to release an insect outbreak and reveal the existence of a higher equilibrium. A more formal mathematical representation is given in Ludwig et al. (1978). A similar argument can be described for release by fire, as a consequence of the slow accumulation of fuel as a forest ages.

To summarize and generalize this example: For long periods in a regrowing forest, the slow variable (trees) controls the faster (budworm or fire) and intermediate-speed variables (foliage or fuel) until a stability domain shrinks to the point where the fast variables for a brief time can assume control of behavior and trigger a release of the accumulated capital.

Back to Myths of Nature

The features summarized in the two preceding sections suggest that the images of Nature Flat and Nature Anarchic described in Chapter 1 are wrong in their incompleteness. Both myths are wrong, because there are clearly regulatory forces that cause ecosystems to pause for longer or shorter periods in one set of relationships and one assemblage of species in one place. Some call those ecosystems. But Nature Balanced is equally wrong. There are strong destabilizing forces that introduce variability, sometimes abrupt, and that variability is the source of much of the diversity of species and the richness of nature we see. Nature Resilient would seem to provide an amalgam of both. It does that, but is it satisfactory? Is it sufficient?

Consider the consequences if a system were highly resilient. Is that entirely a desired condition? Such a system would not change in any fundamental way. In the face of large disturbances, variables would shift and move, but the system would maintain its controls and structure. If that is common, how do we explain the dramatic, changing character of landscapes over geological time? The answer might simply be that the resilience is never infinite and is eventually swamped by some external, large-scale change, and the system is replaced by something else. For example, some ten thousand years ago (very recent in geologic time frames) the treasured Everglades of southern Florida were not wetlands, but a dry savanna. Had we been living then, would we, as people concerned with the conservation of nature, have sought to maintain that savanna state as desirably pristine, holding back the rising seas as glaciers melted? Placing fingers in the dikes we built? Denying the reality of climate change? Is it desirable to have a goal of preserving and protecting systems in a pristine, static state?

These tough questions are not normally addressed by conservationists or environmentalists. They are tough also because they challenge the authors' own values and desire to sustain a rich and diverse natural world. But in a complex evolving world, the function and future of linked human and natural systems evolve and are highly uncertain. Efforts to freeze or restore to a static, pristine state, or to establish a fixed condition are inadequate, irrespective of whether the motive is to conserve nature, to exploit a resource for economic gain, to sustain recreation, or to facilitate development. Short-term successes of narrow efforts to preserve and hold constant can establish a chain of ever more costly surprises—versions of the pathology of resource management and development described in Chapter 1.

It helps to switch, for a moment, from thinking of ecosystems to thinking of sociopolitical ones. Clearly, locking a sociopolitical system into a fixed set of controls can transparently create an unsustainable political system. For a time, at least, the Soviet Union was an immensely resilient "dictatorship of the bureaucracy" (Levin, Barrett et al. 1998). Its very resilience preserved a maladaptive system. What this suggests for social systems, as well as ecolog-

quantity that defines a system, but a dynamically varying one. Resilience can be the enemy of adaptive change. That is, the myth of Nature Resilient is too partial and static in a structural sense.

But what do we do? What is enduring and must always be so? What is sustainable? We need a transition from the structurally static view of Nature Resilient to a structurally dynamic view of Nature Evolving.

Conserving the elements we have is not the goal for a search for what is enduring. Otherwise, we would still be blacksmiths and buggy-whip makers. The challenge, rather, is to conserve the ability to adapt to change, to be able to respond in a flexible way to uncertainty and surprises. And even to create the kind of surprises that open opportunity. It is this capacity that a view of an evolving nature should be all about—i.e., maintaining options in order to buffer disturbance and to create novelty. A living system cannot be kept within some desirable state or on some desirable trajectory if adaptive capacity is continuously lost.

The purpose of theories such as panarchy is not to explain what is; it is to give sense to what might be. We cannot predict the specifics of future possibilities, but we might be able to define the conditions that limit or expand those future possibilities. As a consequence, the properties we need to choose are not those chosen to describe the existing state of a system and its behaviors, but rather ones chosen to identify the properties and processes that shape the future. This introductory exploration identifies three requirements in our quest for a theory of adaptive change:

- First, the system must be productive, must acquire resources and accumulate them, not for the present, but for the potential they offer for the future.
- Second, there must also be some sort of shifting balance between stabilizing and destabilizing forces reflecting the degree and intensity of internal controls and the degree of influence of external variability.
- Third, somehow the resilience of the system must be a dynamic and changing quantity that generates and sustains both options and novelty, providing a shifting balance between vulnerability and persistence.

The Adaptive Cycle

In case examples of regional development and ecosystem management (Gunderson et al. 1995b), three properties seemed to shape the future responses of the ecosystems, agencies, and people:

- the potential available for change, since that determined the range

- the degree of connectedness between internal controlling variables and processes, a measure that reflects the degree of flexibility or rigidity of such controls—i.e., their sensitivity or not to external variation;
- the resilience of the systems, a measure of their vulnerability to unexpected or unpredictable shocks.

Note, at this stage, we choose very general properties because our initial goal is to develop a framework of adaptive change that has generality. Such a framework is hardly a theory, therefore. Rather, it is a metaphor to help interpret events and their gross causes.

The original concept of the adaptive cycle and the review described in this section emerged from experience with productive ecosystems that exist in temperate regions of the world—places where rainfall is consistent, although seasonally variable. They specifically included the boreal coniferous forests of the Northern Hemisphere, productive grasslands on deep soils, and temperate deciduous forests. But many ecosystems have developed in very different conditions—coral reefs, nutrient-poor savannas with low and episodic rainfall, open-ocean pelagic communities, shallow and deep lakes, nutrient-poor tropical forests. In the remainder of this chapter we review the cycle as it was described for productive temperate ecosystems and possible similarities in human organizations and economies. To test its limits, we then consider more extreme types of ecosystems, hoping to discover where the metaphor breaks down. To push that exploration of limits further, we also start to explore large human organizations—bureaucratic and industrial organizations. In the next sections, we review properties of the original adaptive cycle metaphor, beginning with two of the key properties, potential and connectedness, before adding the third property, resilience.

Two Dimensions of Change: Potential and Connectedness

The traditional view of ecosystem succession has been usefully seen as being controlled by two functions: *exploitation*, in which rapid colonization of recently disturbed areas is emphasized; and *conservation*, in which slow accumulation and storage of energy and material are emphasized. In ecology the species in the exploitive phase have been characterized as r-strategists and in the conservation phase as K-strategists. These are names drawn from the traditional designation of parameters of the logistic equation (r represents the instantaneous rate of growth of a population, and K the sustained plateau or maximum population that is attained; Pearl 1927). The r-types are characterized by extensive dispersal ability and rapid growth in an arena where scramble competition succeeds (the first to get the prize wins), while the K-strategists tend to have slower growth rates and flourish in an arena of contest competition (resources become divided and sequestered to separate

uses). To an economist or organization theorist, those functions could be seen as equivalent to the entrepreneurial market for the exploitation phase and the bureaucratic hierarchy for the conservation phase. Baron, Burton, and Hannan (1998) provide a very detailed study of the forces that determine different patterns such as path dependence in the evolution of bureaucracy, even when firms face intense competition.

But subsequent ecological understanding indicates that two additional functions are needed, as summarized in Figure 2-1. The first revision is that of *release*, or “creative destruction,” a term borrowed from the economist Schumpeter (1950, and as reviewed in Elliott 1980). The tightly bound accumulation of biomass and nutrients becomes increasingly fragile (overconnected, in systems terms) until suddenly released by agents such as forest fires, drought, insect pests, or intense pulses of grazing. We designate that as the omega (Ω) phase.

The second additional function is one of *reorganization*, in which soil processes minimize nutrient loss and reorganize nutrients so that they

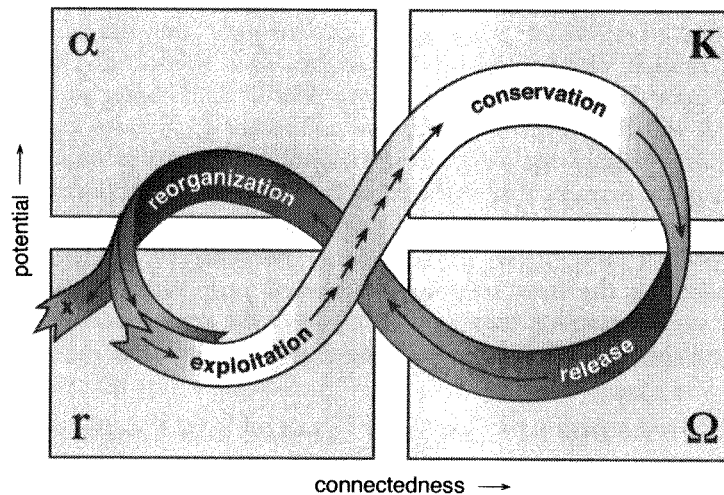


Figure 2-1. A stylized representation of the four ecosystem functions (r , K , Ω , α) and the flow of events among them. The arrows show the speed of that flow in the cycle, where short, closely spaced arrows indicate a slowly changing situation and long arrows indicate a rapidly changing situation. The cycle reflects changes in two properties: (1) Y axis—the potential that is inherent in the accumulated resources of biomass and nutrients; (2) X axis—the degree of connectedness among controlling variables. Low connectedness is associated with diffuse elements loosely connected to each other whose behavior is dominated by outward relations and affected by outside variability. High connectedness is associated with aggregated elements whose behavior is dominated by inward relations among elements of the aggregates, relations that control or mediate the influence of external variability. The exit from the cycle indicated at the left of the figure suggests, in a stylized way, the stage where the potential can leak away

become available for the next phase of exploitation. Part of this reorganization involves the transient appearance or expansion of organisms that begin to capture opportunity—the pioneer species. Their source is from growth of previously suppressed vegetation, from germinating seeds stored in seed banks accumulated from the past, and from dispersal of both endemic and exotic propagules from distant places. The reorganization phase is essentially equivalent to one of innovation and restructuring in an industry or in a society—the kinds of economic processes and policies that come to practical attention at times of economic recession or social transformation. We designate that as the alpha (α) phase.

If the omega phase represents the end, then it is immediately followed by the alpha phase, the beginning—a progression at least as interesting philosophically as it is ecologically.

During this cycle, biological time flows unevenly. The progression in the ecosystem cycle proceeds from the exploitation phase (r phase, Figure 2-1) slowly to conservation (K phase), very rapidly to release (Ω phase), rapidly to reorganization (α phase), and rapidly back to exploitation. During the slow sequence from exploitation to conservation, connectedness and stability increase and a “capital” of nutrients and biomass is slowly accumulated and sequestered. Competitive processes lead to a few species becoming dominant, with diversity retained in residual pockets preserved in a patchy landscape. While the accumulated capital is sequestered for the growing, maturing ecosystem, it also represents a gradual increase in the potential for other kinds of ecosystems and futures. For an economic or social system, the accumulating potential could as well be from the skills, networks of human relationships, and mutual trust that are incrementally developed and tested during the progression from r to K . Those also represent a potential developed and used in one setting that could be available in transformed ones.

As the progression to the K phase proceeds, the accumulating nutrient and biomass resources become more and more tightly bound within existing vegetation, preventing other competitors from utilizing them. The potential for other use is high, but it is expropriated and controlled by the biota and processes of the ecosystem in place. That is, the system’s connectedness increases, eventually to become overconnected and increasingly rigid in its control. The actual change is triggered by agents of disturbance such as wind, fire, disease, insect outbreak, and drought or a combination of these. The resources sequestered in vegetation and soil are then suddenly released and the tight organization is lost. Its potential for other uses drops until the released resources that remain are reorganized so that the potential for other uses reemerges in the α phase.

A number of such patterns have been discovered in several terrestrial and near terrestrial ecosystems at landscape scales (Boxes 2-2 and 2-3). In all instances, periodic flips from one stable state to another are mediated by changes in slow variables that suddenly trigger a fast-variable response,

Box 2-2. Alternative Stable States

G. Peterson

Alternative stable states have been described for a diverse variety of terrestrial and near terrestrial ecosystems. In each of these cases, periodic flips from one state to another are mediated by changes in slow processes that suddenly trigger a fast-process response, or escape from a state. The following cases provide examples:

Meta-population dynamics. A connected set of populations can exist at either a high-density connected state or a low-density fragmented state. In a landscape composed of potential habitats, the population of a particular habitat depends on its neighboring sites. If the population at a site becomes extinct, the probability of recolonization increases with the aggregate size of the surrounding populations. This effect produces a positive feedback between the density of a region's population and the likelihood that that region's population can maintain itself. Consequently, a regional population can rapidly decline if its population begins to fail to recolonize potential sites, because this further reduces the probability of recolonizing sites (Hanski et al. 1995).

Shallow lakes. In shallow lakes the interactions among turbidity, nutrients loading, vegetation, and fish produce two alternative stable states (Scheffer et al. 1993). Lakes can exist either in a state in which water is clear and dominated by rooted aquatic vegetation, or in a state in which water is turbid and dominated by phytoplankton. The large, rooted plants stabilize the substrate sediment, reduce turbidity, encourage the stabilization of nutrients, and provide refugia for phytoplankton-consuming fish. If rooted plants are eliminated, the resulting turbidity blocks light for plants, and resuspended sediment makes nutrients available to phytoplankton. Lakes usually switch between states due to a combination of changes. For example, a clear lake can lose rooted plants and become turbid due to an increase in nutrient loading, a decrease in algae-eating fish, an inflow of sediment, or the removal of vegetation (Blindow et al. 1993). Similarly, a turbid lake can be made clear by reducing the population of bottom-foraging, turbidity-increasing fish, or by decreasing the number of fish that eat algae eating fish.

Reefs. Corals, surface algae, and macro-algae are all components of coral reef communities. Changes in the extent of predation on algae by fish and sea urchins, changes in nutrient concentrations, and the presence of new areas to grow control

switches between states (Knowlton 1992). Consequently, shifts between stable states can be influenced by disturbance events that provide new areas for recruitment, resuspend sediments, and cause variations in the population of algae eaters (Hughes 1994). Fishing and variation in recruitment can strongly influence fish populations, while the interaction of density-dependent recruitment and circulation patterns allows sea urchins to exist at self-maintaining high- or low-density states (McClanahan et al. 1996). These interactions suggest that reefs can exist in three self-maintaining states: coral-fish, turf algae-urchins, and macro-algae (Done 1992; Knowlton 1992).

Sea otters, sea urchins, and kelp forests. Along the coast of the northern Pacific, rocky near-shore communities can be dominated by either dense stands of kelp or few kelp and large concentrations of sea urchins. The presence of these states is controlled by the presence of sea otters that prey upon sea urchins. In the absence of sea otters, urchin populations can increase to a density that prevents kelp forests from establishing. On the other hand, when sea otters are present, their predation on sea urchins allows key kelp forests to become established (Estes and Duggins 1995).

Fire in North Florida. Oak trees and pine trees dominate sandhill communities in northern Florida. Fire mediates the competitive relationships between the abundance of these two species. Longleaf pine (*Pinus palustris*) is a particularly fire-tolerant pine species. Mature longleaf pines shed needles that provide good fuel for ground fires, and young longleaf pines can survive ground fires. Young hardwoods are intolerant of fire, and mature hardwoods shed leaves that suppress the buildup of fuel for ground fires. This lack of fuel tends to suppress fire in hardwood stands, encouraging the growth of more hardwoods, while fuel accumulation in stands of pine tends to encourage fire, suppressing hardwoods and encouraging the growth of pine (Glitzenstein et al. 1995; Rebertus et al. 1989).

Fire spreads itself from burning sites into combustible sites. A fire that is surrounded by noncombustible sites will be unable to spread and will extinguish itself. The mutual reinforcement between fire and longleaf pine will occur only if the fires are started frequently and are able to spread across a large area. Otherwise, sites will burn infrequently, and fire-susceptible vegetation will be replaced by fire-suppressing vegetation. The ability of fire to spread, and consequently the rate at which patches of hardwood or pine either grow or shrink, is determined by the distribution of hardwoods and pine across the landscape. The relative proportion of

continues

hardwood and pine in the area surrounding a site will determine the succession of a forest site.

Elephants, fire, and savanna. Dublin et al. (1990) propose that the elephants and fire interact with competition between grasses and trees to produce two alternative stable states in the Serengeti-Mara. Fire shifts from a woodland to a grassland state. Grassland is maintained by herbivores, particularly elephants, consuming young seedlings. However, this consumption is not sufficient to shift woodland to grassland, as it is significant only at low-seedling densities. Low-herbivore density and infrequent fire allow woodland regeneration to occur (Dobson 1995; Dublin 1995). For example, when rinderpest eliminated a large number of grazers, woodlands experienced a pulse of regeneration (Prins and Jeurd 1993).

As the system shifts from α to r , some of the potential leaks away because of the collapse of organization; some of the accumulated resources literally leave the system. In addition, new entrants, those that survived to the α phase, and the "biotic legacies" of past cycles (Franklin and MacMahon 2000) begin to sequester and organize resources in a process that leads to the r species establishing "founding rights" over the remaining capital. The result of both processes lowers the potential from α to r .

Note that in a sustainable ecosystem, the accumulated resources that determine ecological potential might be eroded, might partially leak away, but are only partially reduced. If they were completely or largely eliminated, recovery would be impossible, and the system would slip into a different, degraded state. Such a condition would occur, for example, if species critical in maintaining structure and function became extinct. That has certainly happened in geological history with extinctions of large herbivores in North America at the end of the Pleistocene some ten thousand years ago. It has also occurred in Australia with the consequence of loss of a stable state (Box 2-3).

But in most swings of the cycle, there is sufficient carryover from cycle to cycle to sustain an ecosystem's possible states. Typically, the actual aggregate resources accumulated would take a different path than the trajectory of potential shown in the figure, modestly fluctuating in amount through one cycle. Or, as in the case of wetlands, like the Everglades, those resources could continually accumulate, cycle by cycle, stored in the immobilized accumulation of peat. The basic cycle of vegetation in the Everglades from ponds to sawgrass to fire takes in the order of decades. However, the accretion of five meters of peat in the Everglades occurs over multiple cycles on the order of a five-thousand-year period (Gleason 1984). What does change dramatically during a cycle in all such systems is the potential. It alternates between high potential in the α and K phases, lower potential in the r phase, and then

Box 2-3. Loss of an Alternative State?

G. Peterson

Occasionally, due to the loss of an important system component, transition between multiple states results in the elimination of a former stable state. The extinction of species that perform a critical ecological function can cause such irreversible transitions. Pleistocene extinctions may provide an example of such a transition.

Sediment cores from Australia show that about 100,000 years ago pollen from fire-tolerant plants and mangroves increased while other species declined. These increases were likely due to the increases in burning that are also documented by an increase in charcoal in the sediment cores. Increases in fire frequency would have allowed fire-tolerant plants to spread, while at the same time leaving more bare soil to be eroded and deposited as coastal sediment and providing increased habitat for mangroves. Similar climatic conditions had existed previously without increases of fire, which suggests that the arrival of humans may have been responsible (Kershaw 1988).

Flannery (1994) proposes that it was overhunting of Australia's large marsupial herbivores that caused this change, rather than anthropogenic modification of fire regimes. During the time in which humanity is thought to have been in Australia, fifty large and medium-sized marsupial herbivores became extinct, along with several large herbivorous birds and turtles. If these herbivores lived similarly to existing large herbivores (Dublin et al. 1990; Owen-Smith 1989), then their extinction also likely eliminated their maintenance, through grazing, physical disturbance, and nutrient cycling, of a variety of vegetative patterns across the landscape. The removal of this small-scale patterning, and a buildup of fuel, may have facilitated the occurrence of larger and more intense fires. Such fires reduce local nutrient cycling by causing larger-scale erosion. Flannery suggests that this process caused the expansion of heathlands of fire-tolerant species at the expense of fire-intolerant vegetation adapted to herbivory. Without large herbivores to prevent and fragment vegetation, an ecosystem of fire and fire-dominated plants could expand at the expense of a system of large herbivores and herbivore-adapted plants. Flannery argues that hunting and use of fire removed large herbivores and volatilized accumulated nutrients, irreversibly switching the system from a more productive state, dependent on rapid nutrient cycling, to a less productive state, with slower nutrient cycling, maintained by fire.

Human enterprises can have similar behavior, as, for example, when corporations such as IBM and General Motors accumulate rigidities to the point of crisis, followed by efforts to restructure (Hurst and Zimmerman 1994; Hurst 1995). The key test of the limits of the metaphor is not whether resources and potential increase from r to K , but whether rigidities inevitably do so as well. Are there designs and actions that allow growth without increasing rigidities to the point of collapse? That kind of test is what is needed to adapt and expand the metaphor.

But before we can start comparing and contrasting different systems in order to discover where the scheme breaks down, it is necessary to add the resilience dimension to those of connectedness and potential. That addition disentangles some of the inconsistencies that emerge when the adaptive cycle is applied to specific situations. It is necessary to add vulnerability to change in addition to the other two properties of limits of change (potential) and degree of internal control over variability (connectedness). That property of vulnerability is determined by the resilience of the system.

Adding Another Dimension: Resilience

Figure 2-2 adds the third dimension, resilience. The appearance of a figure 8 in the path of the adaptive cycle (as in Figure 2-1) is shown to be the consequence of a projection of a three-dimensional object onto a two-dimensional plane. We can view that three-dimensional object from different perspectives, in order to emphasize one property or another. Figure 2-2 revolves the object to expose the resilience axis.

As the phases of the adaptive cycle proceed, a system's ecological resilience expands and contracts as suggested in Figure 2-2. Note that the myth of Nature Resilient described in Chapter 1, in contrast, sees resilience of a system as a fixed quantity for the whole system. In that view, a system is resilient or not in various fixed degrees. But here we see resilience expanding and contracting within a cycle as slow variables change. We had to recognize that feature as an essential attribute for the myth of Nature Evolving and for resolving paradoxes encountered in examining specific examples of sustainable change.

The essential requirement is to recognize that conditions are needed that occasionally foster novelty and experiment. Those become possible during periods when connectedness is low and resilience is high. The low connectedness permits novel reassortments of elements that previously were tightly connected to one another. The high resilience allows tests of those novel combinations because system-wide costs of failure are low. Those are the conditions needed for creative experimentation. This recognition of resilience varying within a cycle is the first element added that provides a way to reconcile the delicious paradoxes of conservative nature versus creative nature, of sustainability versus creative change. Other additions concerning

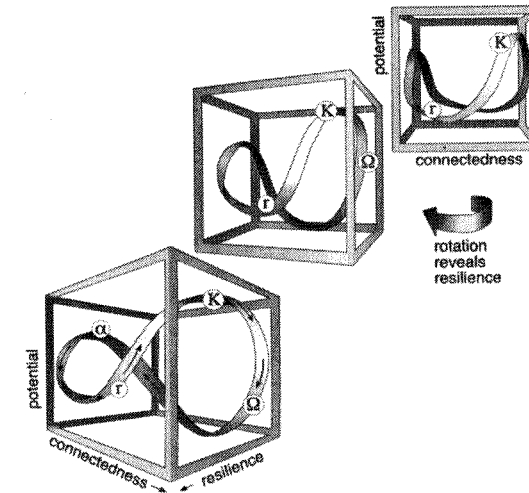


Figure 2-2. Resilience is another dimension of the adaptive cycle. A third dimension, resilience, is added to the two-dimensional box of Figure 2-1, showing that resilience expands and contracts throughout the cycle. Resilience shrinks as the cycle moves toward K , where the system becomes more brittle. It expands as the cycle shifts rapidly into a “back loop” to reorganize accumulated resources for a new initiation of the cycle. The appearance of a figure 8 in Figure 2-1 is shown to be the consequence of viewing a three-dimensional object on a two-dimensional plane.

The α phase begins a process of reorganization to provide the potential for subsequent growth, resource accumulation, and storage. At this stage, the ecological resilience is high, as is the potential. But connectedness is low, and internal regulation is weak. There is a wide stability region with weak regulation around equilibria, low connectivity among variables, and a substantial amount of potential available for future development. Because of those features, it is a welcoming environment for experiments, for the appearance and initial establishment of entities that otherwise would be out-competed. As in good experiments, many will fail, but in the process, the survivors will accumulate the fruits of change.

But the same condition of low connectedness results in the system becoming “leaky.” This leaky-ness is a signal of the α phase. It was first demonstrated empirically by Bormann and Likens (1981) in the famous Hubbard Brook experiment. Various treatments (e.g., tree removal, herbicide) of a small, forested watershed in New England mimicked a K to Ω event. The water flow from the watershed was monitored and showed a pulse of nutrient loss that, within weeks, was slowed and stabilized as the ecosystem processes became reorganized. The same leaky phase has been described for semiarid savannas subject to the persistent disturbance of sheep grazing. If that continues, as it can when ranchers have no viable economic alternative, the rangelands progressively and irreversibly erode into a shrub-

Box 2-4. Quasi-Alternate States

G. Peterson

The dynamics of a system with a single stable state may approximate a system with multiple stable states if a perturbation can cause the system to persist in a slowly changing unstable state. While such a system does not have true alternative states, its dynamics and management may be similar. Semiarid grazing systems provide an example.

Competition between grasses and woody vegetation is mediated by stocking rates of cattle and sheep that graze grass but not woody vegetation. At low grazer densities, grass dominates; however, as stocking density increases, grazing may shift the competitive balance in favor of woody vegetation. If high stocking densities persist, the grass will be unable to persist and the system will be dominated by woody vegetation. This state is relatively self-maintaining, and a reduction of stocking densities does not allow grass to replace woody vegetation. However, in some conditions of relatively good soils, the woody vegetation-dominated state is not stable, because rainfall variation and the death of shrubs allow grasses to re-invade woody sites.

Woody vegetation dies back very quickly in dry years but recovers only slowly in wet years. Grass can recover much more quickly. Grass biomass can expand up to tenfold during a season by utilizing water not used by the slow-growing woody vegetation. In addition, as woody vegetation gradually dies, patches are opened that can be colonized by grasses. Over time, these patches allow fire to invade a woody patch. The grass state of this rangeland is the only stable equilibrium of such a system, but when this state is perturbed by overgrazing, the system will make a slow transition through a woody-dominated period before it returns to a grass-dominated state. High stocking levels over a time period of five to twenty years allow woody plants to replace grasses. However, during the following thirty years, the death of woody vegetation allows fire to invade, replacing woody vegetation with grasses. This type of slowly changing unstable state is not a true alternative stable state, but to a rancher who is making decisions about stocking levels, it may as well be (J. Ludwig et al. 1997; Walker 1988).

If we chose to redefine the system to include ranchers as a dynamic part of it, then the slowly changing state could, however, be converted to a true stable state. In such a case, economic reality could so lock the rancher into continued stocking of sheep that recovery would be impossible.

dominated semidesert that is sustained by low-level grazing (J. Ludwig et al. 1997; Chapter 11; Box 2-4).

Note that the α phase is the condition for the greatest uncertainty—the greatest chance of unexpected forms of renewal as well as unexpected crises. As we emphasize later, this is one of the key elements in Nature Evolving—the condition where, momentarily, novel reassortments of species in ecosystems (or recombinations of genes in cell division) generate new possibilities that are later tested. That is precisely what happens in meiosis, where novel reassortments and recombinations of genes contained within the sex cells launch novel experiments that are tested by natural selection. It is the basis of the modeling use of genetic algorithms invented by John Holland, to generate and explore novelty in economic, social, and mathematical systems (Holland 1995; Chapter 9).

r to K

In both the α and r phases, surviving residual vegetation and physical structures represent biotic legacies from the previous cycle (Franklin and MacMahon 2000). They provide a template on which the seeds from the past or from distant sources germinate. The r phase becomes rapidly dominated by a thriving biota that is adapted to high variability of microclimate and extremes of soil conditions and can further occupy unexploited territory through effective dispersal. Because of these adaptations, resilience remains high. Similarly, it is a condition in which, in the economy, the innovator sees unlimited opportunity. Or in which producers of new products can aggressively capture shares in newly opened markets. Because connectedness is low, the entities are very much influenced by external variability—both as opportunities to exploit and as constraints to bear. As a consequence, they have evolved or are selected from a pool that includes species and individuals adapted to dealing with the stresses and opportunities of a variable environment—the risk takers, the pioneers, the opportunists.

A period of contest competition among entrepreneurial pioneers and surviving species from previous cycles ensues. The ones fastest off the mark and most aggressive are the ones likely to persist. Many fail. Aggressive invasive species start to sequester ecological space. Start-up organizations, whether in businesses, research, or policy, initiate intense activity energized by a pioneer spirit and opened opportunity. Markets start to become controlled by products once they exceed about 5 percent of the potential.

This starts a progression from r to K as the winners expand, grow, and accumulate potential from resources acquired. We use the term *resources* in the broadest sense, including, for example, carbon and nutrients for the biota, production and managerial skills for the entrepreneur, marketing skills and financial capital for the producer, and physical, architectural structure for all systems. Connectedness between interrelated entities begins to in-

inexorably increases as expansion continues. A subset of species begins to develop close interrelations that are mutually supportive—i.e., they form self-organized clusters of relationships. The future starts to be more predictable and less driven by uncertain forces outside the control of the system. Microclimatic variability becomes moderated by vegetation, soils improve, the quality and quantity of supplies become more certain, the trust needed for effective cooperation increases and becomes more dependable. In short, the actors, whether species or people, develop systems of relationships that control external variability and, by so doing, reinforce their own expansion. That is, connectedness increases.

Diversity of species peaks just as intense competition and control begin to squeeze out those less able to adapt to the changing circumstances. It is during the intermediate stages of ecosystem succession, for example, that the greatest variety of species is found (Bormann and Likens 1981; Connell 1978). As the system evolves toward the conservation phase, K, connectivity among the flourishing survivors intensifies, and new entrants find it increasingly difficult to enter existing markets. The future seems ever more certain and determined.

Since the competitive edge shifts from those that adapt to external variability and uncertainty (r-selected entities), to those that control variability (K-selected), more return is achieved by increasing efficiency for utilizing energy, minimizing costs, and streamlining operations. At the extreme, this can result in increasing returns to scale, as Arthur (1990) suggests for some corporations and products, so much so that new entrants, new innovations, might have reduced opportunity to enter despite their potential superiority. Note, however, that the dynamics of competition in many industries where increasing returns would appear to loom large, and would appear to block potentially superior products, are extremely subtle (Shapiro and Varian 1999).

Not only do potential and connectivity change in the progression to the conservation, K, phase, but ecological resilience also changes. It decreases as stability domains contract. The system becomes more vulnerable to surprise. In the forest, fuel for fires and food for insect defoliators reach critical levels as processes that inhibit fire propagation (e.g., fire “breaks”) and insect population growth (e.g., avian predation) are homogenized and diluted (Box 2-1). Markets for products can become saturated and profit margins can narrow, with little flexibility for further efficiency increases. Wages might become a target for cost cutting, and the trust accumulated during growth could thereby be weakened. Organizations can become bureaucratized, rigid, and internally focused, losing sight of the world outside the organization. Those, of course, are tendencies, whose inevitability depends on management and design. The exceptions to these tendencies identify the limits to the metaphor presented to this point, and the possible features of human systems that can react and adapt to future events. More on that in Chapter 4.

K to Ω

In the cases of extreme and growing rigidity, all systems become accidents waiting to happen. The trigger might be entirely random and external—a transient drying spell for the forest, a new critic appointed to the board of directors of the company, an election of a new minister of government responsible for the agency. We have seen all of these in earlier case examples (Gunderson et al. 1995a). Such events previously would cause scarcely a ripple, but now the structural vulnerability provokes crisis and transformation because ecological resilience is so low.

As a consequence, in Schumpeter’s (1950) words, a gale of creative destruction can be released in the resulting Ω phase. Accumulated resources are released from their bound, sequestered, and controlled state, connections are broken, and feedback regulatory controls weaken.

In the shift from K to Ω , strong destabilizing positive feedbacks develop between the revolting elements (the insect defoliator, the aroused stockholder) and the established aggregates (the trees in the mature forest, the bureaucracy of the firm). But that process is transient and persists only until the resources are exhausted. Insect pests run out of food, and fire runs out of fuel. Workers are fired in efforts to reduce costs, and CEOs are fired to set the stage for restructuring. Temporarily, potential plummets.

Ω to α

If the progress from r to K represents a prolonged period during which short-term predictability increases, the shift from Ω to α represents a sudden explosive increase in uncertainty. It is the phase where conditions might arise for formal chaotic behavior. This alternation between long periods of somewhat predictable behavior and short ones of chaotic behavior might result in systems periodically probing and testing limits. The process generates and maintains diversity—of, for example, species in ecosystems or functions in an organization. And that diversity “lies in waiting” to allow the system to respond adaptively to unexpected future external changes.

The potential left over is from the resources that were accumulated in the mature forest or mature firm. Those resources exist in a variety of forms as legacies of past cycles (Franklin and MacMahon 2000)—in the dead branches and tree trunks not consumed by fire or insects; in the nutrients released by decomposing organic material; in the seed banks established in soil; in the animals and propagules that move over small and large distances; in the physical, architectural structure that had been earlier created. The high potential in K shifts, momentarily, to a low potential where the residual resources are unavailable to or not actively involved in ecosystem growth or maintenance. Nutrients released in the soil begin to leak away until processes of immobilization slow the loss and processes of mobilization

begin to make the soil available for reestablishment. The ecosystem is going through a reorganization, with weak interactions between elements.

The result is that the variables and actors have few resources, and there is, momentarily, lower potential until the reorganization is consolidated and exploited. Species and individuals have loose connections to others and function in a wide, loosely regulated domain of stability as they progress to the phase of reorganization, α . Resilience is high. The released capital begins to leak away, but the wide latitude and flexibility allowed variables and actors means that unpredictable associations can form, some of which have the possibility of nucleating a novel reorganization and renewal. This is the time when exotic species of plants and animals can invade and dominate future states, or when two or three entrepreneurs can meet and have the time and opportunity to turn a novel idea into action. It is the time when accidental events can freeze the direction for the future.

Moreover, the totally unexpected associations and recombinations that are possible in the α phase make it impossible to predict which events in this phase will survive to control subsequent renewal. The phase becomes inherently unpredictable.

Similarly, some of the skills, experience, and expertise lost by the individual firm remain in the region. They are not lost, but they exist only as a potential for future utilization in new or old enterprise. It takes time for the reorganizations to expose the potential in surviving resources.

The α phase turns what might otherwise be a fixed, predictable progression or cycle into wonderfully unpredictable, uncertain options for the future. Controls over external variability are weak. Because of the weakness of connections, the potential in resources now becomes more freely available, and the high resilience and low connectedness makes for random assortments among elements, some of which can nucleate unexpected processes of growth. It is what John Holland captures in his use of genetic algorithms to model novelty and change in economic and other systems (Holland 1995).

As an ecological example, when there was a massive planetary transformation during the retreat of the ice sheets fifteen thousand years ago, a protracted phase of α conditions gradually shifted northward. Paleocological reconstructions (Webb 1981; Davis 1986) demonstrate that whole ecosystems did not move as integrated entities. Rather, individual species moved at their own rates to establish themselves where climatic and edaphic conditions made survival possible. Once established, novel associations became possible among previously separated species. Where chance compatibility existed, sustaining relationships then could develop among key species to form and reinforce relationships that were mutually reinforcing. A self-organized system became possible.

In summary, the major ecosystems we know now were nucleated as a mixture of independent species established in an α phase of the adaptive

quences of adaptive cycles then could establish stronger interactions among mutually supporting species in a process of competitive and synergistic sorting. That led to the development of self-organizing processes—of a mix of biotic interactions like competition, facilitation, predation, and herbivory, and abiotic ones like fire and storm—processes that reinforce their own function (Levin 1999). The result is the ecosystems we now know as boreal coniferous forests, temperate deciduous forests, grasslands, and the like.

Front Loop/Back Loop: Embracing Opposites

The adaptive cycle illustrated in Figures 2-1 and 2-2 shows two very different stages. The front-loop stage, from r to K , is the slow, incremental phase of growth and accumulation. The back-loop stage, from Ω to α , is the rapid phase of reorganization leading to renewal. The first stage is predictable with higher degrees of certainty. The outcomes following destruction and reorganization in the back loop can be highly unpredictable and uncertain.

It is as if two separate objectives are functioning, but in sequence. The first maximizes production and accumulation; the second maximizes invention and reassignment. We have no theorem to prove it, but our intuition suggests that any complex system, if it is adaptive, must generate these two phases in sequence, at some scale. The two objectives cannot be maximized simultaneously; they can occur only sequentially. And the success in achieving one tends to set the stage for its opposite. The adaptive cycle therefore embraces the opposites of growth and stability on the one hand, change and variety on the other. This metaphor suggests that attempting to optimize around a single objective is fundamentally impossible for adaptive cycles, although optimizing the context that allows such a dynamic might be possible. In that case, the nested cycles themselves become part of the machinery to probe and explore an adaptive landscape. That concerns the subject of the next chapter.

The economics literature is noted for its search for optimal solutions—economic and social. Standard notions of competitive equilibrium, for example, generate allocations that approximately maximize a weighted sum of objectives for some fixed set of weights. Theory shows that these allocations end up converging to a generically unique optimal steady state (McKenzie 1986). However, the assumptions needed for this kind of behavior in general equilibrium economics are severe. Although some effects of relaxation of these assumptions have been studied by Brock (1988) and Grandmont (1998), it is difficult to sort out which predictions of relaxation of these assumptions are consistent with the adaptive cycle metaphor and which ones are not. In any event, the adaptive cycle metaphor might suggest an interesting future research agenda for economics.

Very similar patterns of interactions, at landscape scales, have been discovered in a number of terrestrial and near terrestrial ecosystems—but not

Where the full adaptive cycle does operate, periodic flips from one state to another are mediated by changes in slow variables that suddenly trigger a fast-variable response or escape (Boxes 2-1, 2-2; Carpenter 2000).

In real situations of ecosystem management, no manager actually knows the ecosystem model. One must simultaneously estimate it and update it while managing the system. It appears that discounting might be an important force in causing recurrent phases of behavior that could, depending upon the detailed properties of the ecosystem being managed, lead to dynamic trajectories that look rather like an adaptive cycle pattern. Carpenter, Brock, and Hanson (1999) offer an example in which the support of the shock distribution is wide enough and there is a slow variable (phosphate in mud) that recurrently builds up vulnerability, which locates an alternative stable state inside that support. Hence, a manager who discounts the future lightly has a difficult time avoiding an occasional "flip" because of the occurrence of rare but large shocks. We suspect that when learning of model parameters is coupled onto this management problem, even more interesting dynamic interactions will appear. It will be interesting to try to identify the conditions for these patterns to look like adaptive cycles. Are they such as to characterize traditional management of complex ecosystems and thereby explain the paradox of regional resource management introduced in Chapter 1?

This is an example in which consideration of the adaptive cycle metaphor steers the investigator toward asking precise questions about the relationship among the location of potential alternative stable states, the rate of buildup of slow variables, the impact of the slow variable upon construction of alternative stable states, and the size of the support of the shock distribution as a function of current stock and stock of the slow variable.

We do have a growing number of specific mathematical models that expose the specific nonlinear processes that produce this behavior. Carpenter, Brock, and Ludwig (Chapter 7) describe one such set for lake systems. Some more analytically tractable models have also been developed that allow more formal exploration of stability properties. These include ecosystem examples of the dynamics of budworm and forest (Ludwig et al. 1978); of grassland grazing systems (Walker 1981); and of lake eutrophication (Scheffer et al. 1993; Scheffer 1999; Carpenter, Ludwig, and Brock 1999).

In economics, Brock and Hommes's (1997) model of information in an economy has the same features of flipping from one phase to another, as an interaction between fast and cheap learning and slow and expensive learning. In that model, agents have a choice between using last period's price to predict next period's price and base their production plans on that or purchase an accurate prediction of next period's price for a fee and base their production plans on that. For high enough values of a parameter that measures how responsive agents are to economic incentives, this system generates patterns that look rather like an adaptive cycle. This is so because instabili-

ties exceed a threshold (which depends upon the size of the fee for more accurate predictive information). This phase looks very much like an r to K phase in the adaptive cycle. When the threshold is exceeded, many agents switch to buying the accurate predictor, which abruptly stabilizes the system. This abrupt change from naive prediction to costly but more accurate prediction resembles a K to Ω phase in the adaptive cycle. At that point the system reorganizes itself after a few periods of stabilization into a new "normal times phase." This looks rather like a compressed version of an Ω to α , α to r phase in the adaptive cycle.

Testing the Limits of the Adaptive Cycle Metaphor

The adaptive cycle is one part of a heuristic theory of change. The other parts concern hierarchies that are formed by nested sets of such cycles at progressively larger scales. Those will be considered in the next chapter. But even at this stage we begin to explore the limits to the adaptive cycle. In itself, the cycle is too general to be viewed as a testable hypothesis. Its value is as a metaphor to classify systems, order events, and suggest specific questions and testable hypotheses that are relevant for our theme of understanding transformations in linked systems of people and nature.

To do that, we examine specific forms of the three properties defining the cycle—potential, connectivity, and resilience—in order to test the limits to this metaphor.

Potential for Change

The potential for ecological, social, or economic change can be expressed and measured in ways specific to specific situations or systems. Ecosystem potential, for example, could be represented by potential productivity—the potential provided by the amount of biomass, physical structure, and nutrients accumulated as a consequence of ecosystem successional dynamics. That is the use Carpenter, Brock, and Hanson (1999) chose when they developed a model and analysis of a prototype watershed where water quality, agricultural productivity, and management decisions interact (Chapter 7).

Social or cultural potential could be represented by the character of the accumulated networks of relationships—friendships, mutual respect, and trust among people and between people and institutions of governance. Folke and Berkes (Chapter 5) and Westley et al. (Chapter 4) use the term *cultural capital* to describe this potential.

In the economy, potential could be represented by the economic potential provided by accumulated usable knowledge, inventions, and skills that are available and accessible. A particularly important version of that is foresight potential, possible because of the unique self-awareness and cognitive abilities of people. We will dwell on that in more detail later (Chapter 4)

ditions on the present. This capacity is one of the features that distinguishes human systems from strictly biological and physical ones. It answers, in part, the question of why human systems are not like ecosystems (Brock 2000; Chapter 4). An early model of a process by which humans build expectational models of the system they cocreate and revise is in Brock (1972). An excellent treatment is in Sargent (1999).

Connectedness

The second property is connectedness. It reflects the strength of internal connections that mediate and regulate the influences between inside processes and the outside world—essentially the degree of internal control that a system can exert over external variability. An organism, ecosystem, organization, or economic sector with high connectedness is little influenced by external variability; its operation and fate are controlled by internal regulatory processes that mediate variability. It could be assessed by a measure of equilibrium stability—of speed of return after a small disturbance, for example. Or, less theoretically, it could be measured by the intensity of control by direct human activity as Carpenter, Ludwig, and Brock (1999) did in a model representing a watershed with a linked ecosystem and agricultural economy.

A particularly clear biological example of strong connectedness of this kind is temperature regulation in endothermic or “warm-blooded” animals. Five different physiological mechanisms (such as evaporative cooling and metabolic heat generation) operate to keep internal temperature of the organisms within a narrow range, independent of external variation. The benefit is to open opportunity for the organisms to exist and exploit habitats and conditions forbidden to an exotherm or “cold-blooded” animal. The cost is the cost of maintenance of the regulation—in this example a metabolic cost ten times greater in endotherms than exotherms.

Ecosystem Resilience

The third property is ecosystem resilience, or its opposite, vulnerability. As described in an earlier section, we use resilience in its ecosystem sense (Holling 1973a, 1996; Holling and Meffe 1996) to represent the capacity of a system to experience disturbance and still maintain its ongoing functions and controls. Resilience of this sort depends on the existence of multistable states, for it concerns the likelihood of flipping from one to another. A measure of resilience is the magnitude of disturbance that can be experienced without the system flipping into another state or stability domain.

Carpenter, Ludwig, and Brock (1999) measured resilience in just that way. And that is the way it is treated in Chapters 6, 7, 8, 9, and 10 for linked ecological and economic systems and Chapter 5 for the approaches of tradi-

These three properties shape a dynamic of change. Potential sets limits to what is possible—it determines the number of alternative options for the future. Connectedness determines the degree to which a system can control its own destiny, as distinct from being caught by the whims of external variability. Resilience determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control. When these properties are used to analyze a model of a linked economic, ecological decision system, the trajectory indeed has the complex “figure 8” form of Figure 2-2 (Carpenter, Brock, and Hanson 1999; Figure 7-4).

Four key features characterize an adaptive cycle and its properties of growth and accumulation on the one hand and novelty and renewal on the other. All are measurable in specific situations and can be used to test the limits of the adaptive cycle representation:

- Potential (e.g., ecosystem structure, productivity, relationships, inventions, and mutations) increases incrementally, in conjunction with increased efficiency but also in conjunction with increased rigidity.
- As potential increases, slow changes gradually expose increasing vulnerability—to fire, insect outbreak, competitors, opposition groups, stockholder revolts.
- Innovation occurs in pulses, in surges of innovation when uncertainty is great and controls are weak so that novel combinations can form.
- Those innovations are then tested; some fail, but some survive and adapt in a succeeding phase of growth.

The adaptive cycle in its most general form is a metaphor and should not be read as a rigid, predetermined path and trajectory—for ecosystems at least, let alone economies and organizations. It suggests periods of waxing and waning tendencies, with various degrees of predictability at different stages. All actors and species can be present throughout—pioneers, consolidators, mavericks, revolutionaries, and leaders. It is their role and significance that change as their actions create the cycle. Phases of the cycle can overlap, but the most distinct separation is between K and Ω . That is the shift that occurs as a stability region collapses, or as a disturbance moves variables into another stability domain. But even the most predictable sequence from r to K can be diverted by extreme or episodic events.

Even though the adaptive cycle heuristic is general, limits to its applicability need to be identified. As described earlier, the model is too general, even as a metaphor. It even seems to apply, superficially, to non-living systems. There is a close parallel, for example, between some phases of the adaptive cycle and the sandpile models inspired by Per Bak (1996). At this level of abstraction, the Bak sandpile process looks rather similar to part of

difference between pile size at the beginning and pile size at criticality is like a "potential" at a very slow time scale); and second, the pile, continually fed by sand falling onto it, recurrently relaxes and releases an avalanche.

In these physical cases, potential is accumulated during the r to K phase and dissipated from K to Ω in the way described for the adaptive cycle. But unlike such physical systems, living systems transform, invent new forms (mutations, mistakes, and inventions), and endogenously control the potential as it accumulates. When released, it provides the stage for novel reassortments and rearrangements of new elements accumulated from r to K . And these experiments are tested in subsequent phases of growth. Sandpiles do not evolve into new forms; living systems do.

But even restricting the cycle to living systems suggests that too many of those systems seem equally to fit the heuristic model of change: cell development, meiotic reproduction, ecosystem formation, evolution, human organizational stasis and transformation, political and social change and transformation. What is different about these very different systems?

Although there are many examples that match the cycle, we need to explore extreme examples that are likely to be exceptions. Four will be briefly discussed here, to set the stage in later chapters for deeper analysis. The criterion to select extreme examples concerns the way external variability is treated by the system.

Broadly, there are three strategies for dealing with external variability. One is to live passively with external variability by evolving appropriate adaptations; one is to control variability actively, minimizing its internal influences; and one is to anticipate, create, and manipulate variability.

The empirical studies that led to the development of the adaptive cycle were all examples of the second strategy—of at least partial regulation of variability. The ecological examples we used were from temperate, productive terrestrial systems where considerable resources of biomass, structure, and nutrients are accumulated and where processes self-organize physical structures and patterns that regulate external variability. An ecosystem is not, in any rigorous sense, homologous to an individual organism, and the regulation is considerably looser (Levin 1999). But the regulation is sufficient to partially moderate external variability. The temperature within the closed canopy of a forest, for example, fluctuates over a narrower range than that outside the forest. And the nutrients from variable rain and erosion are "managed" by the biota to be sustained in soil or biomass. Even at a regional scale, for example, it has been shown, through simulation models, that the landscape-scale attributes of the Amazonian forest can affect regional climate in a way that maintains that forest (Lean and Warrilow 1989). In northern forests, snow melt and initiation of the growing season occur earlier in the spring because of greater heat input associated with low albedo spruce forests (Hare and Ritchie 1972).

Four Extreme Examples

If we are to find exceptions, therefore, the first place to look is for systems that might represent examples of the other two strategies—living passively with variability or creatively manipulating it. We initially focus on two examples of the first: pelagic, open-water communities and semiarid savanna. Each is strongly influenced by external variability, and the species in each evolve adaptations to live passively with that external variability.

We follow with two possible examples of the second: examples of forward expectations viewed through the lens of the economists' market model and examples of large bureaucracies such as AT&T and resource agencies of government. It is in such human systems that we might identify ways to anticipate and manipulate variability creatively, and escape the apparent inevitability of the adaptive cycle and its prediction of rigidity leading to crisis.

Aquatic Systems

Some aquatic communities are built around species that can attach to or build substrate. As a consequence, the physical attributes of the plants or structures can moderate influences of external variability, and the biota can accumulate substantial biomass in individual organisms, much as terrestrial forests can. For example, kelp forests and coral reefs show the existence of multistable states and adaptive cycles like those already described (see Box 2-2). And both kelp and coral moderate the variability of currents and waves. The same is true of shallow lakes and lagoons where rooted aquatic plants become part of the determinants of the state of the ecosystem (Scheffer 1999; Box 2-2; Chapter 10). Scheffer (1999; Chapter 10) shows multistable states and the possibility of boom-and-bust cycles organized by nonlinear relationships like the adaptive cycle.

In contrast, open-ocean or pelagic biotic communities remote from land or substrate exist at the whim of ambient currents and nutrients. They therefore become organized largely by the external physical variability of turbulence, waves, upwelling, and gyres in the ocean and by trophic relationships among the species. Pelagic communities have no way to develop the fixed physical structures that can moderate external environmental variability by establishing self-organized architectural patterns on their landscape or in their waterscape. Ramon Margalef, the Spanish ecologist, noted that such communities are organized into classes defined by two properties—one of extant nutrient level and one of turbulence, similar to two of the axes of the adaptive cycle (Margalef 1981). In these cases, external physical processes at any point in the ocean fix the level of those properties and define the biotic classes. Each class has evolved adaptations to deal passively with the external variability it is exposed to.

In these pelagic examples, the communities are fixed in their condition, developing remarkable adaptations to do that. As communities or ecosystems, they do not cycle through the full suite of phases of the adaptive cycle. Each community finds itself in one of the phases of the adaptive cycle, oscillating because of trophic dynamics. But they stay there because they cannot exert dynamic control over external turbulence or nutrient levels. At best, they experience only part of the cycle as, in the case of highly eutrophic, low-turbulence situations, the communities (like red tides) flip into anoxic states and are dispersed. It is only the individual cells that go through the full cycle as described, in a classic process of individual variation and natural selection, thereby developing the adaptations to deal with the variability they experience but cannot control.

Semiarid Savanna Ecosystems

Arid grassland systems “are simply waiting for the big event, the trigger of rainfall. Using an amazing array of adaptive mechanisms they remain relatively quiet and inactive during dry times waiting for favorable conditions” (J. Ludwig et al. 1997). Hence the potential in biomass and nutrients (r to K) does not accumulate in as regular and continuous a way as in the temperate ecosystem examples. Rather, biomass and nutrients accumulate potential episodically, triggered by external events like a rare pulse of rainfall. After the pulse, there is a slow decline of potential and accumulated resources. Growth along the trajectory from r to K is therefore sporadic, ratchet-like rather than continuous. Marvelous adaptations have evolved to keep the potential for spurts of growth in waiting for the rare but large rainfall event and to slow its loss in succeeding periods of drought. Physical topographic patterns at micro, meso, and landscape scales provide a heterogeneous template for sustaining nodes of potential for increase.

If enough growth does accumulate, the larger amounts of biomass can begin to control the variability of exogenous resources. For example, there is evidence for regulation of nutrient variability and soil moisture by patchy distribution of biotic material acting as traps for water and nutrients (Tongway and Ludwig 1997a). Moreover, prior to European settlement, there is evidence in these savannas of cumulative sequences of vegetative growth that were ultimately released in a K to Ω break by an interaction between fire and grazing by mid-sized marsupial herbivores. The result was similar to the adaptive cycle described earlier, and, as in such cycles, the cycle maintained a balanced set of species, serving different ecological functions—in this case, annual and perennial grasses, shrubs, and trees. A changed fire regime after European settlement, combined with the extinction of mid-sized mammals, establishment of the European rabbit, and sheep grazing, led to a simplified system much more driven by external episodic events, with less accumulation of biomass.

connectivity is low, and resilience is high. It is where novel adaptations of species to external variability are continually generated and tested through natural selection. It is the condition in which external variability controls the system's development. Although these grasslands are not very productive for use in grazing, they are astonishingly resilient to the effects of overgrazing. Remove grazing pressure and they recover—slowly, but they do recover (see Box 2-3). They have evolved adaptations to persist through extremes. When the productivity is so low that insufficient biomass can accumulate to trigger a K to Ω shift, they are therefore dominated by properties of the α and r phases, where there are continual adaptations to external variability being developed. This therefore represents a variant of the adaptive cycle seen in more productive systems, where variation is more predictable and is controlled.

Large Organizations: Bureaucracies and an Industry

Alfred Marshall, the dean of British economics, has stressed life-cycle theories of firms and industries since his *Principles of Economics* was published in 1890. Indeed, Marshall thought much more like a biologist than an economist but was constrained by the types of mathematics available at his time. A reread of Marshall with modern mathematical equipment from mathematical biology and pattern generation and recognition might be a useful way to develop the adaptive cycle idea for serious use in economics. That is beyond this chapter and this book, but perhaps we can set the stage by reviewing patterns of change in human-dominated systems, structuring events with the help of Figures 2-1 and 2-2, and seeking to identify the kind of empirical evidence needed to discover exceptions.

We start with a bias. Not that the adaptive cycle applies in all details to human organizations, but that it does not. Human cognitive abilities provide the ability for developing forward expectations that should allow human-dominated systems to respond not just to the present and the past, but to the future as well. In theory, at least, that is what happens in true markets—future risks and opportunities are identified by a myriad of entrepreneurs, and specific solutions are given present value through a futures market. Such forward expectations, together with an effective market mechanism, would stabilize the boom-and-bust cycles of the adaptive cycle. In fact, that is what has happened over the past decades as societies have encountered potential scarcity of resources (Solow 1973; Chapter 4). More accurately, that would transfer those cycles from the economy as a whole to smaller elements within it—to the gamblers who bet on the future. It suggests a hierarchical structure of cycles, a construct that will be discussed in the next chapter.

We have barely started this effort to rationalize such theoretical features of market economics with the adaptive cycle. Chapter 10 faces the issue directly, as does Chapter 7. Both encounter serious analytical problems when

Box 2-5. The Telephone Great Fits the Figure Eight?

W. A. Brock

In the following paragraphs, I explore the use of the adaptive cycle diagram in the history of telephony in the United States. This box makes a feeble attempt to subject the adaptive cycle diagram to a weak type of Popperian falsification test using the history of the Bell System. The terms AT&T and Bell System are used synonymously. The story is based on work by Bornholz and Evans, in Evans 1983.

The industrial organization of telephony in the United States has gone through several growth, reorganization, and renewal eras: (1) Open competition at the birth of the industry led to temporary dominant monopoly of the Bell System due to patent and other head-start advantages. (2) A serious threat to the Bell System and partial breakdown of its temporary dominant monopoly due to patent expirations in 1893 and 1894 caused a reorganization, in order to face another period of open competition from independent telephone companies (called telcos). (3) After finding (around 1907) a workable strategy to fight the competition unleashed by patent expiration, the Bell System evolved into a dominant monopoly, which led to a crisis (circa 1915–19) resulting from antitrust action and possible government nationalization of the telephone industry. (4) Resolution of this crisis led to a regulated monopoly of the Bell System, which prevailed essentially until the early 1980s when the settlement of a lawsuit restructured the entire industry. The U.S. government filed the suit against AT&T in 1974. The case was settled in 1982 with an ordered breakup of the company.

I'll organize the telling of the history of the above phases using the adaptive cycle diagram (Figure 2-2). One could ask whether the historical sequence is consistent with the adaptive cycle diagram and, in a falsification sense, what it means to be consistent or inconsistent with that diagram. In other words, can one use the Bell System history to hint at what it would take to identify a sequence of events that we would rule as being in agreement with the adaptive cycle or not?

The adaptive cycle diagram suggests a certain inevitability to the occurrence of the following sequence of phases: r to K , K to Ω , Ω to α , α to r (with a possible flip between Ω and α enroute to r);

repeat. Furthermore, resilience to shocks supposedly decreases toward the end of the r to K phase as capital gets bound up more and more tightly. That is, the internal dynamics of the industry and AT&T are predicted during the initial r to K phase of the cycle to push the company toward an edge of precariousness, due to this binding and rigidification, where the company would be "an accident waiting to happen."

But the first crisis it faced at the end of phase 1 was due simply to the expiration of its two most basic patents in 1893 and 1894. This was a mammoth shock since the whole business was based on exploiting the temporary monopoly granted by those patents. Testing the predictive power of the validity of an r to K phase in era 1 would involve a detailed historical reading of the record of response to see if the Bell System had rigidified. This examination would reveal whether the natural accumulation of habits, protocols, and other efficiency-enhancing procedures when one optimizes in a stable, recurrent, setting had occurred during the period when the company was protected by the two basic patents. That is, before the expiration of the patents had the company's resilience to shocks lessened? Since the management knew when the patents would expire, this kind of analysis could reveal whether management created more resilience in anticipation of the shock it should have known was coming. If the historical record showed an increase (rather than a decrease) in a usable measure of resilience before the patent expirations in 1894, that might be viewed as contradictory to the r to K to Ω part of the diagram. It is beyond the scope of this box to answer the question, but it appears to be well posed.

The record does show that a type of reorganization occurred following the expiration of the patents, in the form of a vigorous counterthrust by the Bell System toward new entrants in the market. Bell faced the competition head-on by prohibiting interconnection, prohibiting supply to independents by its manufacturer, rapidly expanding its own network, filing patent suits against the independents, and cutting its own prices when independents appeared (Evans 1983).

The second crisis occurred around 1907, when Bell System management had to create a new style appropriate to dealing with the surge of new entrants into the business after the strategy described above had failed. In 1907 a changing of the guard took place along with an abrupt change in policy to "financial competition through absorption and purchase of independents" (Evans 1983).

The third crisis was the reaction of the independent telcos and the U.S. government to the monopolization of the business. Acquisition of independent telcos in the early 1910s led to the emergence of the structure of a regulated monopoly with a fringe of independents, which characterized the industry until the early 1980s.

The phase that lasted from the early 1920s to 1982 might fit the adaptive cycle diagram quite well. During that phase, over a sixty-year period, the Bell System evolved an elaborate, routinized way of doing business. Furthermore, almost all of the top positions were ingrown and the top officers were hired from within the organization. This structure would appear to be rigidified by any measure.

The crisis that led to the court-ordered breakup of AT&T in 1982 may have occurred because technological change had made the old cost allocation across the set of users unsustainable. The long-distance calling portion of the business was heavily subsidized by local calls. A common sound bite was "6 percent of the users generate 60 percent of the revenue, and these users now have the technology to bypass Bell's network." Hence, when these high-density users put pressure on the regulatory framework, AT&T reacted in a rather routinized, knee-jerk fashion by using the regulatory process to bar entry while claiming to act in the public interest. The reaction happened even though any definition of the public interest, using available, standard economic science, would have suggested something like an analogue of taxation on revenue diversion with tax rate based on estimated depth of AT&T scale economies and with surtax on sales of the whole industry to fund public interest services such as lifeline service for the poor. The seeming inability of AT&T to react creatively may have been due to an r-to-K-type phase of rigidification from the narrow-based type of optimization ideal for the sixty-year-old industrial structure in which they operated.

The forced breakup (a K to Ω phase) led to a powerful reorganization of the component parts of the Bell System as it struggled to adapt to a brand-new competitive environment after operating in much the same way for almost sixty years (an Ω to α phase followed by α to r). The computer revolution and AT&T's role in that revolution could be viewed as the latest r to K phase, which is still ongoing.

and multistable states, and when there are interactions among nested sets of fast and slow variables. At a minimum we conclude that, in those circumstances, anticipating and creating useful surprises needs an actively adaptive

We hoped to discover useful exceptions in a deeper examination of change in specific large human organizations. But we failed. The book that motivated the Resilience Project, *Barriers and Bridges to the Renewal of Ecosystems and Institutions* (Gunderson et al. 1995a), offers a number of case examples of bureaucracies dealing with natural resources in ecosystems and with people's needs and desires. All cases seem slavishly to follow the adaptive cycle, with the bureaucracy attempting to reinvent itself in a series of crises and responses to crises but having difficulty doing so because of a lack of external competitors (Light et al. 1995; Chapter 12).

The history of telephony in the United States has a rather similar shape to that of the case studies discussed in Gunderson et al. (1995a) and in this volume. That history is summarized in Box 2-5. In the adaptive cycle storytelling framework, one can label the year 1894 as the point at which AT&T ended the first r to K phase, swept through the release of the "old ways of doing business" accumulated during the period of patent protection, and reorganized itself to deal with the new influx of entrants to initiate a second r to K phase. Much like the initial stage of r-selected species in ecosystems, young, brash, fast-growing, aggressive entrepreneurial companies sprang into existence and raced each other across the landscape to lay out telephone wire and poles ahead of rivals. It looked like a race to build networks since each realized the competitive advantage of the largest interconnecting network, and each realized that the first to lay the largest network would ultimately lock in most of the market. Thereafter, two additional waves of growth, collapse, restructuring, and innovation have occurred.

The empirical evidence suggested in Box 2-5 to test the reality of elements of the cycle has not been collected and analyzed for the telephone industry. But there is at least the suggestion that early in development, the early telephone companies did show enterprise and sensitivity to outside variability (α to r). There is even the suggestion that they structure themselves with sufficient flexibility (low connectedness) so they are poised to take quick advantage of episodic opportunities. But then gradually resources accumulate and rigidification sets in. Baron et al. (1998) provide measures of bureaucracy and time histories of the development of those measures that document parts of the phase of rigidification of an adaptive cycle. As hard as we try, we cannot see these specific examples of bureaucracies and industries as exceptions to the adaptive cycle pattern.

We argue that a formal effort is needed to disprove the patterns of the adaptive cycle, using other examples of companies that have apparently solved the challenge of adapting to external variability and internal rigidities by developing foresight capabilities and a market for them within the company. Some claim that that is what Jack Welch, CEO of General Electric, was able to design in the reinvention of that company (Hurst 1995).

Where does the extraordinarily important argument of economists regarding the role of foresight potential exert its stabilizing role? There

tence of a futures market that turn future conditions into present decisions and actions. In theory and in practice this can reduce variability, establishing these examples as cases of the third strategy: to anticipate and manipulate the variability creatively. When it works, does this keep the system/sector in the lower quadrant of the adaptive cycle, cycling largely between α and r , perpetually inventing and innovating and adapting? If so, this is another cycle that is qualitatively distinct because of the strategy of creatively manipulating variability. But is its very success transient, creating the resources that launch the other phases of the adaptive cycle? All we can do at this stage is to pose questions in forms that have broad relevance for sustainability and development:

- Under what conditions does increasing accumulation of potential not lead to increasing rigidity?
- Are there patterns of evolutionary change that do not experience an alpha phase of reorganization and reassortment?
- How is a loosely structured set of relationships maintained in order to be alert to unexpected opportunity?
- When does foresight potential or forward expectations not reduce variability?

Adaptive Cycles, Maladaptive Consequences

Management and resource exploitation can overload waters with nutrients, turn forests into grasslands, trigger collapses in fisheries, and transform savannas into shrub-dominated semi-deserts.

There are many examples of managed ecosystems where loss of resilience is followed by a shift into an irreversible state or a very slowly recovering state—e.g., in agriculture, forest, fish, and grasslands management, as summarized in Holling (1986) and Box 2-3. In each of these cases the goal of management was to stabilize production of food or fiber or to moderate extremes of drought or flood for economic or employment reasons. In each case the goal was successfully achieved by reducing natural variability of a critical structuring variable such as insect pests, forest fires, fish populations, water flow, or grazing pressure. The result was that the ecosystem evolved to become more spatially uniform, less functionally diverse, and thereby more sensitive to disturbances that otherwise could have been absorbed. That is, ecological resilience shrank even though engineering resilience might have been great. Short-term success in stabilizing production reduces natural variability, so that the stability landscape shifts and evolves to reduce adaptive capacity. Short-term success in optimizing production leads to long-term surprise.

Moreover, such changes can flip the system into an essentially irreversible state because of accompanying changes in soils, hydrology,

control of ecological structure and dynamics. In those situations, control of ecosystem function shifts from one set of interacting physical and biological processes to a different set (Holling 1995).

But at the same time that the natural systems become less resilient—more vulnerable—changes occur in three other connected entities: the management agencies, the associated industries, and society at large. Specifically, the management agencies, in their drive for efficiency, become progressively more myopic and rigid; the relevant industries become more dependent and inflexible; and the public loses trust. This seems to define an ultimate pathology that typically can lead to a crisis triggered by unexpected external events, sometimes followed by a reformation of policy (Gunderson et al. 1995b).

Examples of this pathology were first described in systems of forest development, of fisheries exploitation, of semiarid grazing systems, and of disease management in crops and people (Holling 1986). These examples have been greatly expanded and the analysis deepened (Gunderson et al. 1995b), adding examples of development, exploitation, and management of wetlands (e.g., the Everglades, Light et al. 1995); rivers (Columbia River, Lee 1995); marine bays (Chesapeake Bay, Costanza and Greer 1995); and large enclosed bodies of water (Great Lakes, Francis and Regier 1995; Baltic Sea, Jansson and Velner 1995).

That is what led us to define a pathology of regional development and renewable resource management (Gunderson et al. 1995).

Policies and development initially succeed, leading to agencies that become rigid and myopic, economic sectors that become slavishly dependent, ecosystems that are more fragile, and a public that loses trust in governance.

This occurs as a consequence of efforts to constrain the adaptive cycle in the ecosystem and in the management agency. Adaptive capacity is lost, and each swing of the cycle demands larger and more expensive solutions. At the moment, for example, critical processes of the Everglades of Florida are being restored in what is the largest and most expensive effort of restoration ever attempted.

The examples of adaptive systems suggest a remarkable persistence, in roughly similar form. What explains such persistence not always, certainly, but frequently? Systems do change if external conditions change sufficiently, or if internal accumulation of capital passes critical thresholds. But such conditions occur rarely, relative to the speed of the basic adaptive cycle. There is another paradox. On the one hand, experiment and novelty are essential for an adaptive system; but on the other, experiments can destroy the experimenter, and novelty can be maladaptive. Something is missing in the story, something that speaks to the sustainability part of the phrase *sustainable development*. That missing part concerns dynamic cross-scale interactions—the panarchy. That is the subject of the next chapter.

Summary and Conclusions

Abrupt shifts among a multiplicity of very different stable domains have been observed in a number of regional ecosystems (lakes, marine fisheries, benthic systems, wetlands, forests, savannas, and rangelands), some economic systems, and some political systems.

A fundamental unit for understanding complex systems from cells to ecosystems to societies to cultures is an adaptive cycle. Three properties shape the pattern of dynamic change in the cycle: *Potential* sets limits to what is possible—it determines the number of options for the future. *Connectedness* determines the degree to which a system can control its own destiny, as distinct from being caught by the whims of external variability. *Resilience* determines how vulnerable a system is to unexpected disturbances and surprises that can exceed or break that control.

Different classes of systems represent variants of or departures from the adaptive cycle. Some examples of exceptions are:

- Physical systems in which a lack of invention and mutation limits the potential for evolutionary change (examples: tectonic plate dynamics, Per Bak's sandpiles (1996)).
- Ecosystems strongly influenced by unpredictable episodic external inputs, with little internal regulation and with highly adaptive responses to opportunity (examples: exploited arid rangelands, pelagic biotic communities); they can remain largely in the lower quadrant of the cycle, oscillating in the α and r phases, dominated by trophic dynamics.
- Ecosystems and organizations with predictable inputs and some significant internal regulation of external variability over certain scale ranges (examples: productive temperate forests and grasslands, large bureaucracies); they represent the full cycle of boom-and-bust dynamics.
- Biological entities with strong and effective homeostatic internal regulation of external variability (examples: cells and ionic regulation, "warm-blooded" organisms with endothermic control of temperature). System variables remain near an equilibrium, and the individual is freed to exploit a wider range of opportunities within a community or ecosystem. It is an example of local control that can release external opportunity and variability at a different scale—a transfer of the adaptive cycle to a larger arena.
- Human systems with foresight and adaptive methods that stabilize variability and exploit opportunity (examples: entrepreneurial business, futures markets and resource scarcity, some traditional cultures). The high variability of the adaptive cycle is transferred

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- Ecosystems and organizations with predictable inputs and some significant internal regulation of external variability over certain scale ranges (examples: productive temperate forests and grasslands, large bureaucracies); they represent the full cycle of boom-and-bust dynamics.
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- Human systems with foresight and adaptive methods that stabilize variability and exploit opportunity (examples: entrepreneurial business, futures markets and resource scarcity, some traditional cultures). The high variability of the adaptive cycle is transferred from the society to the individual entrepreneur.

CHAPTER 3

SUSTAINABILITY AND PANARCHIES

C. S. Holling, Lance H. Gunderson, and Garry D. Peterson

*Goat-legged, enthusiastic, lover of ecstasy, dancing among stars,
Weaving the harmony of the cosmos into playful song.*
—Description of Pan from *The Orphic Hymns*

In the late 1960s the first photographs of Earth from space provided an evocative perspective of the planet. The planet appeared as an integrated entity made up of a membrane of life intermixed with atmosphere, oceans, and land. To many, the image suggested that humans were part of that entity, nurtured and challenged by it and responsible for its protection. To others, it suggested the possibility that humans could control planetary development for human opportunity. An advertisement of the development arm of a bank, for example, published the photograph with the caption: "Businessmen, Devour This Planet!" What seemed to be a delicate jewel to some was a digestible morsel to others. But it was the image itself that suggested the integrated nature of the planet. The photograph showed that scale of observation shapes both explanations of patterns in nature and actions conceived.

What is the appropriate scale of observation in our search for theories and actions for sustainable futures? Our focus here is local, regional, and global; so there can scarcely be any single appropriate scale. Moreover, we are concerned with interactions across scales from the very small and fast to the very big and slow. A sense of the patterns and processes across those scales is provided by a marvelous set of images in the book *Powers of Ten* (Morrison and Morrison 1982). These images range in scale from microscopic to the universe, each photograph covering a size that is one order of magnitude larger than the preceding. Hence the evocative image of Earth from space is only one of a sequence of thought-provoking images. And that sequence suggests another kind of integration that emerges from small things affecting larger ones, and large ones influencing small things.

A disrupted society and an expanding transportation system can transform a local infection of chimpanzees into a global epidemic. AIDS is an example.

Our interest is in a subset of those scales shown in *Powers of Ten*, where life, including human activities, interacts strongly with physical processes. To help communicate the significance of those scales for issues of sustainability, we assembled two series of powers of ten images for one of the case studies that informs this book—the Florida Everglades. One set started with a sugar cane plant in the extensive agricultural area south of Lake Okeechobee, and one set started with a sawgrass plant in the very heart of the Everglades. Both ended with the image of the planet from space. Some selections from the latter set are shown in Figures 3-1 through 3-6.

Over fifteen orders of magnitude separate a plant in the Everglades from the planet in space. Distinct regions of scale appear with unique objects and distinct processes in each. At the smaller scales, individual plants suggest the physiological processes of plant growth, nutrient exchange, and decomposition (Figure 3-1). At coarser scales, microtopography and small-scale disturbances establish plant associations of sawgrass, pond, and wet prairie (Figure 3-2). Still coarser scales show how the slowly moving water in the “river of grass” (Douglas 1947) establishes tree islands whose elongate patterns reflect the direction of the movement of water (Figure 3-3). Coarser yet, and landforms emerge, representing human and natural land-use patterns and conflicts between wilderness areas of Everglades National Park, water conservation areas, large-scale industrial agriculture, and urban development (Figure 3-4). A network of canals defines each, developed as responses to one or more of the crises of the past caused by interactions among those land uses (Chapter 12, Figure 12-1). Still larger scales suggest geomorphological structures and land-ocean-atmosphere interactions that mediate climate warming and sea level rise (Figure 3-5). At that same large scale, geopolitical and international trade policies have set indirect subsidies for sugar (Figure 3-6). They establish dependencies and trigger conflicts that affect life and the environment in places as far flung from the Everglades as sugar-growing regions in Louisiana, Cuba, Zimbabwe, and eastern Australia.

This examination of the Everglades from the perspective of a plant to that of the planet provides a starting point for a discussion of the relationship between sustainability and scale. Four points launch this chapter from this impressionistic journey.

First, as scale increases, distinct objects appear and persist over distinct scale ranges and disappear, to be replaced by others that are aggregates of those objects. At each such range of scales, the objects have geometric properties of size measured as extent and grain. They also have temporal qualities of duration measured as generation time and turnover time. They are dynamic, not static, entities. This is summarized in Figure 3-7, where each object is shown in axes of space and time.

Second, there are abrupt breaks in patterns, across scales. We cannot simplify by assuming fractal constancy across scales. We might expect such self-similarity if the only processes were physical processes like those in air

Figure 3-1. Everglades alligator hole. The linear extent of one side of the picture (or window size) is 10 meters. The alligator hole is the dark area of the water in the middle of the picture, surrounded by marsh plants, including sawgrass. The open water is kept free of plants by alligators. Small fishes such as the mosquito fish spend their life within the area of this picture.

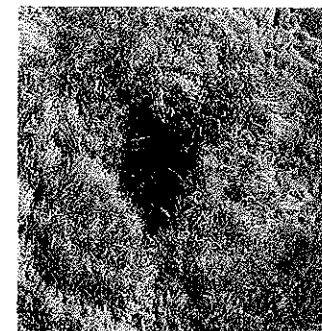


Figure 3-2. Everglades landscape. At a window size of 1 kilometer, plant communities are major features. Hardwood tree islands are the teardrop-shaped objects and are oriented with direction of water flow. The remaining matrix is comprised of sawgrass stands (lighter gray) and wet prairies (dark areas). The wet prairies have few vascular plants, but support most of the fish and invertebrates of the Everglades.

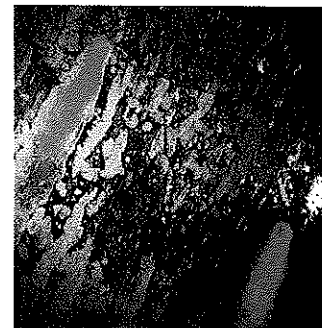
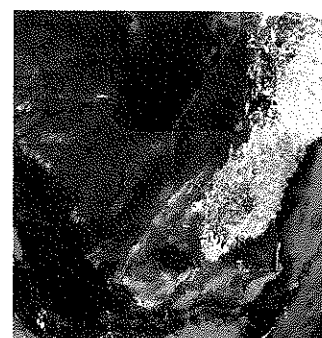


Figure 3-3. South Florida physiographic and land-use patterns. The major drainage feature of the southern Everglades (Shark River Slough) cuts a large swath through the frame that covers 100 kilometers. Water management structures (levees and canals) are the white straight lines cutting across the Everglades. The densely populated human developments centered on Miami are visible in the upper right of the picture.



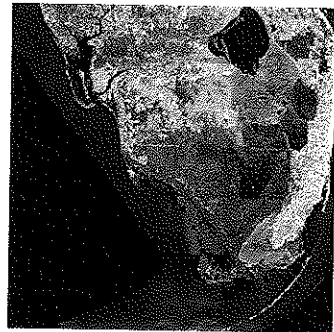


Figure 3-4. Southern Florida. The peninsula of Florida and the drainage basin of the Everglades are depicted in this satellite image that covers 300 kilometers on a side. The hydrologic unit is comprised of the Kissimmee River (north), Lake Okeechobee (central), and the Everglades. This is the scale where the interaction between the heating of the land mass and surrounding oceans during the summer months generates about 80 percent of the rain that falls on the Everglades.

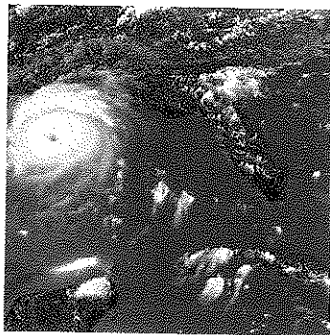


Figure 3-5. The Gulf of Mexico bioregion. The peninsula of Florida, the island of Cuba, and, in the upper left-hand corner, Hurricane Andrew are dominant features in this window of 1,000 kilometers. During the twentieth century, this picture covers the spatial scale at which wading birds have made decisions about location of nesting sites. Since the 1930s the number of wading birds that nest in the Everglades has dropped by about 95 percent. During the same period, the number of nesting sites in Central Florida, Georgia, Louisiana, and South Carolina has increased.

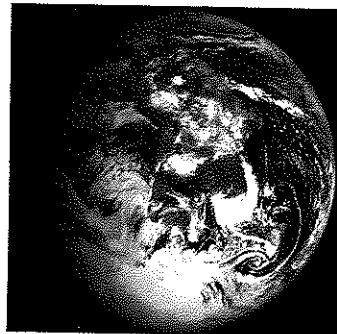


Figure 3-6. The planet Earth. International policies, trade, and tourism as well as global climate change affect the Everglades at this scale. (NASA archives)

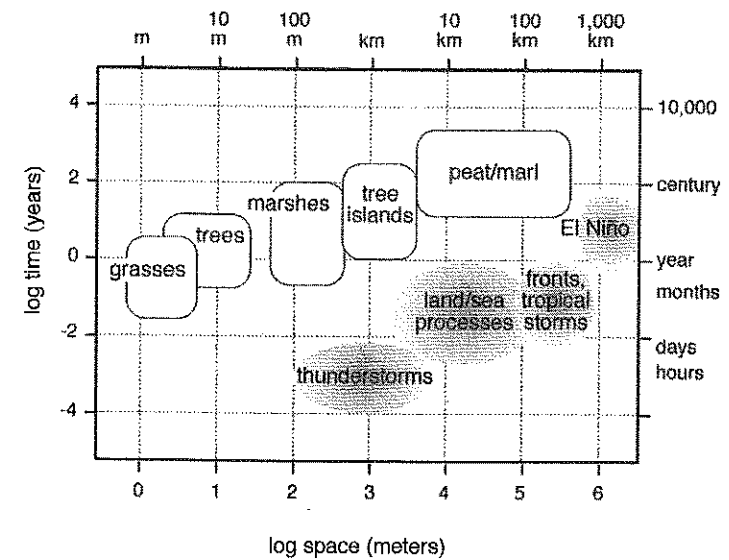


Figure 3-7. Hierarchy of vegetation, landform structures, and the atmospheric processes for the Everglades system. This plot depicts in scales of space and time the structures apparent from the shifting "powers of ten" windows of Figures 3-1 through 3-6.

or water. But biological processes, interacting with abiotic ones, add scale-dependent patterns on the physical templates. Vegetation affects hydrological processes, creating depositional rates for sediments and decomposed material to form structures that reinforce the vegetation processes. For example, once a tree island begins to form on depositions that rise above some water level threshold, the islands expand, stabilize, and persist (Figure 3-7). Meso-scale disturbances of fire and storm establish successional patterns that shift from ponds to wet prairie to sawgrass and back in a multidecadal dynamic. They create the conditions for their own existence. They represent processes of biotic self-organization over specific scale ranges on a physical template.

Third, human impacts depend on the scale and on the medium affected—land, atmosphere, or water. Human influence on atmosphere occurs at all scales and has become planetary, as indicated by atmospheric CO₂ accumulation and the greenhouse gas effect. Human influences on water are largely up to the scales of regions through construction of dams, dikes, and canals that allow water storage and transfers. Human influence on land, however, does not have that sweep; it is more local. For example, industrial agriculture homogenizes patterns at scales of fields within agricultural areas, but at coarser scales, human land-use patterns (agricultural area, park, and urban) largely reflect the existing landscape topography, formed by slow and extensive geomorphological processes. People farmed where soils exist; cities formed above flood-prone areas on the Atlantic ridge. And those utilization patterns change slowly. Humanity has yet to become the terraformers at the planetary scales suggested in science fiction.

Finally, issues, problems, and opportunities are not just local; they can have integrated causes from processes at several scales. Some of those are local and are perceived locally. Some can originate half a world away, formed by geopolitical hemispheric policies, world trade, and climate change.

In the remainder of this chapter we seek to understand how these cross-scale processes shape ecological and social dynamics. We first discuss the nested nature of temporal dynamics and spatial structures in both human and social systems. We then develop an alternative theoretical construct (dubbed panarchy) to capture these relationships. We then discuss the structure and dynamics produced by panarchical constructs and end with a brief description of what a panarchical perspective suggests about inherent differences between human-dominated systems and ecosystems.

Nested Cycles

Three decades of studies of regional ecosystems from northern forest, southern wetlands, dry grasslands, lakes, and seas show that the interaction between fast and slow processes establishes the key features of ecosystems described in Chapter 2. The entities created by those interactions form hierarchies, such as those illustrated for the Everglades in Figure 3-7 or for northern boreal forests in Figure 3-8.

A growing body of empirical evidence, theory, and models suggests that these hierarchical ecological structures are primarily regulated by a small set

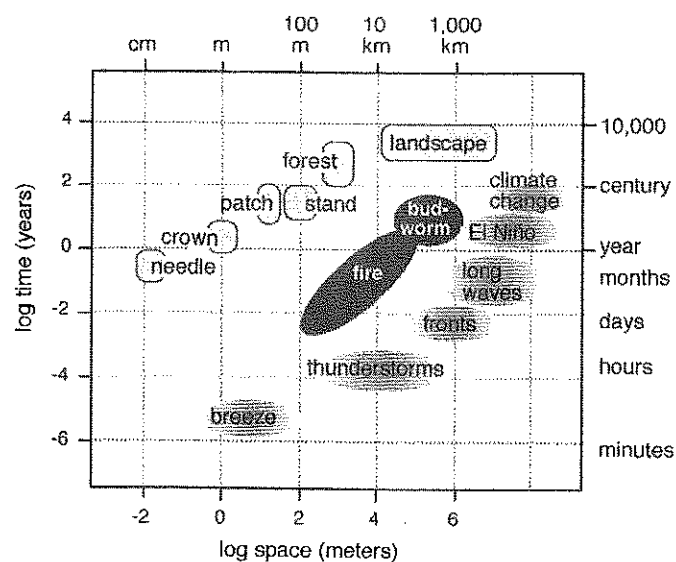


Figure 3-8. Time and space scales of the boreal forest (Holling 1986), of the atmosphere (Clark 1985), and of their relationship to some of the processes that structure the forest. Contagious meso-scale processes such as insect outbreaks and fire mediate the interaction between faster atmospheric processes and slower vegetation processes.

of plant, animal, and abiotic processes (Carpenter and Leavitt 1991; Holling 1992; Levin 1992). Each of these key processes operates at characteristic periodicities and spatial scales (Holling 1992; Figure 3-8). Small and fast scales are dominated by biophysical processes that control plant physiology and morphology. At the larger and slower scale of patch dynamics, interspecific plant competition for nutrients, light, and water influences local species composition and regeneration. At a still larger scale of stands in a forest, meso-scale processes of fire, storm, insect outbreak, and large-mammal herbivory determine structure and successional dynamics from tens of meters to kilometers, and from years to decades. At the largest landscape scales, climate, geomorphological, and biogeographical processes alter ecological structure and dynamics across hundreds of kilometers and over millennia (Figure 3-8). These processes produce patterns and are in turn reinforced by those patterns; that is, they are self-organized (Kauffman 1993).

In over thirty examples, the complexity of the behaviors and the challenges to policy can be traced to interactions among three to five sets of variables, each operating at a qualitatively distinct speed (Holling 1986; Table 3-1). We conclude that some small number of variables is important

Table 3-1. Representative Key Variables and Speeds in Seven Classes of Systems

The System	The Variables			References
	Fastest	Slower	Slowest	
Forest-pest dynamics	insect	foliage	tree	Clark et al. 1979; Ludwig et al. 1978
Forest-fire dynamics	intensity	fuel	trees	Holling 1986
Savanna	annual grasses	perennial grasses	shrubs and grazers	Walker 1981; Chapter 11
Shallow lakes and seas	phytoplankton and turbidity	sea grasses	grazers	Scheffer et al. 1993; Chapter 8
Deep lakes	phytoplankton	zooplankton	fish and habitat; phosphate in mud	Carpenter, Brock, and Hanson 1999; Carpenter, Ludwig, and Brock 1999
Wetlands	periphyton	saw grass	tree island; peat accretion	Gunderson 1994, 1999a
Human disease	disease organism	vector and susceptibles	human population	MacDonald 1973; May 1977

Box 3-1. Malaria and Adaptive Dynamics

M. Janssen and G. Peterson

Malaria is one of the world's most important vector-borne diseases, and its impact is expected to become more severe in the coming decades. It is caused by several species of parasites (*Plasmodium vivax*, *P. falciparum*, *P. ovale*, and *P. malariae*). The primary vector is the mosquito. Every year about 6 million people become sick with malaria, and of that number 1–1.5 million die. Many of those who die are children, and chronic nonsymptomatic infections usually persist in surviving children.

After World War II the effective use of DDT and other insecticides led to the eradication or near eradication of malaria in temperate zones and in some tropical areas. The rate of decrease has now slowed considerably, and a resurgence of malaria has occurred in several countries (Krogstad 1996; World Health Organization 1996).

The resurgence of malaria is partially due to the success of previous control efforts. The malaria parasites have become increasingly resistant to antimalarial drugs, and mosquitoes have become more resistant to insecticides. The evolution of resistance in the parasite and in mosquitoes can reduce the resilience of malaria control and may lead to higher levels of malaria than before the control strategy was introduced.

When a person survives malaria infection, he or she develops some immunity to malaria. When insecticides or drugs reduce the number of people who are exposed to malaria, fewer people build up immunity and more people become susceptible. The greatest increases in susceptibility are among older people. A combination of increased resistance of the malaria parasite or malaria mosquito and an increase in the number of susceptible people can produce a higher incidence for malaria (Janssen and Martens 1997).

These dynamics can convert an endemic disease to a potentially epidemic disease. Disease control leads to a loss of disease resistance in people and an increase in control resistance in the disease system. These changes can increase the difficulty of controlling the disease, as the risk of a disease outbreak increases and the ability to control it decreases. Consequently, the management of malaria must manage not only the fast dynamics of malaria and mosquito populations, but also the slower dynamics of malaria susceptibility, drug resistance, and pesticide resistance and the still slower dynamics of human populations and development.

because a minimum number of interactions must be represented for any particular problem or policy. A dynamic of one or two variables, while convenient for analysis, misses critical properties of stability and instability for adequate understanding of predictability and uncertainty for effective policy and action. Simple graphical stability analyses explain how nonlinear attributes can generate novel patterns in ecosystems (see Chapter 8; Scheffer 1998). Such graphical techniques also explain, in an accessible way, how unique properties and behavior of ecosystems emerge as interactions go from one to two to three variables (Holling 1986). These case studies suggest that a handful of critical variables—more than two, certainly, and probably fewer than six—can capture key behavior.

We particularly emphasize that the speeds of each set are distinctly different from those of their neighbors. Needles, for example, cycle with a generation time of one year, foliage cycles with a generation time of ten years, and trees cycle with a generation time of one hundred years and more. In the cases noted in Table 3-1, there is typically at least an order of magnitude difference between speeds. Thus frequency plots of variables show a small number of peaks, each reflecting the influence of one of the set of critical variables. The three to five fast/slow sets of variables, the nonlinear relationships between them, and stochastic processes generate the multistable behavior and the kinds of policy surprises discussed in Chapter 2. An example for malaria is described in Box 3-1.

A beautiful example of the consequences of such attributes for understanding and for policy has been shown by Carpenter, Brock, and Hanson (1999) in a model of a prototypical watershed where a lake ecosystem with three speeds of environmental variables interacts with phosphate from agriculture and decisions of managers. That model and others with similar attributes are summarized in Chapter 7. These models suggest that a minimal set of attributes needs to be incorporated into a modeling framework to deal with the issues of scale. Among the ingredients needed for such policy-relevant tools are a small set (three to five) of key variables that operate at at least three different speeds, nonlinear interactions among the variables, relationships that create shifting controls, and changing vulnerability that tracks the slowly moving variables. The results from these models present a major challenge to traditional optimization and traditional policy assumptions, as described in later chapters.

Chapter 2 focused on resilience and the adaptive cycle of growth, reorganization, and renewal as it might apply to a landscape scale. But each element in the hierarchy—from plant to patch, to stand, to ecosystem, to landscape—has its own adaptive cycle. There are nested sets of such cycles. The rate of cycling and the size of the element establish its position in the space-time hierarchy. But how do those elements interact with each other? The answer reveals that hierarchies are dynamic structures whose features retain both the creative and the conservative properties that define sustainability.

Hierarchies and Panarchies

The adaptive cycles described in Chapter 2 represent one of the two features that distinguish the scheme presented here. The second feature concerns the manner in which elements of complex adaptive systems nest in one another in a hierarchy. Simon (1974) was one of the first to argue the adaptive significance of such structures. He called them hierarchies but not in the sense of a top-down sequence of authoritative control. Rather, semi-autonomous levels are formed from the interactions among a set of variables that share similar speeds (and, we would add, geometric attributes). Each level communicates a small set of information or quantity of material to the next higher (slower and coarser) level. An example for a forested landscape was presented earlier as Figure 3-7. Another example comes from social scientists who argue that social action is predicated on a hierarchy of three structures: slowly developed myths (structures of signification), faster rules and norms (structures of legitimation), and still faster processes to allocate resources (structures of domination) (Westley 1995; Chapter 4). And the attributes of the slower levels emerge from experience of the faster.

As long as the transfer from one level to the other is maintained, the interactions within the levels themselves can be transformed or the variables changed without the whole system losing its integrity. As a consequence, this structure allows wide latitude for experimentation within levels, thereby greatly increasing the speed of evolution.

Ecologists were inspired by this seminal article of Simon's to transfer the term *hierarchy* to ecological systems and develop its significance for a variety of ecological relationships and structures. In particular, Allen and Starr (1982) and O'Neill et al. (1986) launched a major expansion of theoretical understanding by shifting attention from the small-scale view that characterized much of biological ecology to a multiscale and landscape view that recognized that biotic and abiotic processes could develop mutually reinforcing relationships.

These hierarchies are not static structures; rather, the hierarchical levels are transitory structures maintained by the interaction of changing processes across scales. A critical feature of such hierarchies is the asymmetric interactions between levels (Allen and Starr 1982; O'Neill et al. 1986). In particular, the larger, slower levels constrain the behavior of faster levels. In that sense, therefore, slower levels control faster ones. If that was the only asymmetry, however, then hierarchies would be static structures, and it would be impossible for organisms to exert control over slower environmental variables.

However, it is not broadly recognized that the adaptive cycle, shown in Chapter 2 (Figure 2-1), transforms hierarchies from fixed static structures to dynamic, adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the Ω phase) and the transition from reorganization to rapid growth (the α phase). During other times, the

processes are stable and robust, constraining the lower levels and immune to the buzz of noise from small and faster processes. It is at the two phase transitions between gradual and rapid change and vice versa that the large and slow entities become sensitive to change from the small and fast ones.

The structural, top-down aspect has tended to dominate theory and application, however, reinforced by the proper, everyday dictionary definition of *hierarchy* that is vertical authority and control. The dynamic and adaptive nature of such nested structures has tended to be lost.

It certainly is true that slower and larger levels set the conditions within which faster and slower ones function. Thus a forest stand moderates the climate within the stand to narrow the range of temperature variation that the individuals within it experience. But missing in this representation is the dynamic of each level that is organized in the four-phase cycle of birth, growth and maturation, death, and renewal. That adaptive cycle is the engine that periodically generates the variability and novelty upon which experimentation depends. As a consequence of the periodic but transient phases of creative destruction (Ω stage) and renewal (α stage), each level of a system's structure and processes can be reorganized. This reshuffling allows the possibility of new system configurations and opportunities from the incorporation of exotic and entirely novel entrants that had accumulated in earlier phases.

For organisms, those novel entrants are mutated genes or, for some bacteria, exotic genes transferred occasionally between species. For ecosystems, the novel entrants are exotic species or species "in the wings" waiting for more appropriate conditions. For economic systems, those novel entrants are inventions, creative ideas, and people that emerge in the earlier phase of growth where they were constrained from further realization of their potential. The adaptive cycle explicitly introduces a slow period of growth where mutations, invasions, and inventions can accumulate, followed by a brief period of rearrangements of those. It is a periodic process that can occur within each hierarchical level, in a way that partially isolates the resulting experiments, reducing the risk to the integrity of the whole structure.

In many ways the hierarchy and its nested adaptive cycles could as well represent biological evolution. For example, for a cell, the α phase represents the stage at meiosis when translocations and rearrangements generate a variety of experimental genetic recombinations that natural selection operates on at the level of the individual organism. Hence species attributes can periodically be reshuffled and invented to explore the consequences of novel associations that are then tested in the longer phase of organismal growth from r to K.

The organization and functions we now see embracing biological, ecological, and human systems are therefore ones that contain a nested set of the four-phase adaptive cycles, in which opportunities for periodic reshuffling within levels maintain adaptive opportunity, and the simple interactions across levels maintain integrity. What distinguishes the biological, ecologi-

cal, and human systems from one another is the way inventions are accumulated and transferred over time. More on that later.

Since the word *hierarchy* is so burdened by the rigid, top-down nature of its common meaning, we prefer to invent another term that captures the adaptive and evolutionary nature of adaptive cycles that are nested one within the other across space and time scales. We call them *panarchies*, drawing on the image of the Greek god Pan—the universal god of nature. This “hoofed, horned, hairy and horny deity” (Hughes 1986) represents the all-pervasive, spiritual power of nature. In addition to a creative role, Pan could have a destabilizing, creatively destructive role that is reflected in the word *panic*, derived from one facet of his paradoxical personality. His attributes are described in ways that resonate with the attributes of the four-phase adaptive cycle: as the creative and motive power of universal nature, the controller and arranger of the four elements—earth, water, air, and fire (or perhaps, of K , r , α , and Ω !). He therefore represents the inherent features of the synthesis that has emerged in this quest for a theory of change.

Two features distinguish this panarchy representation from traditional hierarchical ones. The first, as discussed earlier, is the importance of the adaptive cycle and, in particular, the α phase as the engine of variety and the generator of new experiments within each level. The levels of a panarchy could therefore be drawn as a nested set of adaptive cycles, as suggested in Figure 3-9.

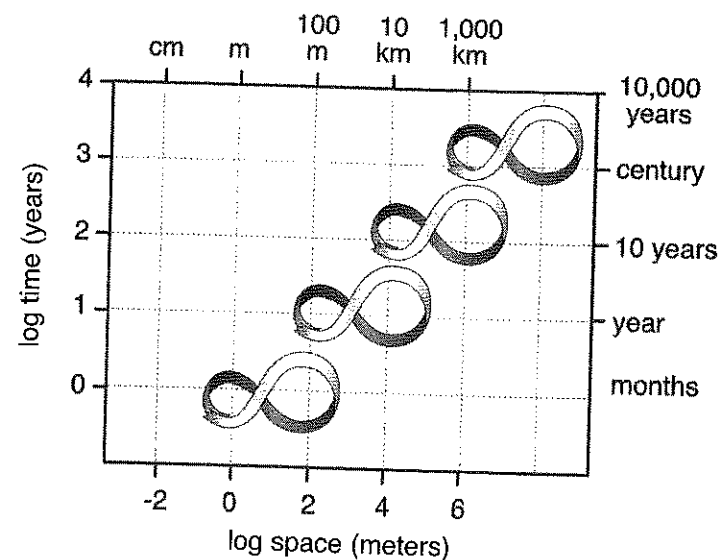


Figure 3-9. A stylized panarchy. A panarchy is a cross-scale, nested set of adaptive cycles, indicating the dynamic nature of structures depicted in the previous plots.

The second is the connections between levels. There are potentially multiple connections between phases at one level and phases at another level. But two are most significant in our search for the meaning of sustainability. Those are the connections labeled “Revolt” and “Remember” in Figure 3-10, where three levels of a panarchy are represented. The Revolt and Remember connections become important at times of change in the adaptive cycles.

When a level in the panarchy enters its Ω phase of creative destruction and experiences a collapse, that collapse can cascade up to the next larger and slower level by triggering a crisis, particularly if that level is at the K phase, where resilience is low. The “Revolt” arrow suggests this effect—where fast and small events overwhelm slow and large ones. And that effect could

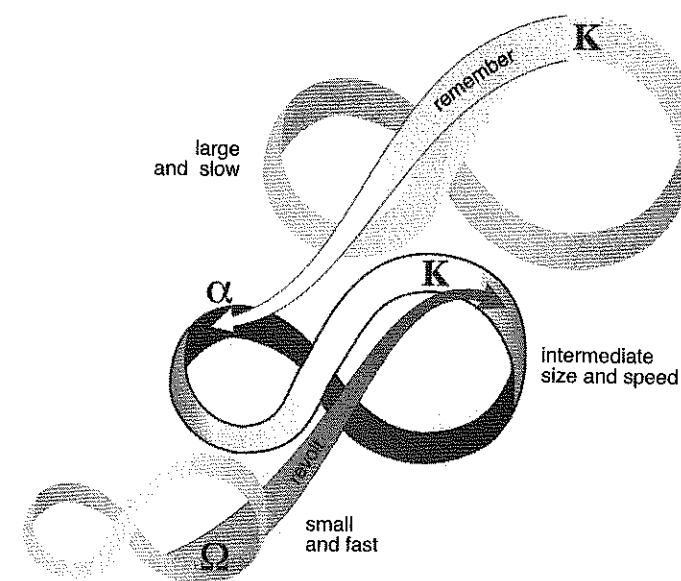


Figure 3-10. Panarchical connections. Three selected levels of a panarchy are illustrated, to emphasize the two connections that are critical in creating and sustaining adaptive capability. One is the “revolt” connection, which can cause a critical change in one cycle to cascade up to a vulnerable stage in a larger and slower one. The other is the “remember” connection, which facilitates renewal by drawing on the potential that has been accumulated and stored in a larger, slower cycle. Examples of the sequence from small and fast, through larger and slower, to largest and slowest for ecosystems are shown in Table 3-1. For institutions, those three speeds might be operational rules, collective choice rules, and constitutional rules (Ostrom 1990; Chapter 5); for economies, individual preferences, markets, and social institutions (Whitaker 1987); for developing nations, markets, infrastructure, and governance (Barro 1997); for societies, allocation mechanisms, norms, and myths (Westley 1995, Chapter 4); for knowledge systems, local knowledge, management practice, and worldview (Gadgil et al. 1993; Berkes 1999; Chapter 5).

cascade to still higher slower levels if those levels had accumulated vulnerabilities and rigidities.

An ecological example of this situation occurs when conditions in a forest allow for a local ignition to create a small ground fire that spreads to the crown of a tree, then to a patch in the forest, and then to a whole stand of trees. Each step in that cascade moves the transformation to a larger and slower level. A societal example occurs when local activist groups succeed in efforts to transform regional organizations and institutions because they had become broadly vulnerable. Such a change occurred in New Brunswick when small groups opposed to spraying insecticide over the forest succeeded in transforming increasingly vulnerable regional forest management policies and practices (Baskerville 1995), as part of a slowly unrolling saga of lurching understanding—both scientific and political.

The downward arrow labeled "Remember" in Figure 3-10 indicates the second type of cross-scale interaction that is important at times of change and renewal. Once a catastrophe is triggered at a level, the opportunities and constraints for the renewal of the cycle are strongly organized by the K-phase of the next slower and larger level. After a fire in an ecosystem, for example, processes and resources accumulated at a larger level slow the leakage of nutrients that have been mobilized and released into the soil. And the options for renewal draw upon the seed bank, physical structures, and surviving species that form biotic legacies (Franklin and MacMahon 2000) that have accumulated during the growth of the forest. It is as if this connection draws upon the accumulated wisdom and experiences of maturity—hence the choice of the word *remember*.

It is what Stewart Brand (1994) describes in his marvelous treatment of buildings as adaptive, hierarchical entities. The mature evolved buildings of lasting character are a reflection of seasoned maturity—an accumulation of idiosyncratic, wise, sustaining, and thought-provoking experiments accumulated in the form and content of the evolved structure. In *The Clock of the Long Now*, Brand (1999) goes further and generalizes the role of remembrance and revolt for society as a whole. In a healthy society, each level is allowed to operate at its own pace, protected from above by slower, larger levels but invigorated from below by faster, smaller cycles of innovation.

That summarizes succinctly the heart of what we define as sustainability. The fast levels invent, experiment, and test; the slower levels stabilize and conserve accumulated memory of past successful, surviving experiments. The whole panarchy is both creative and conserving. The interactions between cycles in a panarchy combine learning with continuity. That clarifies the meaning of sustainable development. Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity. The phrase that combines the two, sustainable development, is therefore not an oxymoron but represents a logical partnership.

Panarchies and Lumps

The concept of the adaptive cycle and the observation that scales among key variables are separated came from a synthesis of empirical studies (Holling 1986). But were that concept and observation the consequence of the way analysts and modelers make convenient modeling decisions, or are they the way real ecosystems, industry, and management actually organize and function?

It does help that the regional models were based on extensive knowledge and analysis of actual ecological processes, and the parameters were usually independently estimated in the field. Moreover, predictions of some of the critically informing studies, such as the budworm-forest one (Clark et al. 1979; Holling 1986), were extensively tested by comparing them to observed behavior from different regions of eastern North America having radically different climatic conditions and forest dynamics. The models consistently had strong predictive powers even in such extreme, limiting conditions. Ecosystems do grow, collapse, reassemble, and renew. Small sets of critical structuring variables are separated in scale—both speed and size—in example after example (Table 3-1). This was not deductive theory derived from first principles dictating what should be observed, but observations in nature and practice dictating theory. The panarchy is such an inductive representation.

Evidence for Panarchies

Nevertheless, it was skeptical students, with newly refined ways of critical thought and historical awareness of the hubris of those who generalize, who asked the critical question: "How do you *really* know?" Deductive economic theorists, themselves vulnerable to this challenge, agreed. We needed to move the metaphor of the panarchy into sets of competing and testable hypotheses.

There has turned out to be lots of those. Fruitful metaphors generate useful and relevant hypotheses. As the hypotheses and tests evolved, the metaphor of the panarchy was deepened and extended to take the form described in the previous section.

All the hypotheses and tests so far have come from an overall proposition that panarchies of living systems, social as well as ecological, provide a discontinuous template in space and time that entrains attributes of variables into a number of distinct lumps. By lumps we mean not only the discrete aggregates that Krugman (1996) explains and describes for human settlements—cities, towns, villages, and the like. He isolates centripetal and centrifugal forces that cause instabilities, which produce agglomerative patterns and discrete aggregates. There are such discrete aggregates in ecosystems—some obvious like individual organisms, some more amorphous like plant associations and ecosystems themselves. But in addition, we mean that attributes of size, speed, and function of each of those discrete aggregates should themselves be distributed in a lumpy manner. Those attributes

could be periodicities of fluctuations, size of objects at different scales on a landscape, the scales of decision processes of animals and humans, or the morphological and functional attributes of animals and plants.

There are two reasons an ecosystem/landscape panarchy as described would create a lumpy template. One is the gappy, discontinuous nature of the processes that form elements of the panarchy. Those are the ones that create a disjunct separation of scales among key, structuring variables. The other is the nature of the adaptive cycle itself. The phases of the cycle are distinct and the shift in controls from one to another is abrupt, because the processes controlling the shifts are nonlinear and the behavior multistable. Each phase creates its own distinct conditions that in turn define distinct attributes of size and speed of aggregates that control the phase or are adapted to its conditions. *K*-species and firms tend to be big and slow; *r*-species and firms tend to be small and fast. We are not saying that the four phases of a cycle entrain four lumps, though it would be fun to further develop and test that hypothesis. We are saying that the combination of panarchy-level discontinuities and adaptive cycle ones will generate a number of lumps, the number defined by the resolution of the observations and the range of scales tested. Panarchies form a lumpy template that entrains the same lumpy attributes in organisms that create or are part of them.

Distributions, the proposition states, will not be continuous or unimodal. Rather, they should be discontinuous (gaps in a distribution) and/or multimodal. Similarly, scaling relations should produce clusters of attributes along regression lines (lumps) or indicate breaks between scaling regimes.

In contrast to that proposition, much of modern science, including ecology, seeks simplifying, universal laws by searching for continuous, unimodal properties. For example, the scaling of physical, biological, ecological, and social phenomena has become a major focus of efforts to develop simple and universal representations of complex systems (Gell-Mann 1994). From that has come the identification, explanation, and testing of scaling laws for systems as wide ranging as biophysical (Bak 1996; West et al. 1999); ecological (Keitt and Stanley 1998); firms and countries (Brock and Evans 1986; Stanley et al. 1996); and human aggregations (Krugman 1996). But there has been little focus on the pattern and dynamics of departures from those scaling relationships—either as clustering of attributes (lumps) or as breaks between two scaling regimes. Brock (1999b) reviews and discusses the perils and pitfalls of the application and interpretation of scaling laws in economics.

There is empirical evidence that biological and ecological attributes of specific landscapes exhibit multiple scale regimes—there are breaks between scale levels as processes controlling structure shift from one set to another, and there is clustering of attributes at distinct scales. That was suggested impressionistically in Figures 3-1 through 3-6, but, in addition, formal analysis of vegetation pattern on landscapes has shown that different scaling regimes exist, each with its own fractal dimension (Krummel et al. 1987).

Analyses of animal communities on specific landscapes also have revealed cross-scale, multimodal, or gappy patterns in animal attributes such as body mass (Holling 1992). Architecturally simple landscapes have few lumps in body mass of animals living in them; complex ones have many. For example, Schwinghammer (1981) and Raffaelli et al. (2000) show that architecturally simple marine sediments have communities living within them with three, and perhaps four, lumps in the size of their inhabitants. Boreal forest landscapes (Holling 1992) are somewhat more complex; their mammal and bird communities show about eight lumps in body mass. Tropical forests systems are still more complex, and their bird inhabitants show a still larger number of lumps (Restrepo et al. 1997). We suspect a strong correlation between complexity of lump structure and productivity or other correlates of net energy flux through terrestrial ecosystems.

In addition, plant as well as animal attributes show the phenomenon. For example, Walker et al. (1999) show that morphological attributes of plants, as well as of animals, have lumpy distributions and that each lump corresponds to a functional role plants play in an ecosystem. They demonstrate that functionally significant morphological attributes of grass and forb species show three to five lump clusters in savanna ecosystems.

There is skepticism that such lumps are real. Part of that skepticism is because so many apparent patterns in nature proposed in the past have subsequently been shown to be artifacts. Manly (1996) applied an elegant but conservative statistical test to the original data sets presented by Holling (1992) and concluded that only two lumps or aggregations of body mass were significant, rather than the eight or more that Holling identified. Conservative tests, of course, reduce the chance of being wrong (Type I error)—but they also reduce the chance of being able to detect real patterns (Type II error). Siemann and Brown (1999) argue that no lumps at all exist in body mass data of animal communities. But they asked a different question than one that was relevant for testing the proposition discussed here. Their test concerned the sizes of individual gaps, not the existence of a pattern of lumps and gaps.

But more convincing tests come from proposing and invalidating alternative hypotheses of causation. It is those tests, together with appropriate statistical ones of the kind suggested by Manly (1996), that can lead to multiple lines of evidence that converge on a credible line of argument. It took over three decades to confirm the existence and management significance of multistable states in ecosystems (Chapter 2; Carpenter 2000). It might take as long for establishing the reality, cause, and significance of lumps.

Causes of Lumps

There are at least six proximate causal mechanisms that could directly produce lumpy distribution of body masses. Some represent slow processes, some fast.

As an example of a generic slow process, panarchies form patterns on the landscape that result in a mosaic of different-sized resource aggregations at different scales. Each reflects the influence of one of a few dominant ecosystem processes. The resource aggregations across scales and well-known allometric relationships can explain aggregations of body sizes. There are well-established allometric relationships between the body size of an animal and its energy needs, speed, distance of movement, and life span (Peters 1983). As a consequence, not all sizes could survive—only those whose scaled physiological, behavioral, and life cycle features matched the lumpy resource availability. Morton (1990) used that possibility to explain the total extinction of all middle-sized mammals after European settlement in Australia. He proposed that changed fire regimes, the vegetative impacts of introduced rabbits, and predation by introduced fox reduced the resource in patches at intermediate scales and increased mortality of the mammals exploiting them. The significance for land management is obvious.

Phylogeny and organizational constraints also reflect the operation of slow processes that might explain the lumps, because organisms might have evolved a limited number of body sizes that can function efficiently. That is, evolution may produce a lumpy universe of species from which assemblages are drawn. Any one assemblage from an area might show lumpy attributes because assemblages are drawn from a lumpy universe of species created through evolution. Or there could be founder effects—the luck of the draw might mean that only a limited number of sizes established themselves and their sizes thereafter constrained the sizes of those that followed.

Competitive and trophic relationships are faster processes that could also produce lumps. Roughgarden (1997), for example, showed that lumpy distributions can be produced in an elegant model that combined the fixed carrying capacity of an animal with growth and size-dependent competition. Such lumpy distributions result for much the same reason that Krugman's agglomeration of products does (Krugman 1996). Trophic relationships could also result in lumpy distributions as size resonances form in communities because big beasts eat little ones (Carpenter and Kitchell 1993).

Evidence to test these alternatives is accumulating. It demonstrates that body masses are distributed in a lumpy manner both on land and in water, and that the cause must be associated with slow, conservative properties of landscapes and waterscapes.

The most extensive test has been performed by Havlicek and Carpenter (2000). They analyzed data on species, populations, and species sizes of phytoplankton, zooplankton, and fish collected over years from eleven lakes in Wisconsin. All lakes showed body mass distributions of species with an extensive lump and gap structure. Moreover, that structure was very similar in all lakes, even though the lakes differed widely in area, depth, nutrient status, food web structure, species composition, and productivity. That was even the case after experimental additions of phosphate and removal of fish produced massive differences in community structure, primary production, nutrients,

chlorophyll, and bacterial production. Despite substantial differences in species composition, community structure, and physical/chemical characteristics of the lakes, many of those lumps and gaps persisted at similar size ranges across all lakes and treatments.

The same conservative nature of the body mass lump structure was demonstrated on a smaller scale by Raffaelli et al. (2000). They perturbed enclosures of marine littoral sediments in a way that changed trophic structure, species composition, and sizes of communities. The lump structure remained little affected. It is a highly conservative feature, reflecting, therefore, slow processes that structure panarchies at all levels of scale.

It takes the kind of extreme disturbances seen over paleoecological time and space scales to change the body mass lump structure in a major way. Eleven thousand years ago, for example, all the very large herbivores, such as giant ground sloths and the shovel tusked elephant, became extinct in North and South America in less than one thousand years (Martin 1967). Lambert and Holling (1998) analyzed two reconstructed fossil data sets from either side of the continent to identify the body mass lump structure before and after that massive extinction pulse. The data demonstrate a significant lump structure that remained entirely unchanged for animals of less than 41 kilograms, even though extinction occurred among those species. Replacement by new species of similar sizes maintained the structure. But above 41 kilograms, the lump structure was entirely transformed, and the largest lump of animals with masses greater than 1,000 kilograms was eliminated entirely. Climate change associated with global deglaciation, changed fire regimes, and hunting by a new, efficient hunting culture conspired to completely change the template at coarse scales, but only at coarse scales.

It is likely, moreover, that the large herbivores created and maintained that coarse pattern of grasslands and forest in the manner proposed by Zimov et al. (1995) for the megaherbivores of northern Russia and Alaska during the same period. Grazing by the large herbivores likely created and maintained vegetative patterns appropriate for their own existence, as is still true for large herbivores in Africa (Owen-Smith 1998). These herbivores were therefore likely to have been part of one set of critical, ecosystem self-organizing processes that created a slow, large adaptive cycle at coarse scales in the panarchy. As indicated in Chapter 2, such self-organizing processes and the adaptive cycle they create are very resilient, but once they collapse, they unravel precipitously in a positive feedback chain of collapse. Thus one slow, large level of the panarchy collapsed, explaining the sudden and continental scale of the transformation. But the collapse did not cascade to smaller scales, so that the body sizes appropriate for them remained unchanged.

On a shorter time scale, parts of panarchies and the lumps they form can change because of the occupation of some scales by an external invader. A particularly clear example of the effects of interaction between an invasive grass and human exploitation of new opportunity is described in Box 3-2.

Box 3-2. An Invasive Species (*Imperata cylindrica*) and Human Exploitation Change a Panarchy

G. Peterson

Imperata cylindrica (also known as cogon grass, or alang alang) has colonized and established large grassland areas in Southeast Asia's uplands (Terry 1994; Whitten et al. 1987). It is a common weed throughout the world and rapidly invades lands following clearing. Cogon grass has a number of characteristics that make it successful as an invader of landscape disturbed by massive human modification.

Cogon grass is a perennial that spreads vegetatively through creeping roots. It also produces copious seed that is able to disperse long distances along roads and trails (Sauer 1988). Cogon grass frequently flowers following environmental stress, such as fire, cutting, or drought. These attributes allow it to rapidly invade areas in which vegetation has been disturbed.

Cogon grass is maintained by fire. It burns readily, but because its roots are protected below ground, it can rapidly resprout. It is shade intolerant, so food crops, trees, and legumes out compete it in the absence of fire, but fire kills tree seedlings and other potential competitors.

As human population density has increased, the increased burning of agricultural sites and accidental fires have encouraged the expansion of Cogon grass. Furthermore, the difficulty of removing Cogon grass has encouraged it to be used and purposefully burned for grazing. Cogon grass grasslands are difficult to farm. The grass's rapid regrowth and the strength of its roots make farming difficult. However, such grasslands can be used for cattle forage.

The features of rapid growth, fire adaptation, and complementarity with human action have enabled Cogon grass to spread across large areas of the tropics. However, it is particularly Cogon grass's relationship with fire that provides it with its resilience. Unlike many ecological processes, fire experiences increasing returns to scale. That is, larger connected areas of combustible Cogon grass are more likely to burn than smaller areas, because larger areas are more likely to be ignited than smaller areas. Consequently, as areas covered by Cogon grass become larger, they become more resilient. By regulating their own disturbance to exclude potential competitors, Cogon grasslands are able to maintain a high biomass and

remain tightly connected and resilient. Furthermore, by being useful to people, they are able to coexist with, and even benefit from, anthropogenic ecological transformation.

The conservative, persistent structure of lumpy body mass distributions reflects the robust, sustaining features of the panarchy described earlier that are formed by slow ecological and evolutionary processes. The distribution of lumps and gaps is a kind of bioassay of the structure of a panarchy. Although lumps themselves are stable, populations of species within them are not—they are highly labile and reflect the effect of stochastic processes, competition, and dynamic changes that structure adaptive cycles. Recently, Allen et al. (1999) have shown that such turbulence is particularly evident at the edge of gaps in body mass distributions.

They showed that endangered and invasive species in a community have body masses that occur at the edges of body mass clumps two to four times as often as expected by chance. That correlation is consistent in all eight data sets examined in that study. Those comparisons now have been expanded, with exactly the same result, to include four different taxa (birds, mammals, herpetofauna, and bats) in examples of two different ecosystem types (Mediterranean and wet savanna) on three continents (Australia, North America, and Europe). It is suggestive that the most invasive species of all, humans, had a body size on the plains of Africa also at the edge of a body mass lump (Holling 1992). Humans' generalist morphology, combined with gradually developed technologies, allowed actions and influence at wider and wider scales—from home territories to, ultimately, the planet as a whole.

Moreover, a set of poorly understood biological phenomena that seem to mix contrasting attributes correlates with those same edges of body mass lumps/gaps. These phenomena include endangerment, extinction, and nomadism on one hand, with invasiveness, high variability, and migratory behavior on the other. All these phenomena that cluster at the edges of body mass lumps, or at the edge of gaps, are opposite faces of rapid, turbulent change—of both success and failure. Generalists are able to exploit opportunity created by the uncertainty and turbulence. Specialists are vulnerable to that same uncertainty and turbulence.

That suggests that the potential for crisis or opportunity is greatest at the scales exploited by these "lump/gap edge species." In Chapter 2, we described why opportunity and crisis are greatest at the edge of a stability shift in time (from creative destruction to reorganization, or from Ω to α in the adaptive cycle). It seems that the same conditions occur in space as well, and that the edge of a body mass lump/gap represents a scale of landscape transition equally turbulent and rich in potential. It gives specific content to Kauffman's intuition that life flourishes at the edge of chaos (Kauffman 1993).

Significance of Lumps

Once the pattern of lumps and gaps is formed in a distribution, it entrains a complex set of related variables. The consequences determine, in part, how resilient the pattern is and how robust to modification by policy or by exogenous change. For example, understanding the scaled nature of animal communities and the scale breaks intrinsic within them has led to a better understanding of the manner in which ecological resilience and sustainability are generated from biological diversity.

There are two types of such diversity, one concerning how diversity affects biological function within a range of self-similar scales—within a lump (Walker et al. 1999); and one concerning the way it affects biological function across scales—between lumps (Peterson et al. 1998). Both types of diversity contribute to the resilience and sustainability of the system.

For example, the properties and patterns of the boreal forest described in Box 2-1, Chapter 2, are maintained by a set of processes involving an insect defoliator (the spruce budworm), two species of trees, and avian predators of the budworm. The thirty-five species of bird predators are critical. They are distributed over five body mass lump categories (Holling 1988). Species in the same lump compete with one another because they forage at similar scales. But they have different responses to climatic and other environmental changes. The result is that there are at least some species present from a particular size cluster, over a large range of fluctuating external conditions.

But species in different lumps forage at different scales, initiating their foraging responses to different-sized aggregations of budworm. Small warblers, for example, respond to aggregations on branches, larger ground sparrows to aggregations on trees, and still larger grosbeaks to aggregations in forest patches. Hence, as budworm populations start to jump from one level of the panarchy to influence larger ones, a strong counteraction develops that brings more and larger avian predator species into play, with larger appetites from larger areas. When the regulation eventually breaks, it does so suddenly and over large spatial scales of hundreds of kilometers. The creative destruction phase of the forest's adaptive cycle is released.

Diversity of functional types of plants in different morphological lump categories contributes to resilience and persistence of functions in a similar way, as Walker et al. (1999) demonstrated when they compared savannas exposed to different intensities of grazing. We suppose that the variety of grazer and browser species in African savannas also provides a wide range of both within- and between-scale sustainability and resilience.

This effect of diversity is not redundancy in the replicated sense that an engineer might apply it to achieve engineering reliability. Rather, each species in the same size lump has a similar scale of function but has different responses to unanticipated environmental change. If the ecosystem were a theater, the species within a lump would be like stand-in actors who are prepared to replace each other in the event of unexpected external surprises and

crises. Species in different lumps can also engage in similar or related ecosystem functions, but, because of their different sizes, they differ in the scale and degree of their influence. In our ecosystem theater, species in different lumps are like actors waiting in the wings to facilitate a change in pace or plot when needed. The within-scale and between-scale diversity produces an overlapping reinforcement of function that is remarkably robust. We call it imbricated redundancy.

The same kind of imbricated redundancy is a common property of many biological phenomena. For example, physiological regulation of body temperature in homeotherms (warm-blooded animals) is regulated by five different mechanisms ranging from metabolic heat generation to evaporative cooling. Each operates over different ranges of temperature with different efficiencies and speed of feedback control. The result is remarkably robust regulation of temperature around a narrow range. As a behavioral example, migratory birds navigate with great success between summer and winter feeding areas over enormous distances, by using at least four different signals for direction—magnetic, topographic, sound, sidereal—each of which has different levels of precision and accuracy. It is the overlapping, reinforcing nature of those separate mechanisms that makes the total effect so robust.

Decision Panarchies

The objects encountered by animals are either edible, frightful, lovable, ignorable, or novel. The first three define the resources on the landscape needed to provide food, protection, and opportunity for survival and reproduction. The latter two are items that should simply be forgotten or should be investigated for the potential they might represent. That is, forgetting, curiosity, and memory are essential in order to develop rules that are flexible and adaptive enough so that a species can persist in a fluctuating, changing world.

All five kinds of objects are created or sustained by the template formed by the ecosystem/landscape panarchy (e.g., such as those illustrated in Figures 3-7 for the Everglades and 3-8 for the boreal forest) and by external introductions, events, and variability. Because the template formed by the panarchy is so remarkably conservative and persistent, animals can develop rules for actions that take advantage of that persistence while retaining enough flexibility to adjust to variability and the unexpected. That is, those decision rules have the features of the adaptive cycle—both conservative and changeable.

The rules become rules of thumb or schemas that minimize information needs and processing. The ones that persist are those with the least demand on information, while contributing to survival and reproduction over long periods. They are not detailed, accurate, and precise, but they are economical, just sufficient, and adaptive. And if some decisions do not encounter or generate variability, they can gradually become more and more stereotyped and automatic. A simple example is the entrained rules a person learns in

driving to and from work along the same route. And among insects and birds, there are many examples of rules that become genetically encoded and guide instinctive behaviors. In humans such rules can become encoded in the myths and rituals of the culture. A beautiful example is that of the Milpa, the maize culture of Mexico, that is so remarkably integrated within the natural ecosystem panarchy while providing opportunities for experimentation within that context (Chapter 5, Box 5-2).

Holland (1995) and Holland et al. (1989) describe these rules as schemas or scripts in which information stored in clusters serves to generate plausible inferences and problem solutions. When unexpected events occur that provide a poor match with experience, then new rules can form out of the stored bits and pieces that become recombined in novel ways, much as described for the adaptive cycle. Bricolage (Levi-Strauss 1962) and self-organization are as central to the formation of rules for decision making as they are for forming biological or ecological structures.

Such sets of rules are also organized as a hierarchical sequence, each set operating over a particular range of scales. Holling (1992), for example, described a typical sequence for a large wading bird of the Florida peninsula and Cuba. At very coarse scales, tagging records indicate that the decisions for an area in which to locate are made over several hundred to one or two thousand kilometers from a bird's birthplace. Once an area is found and accepted, a home range or foraging area is established within an area covering tens of kilometers. Within that, smaller habitats are identified and exploited among a set of ponds of various sizes; within those, still smaller patches of food aggregation are selected; and within those, specific types and sizes of food items. Each of those elements also has a turnover time that correlates with its geographic size. There are sufficient data from enough species that general equations have been developed that fix the spatial and temporal position of choices for food, home range, and area of animals of different sizes (Holling 1992). An example is provided in Figure 3-11 for animals in a boreal forest landscape.

The figure shows that the spatial range for decisions covers the same range as the ecosystem/landscape hierarchy. That is, there is a tight spatial coupling between these two hierarchies. That is precisely what one expects if spatial discontinuities are the primary source of body mass discontinuities. The specific position in the hierarchy of each of three species representing three very different body mass lump categories is also shown. A deer mouse, for example, establishes a home range over tens of meters; a moose, over tens of kilometers. The differences in the size of choice areas of the smallest and largest animals cover some three orders of magnitude.

Finally, the two hierarchies do not overlap completely in time. The overall decision hierarchy operates at a speed three to four orders of magnitude faster than that of the overall ecosystem hierarchy. That means that the slower dynamics of the ecosystem and the landscape largely constrain and control the variability experienced for animal decisions. And hence it is those

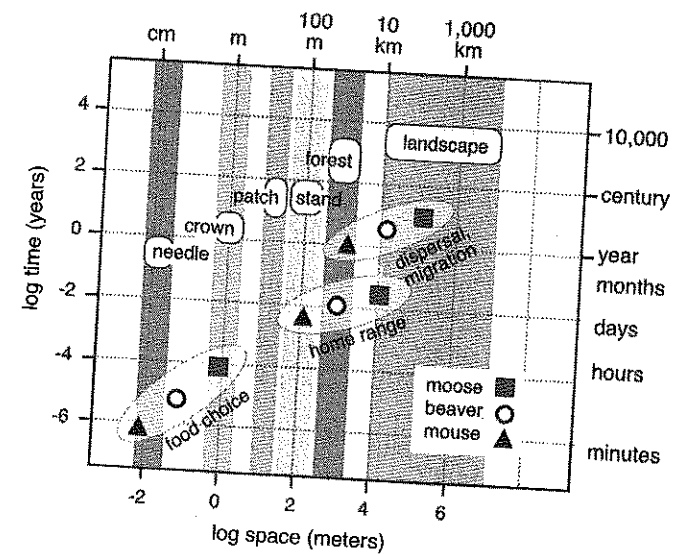


Figure 3-11. Decision hierarchies in the boreal forest. Shown are relative positions in the hierarchy for decisions about food choice, home range, or migration that would be made by each of three species from three different body mass lump categories. For example, a deer mouse establishes a home range over tens of meters, a beaver over kilometers, and a moose over tens of kilometers.

slower ecological, evolutionary, and geological dynamics that determine the lumpy distribution of animal body sizes.

These panarchies of landscape provide a template that clusters opportunity and choices over a wide range of scales. They therefore provide a template for species diversity and restrict competition largely to those species within a cluster or lump size.

Lumps in Human Systems

Is this lumpy structure arising from panarchies likely to occur in other systems? If there are such lumps in the size of firms, are the ones on the edge of lumps similarly functionally unique as a growing firm shifts from the edge of one scale of operation to that of a larger one? In the size of cities? In the size of the GNP of nations? Might that be true of nations as they shift into a different development path?

For nations, Barro (1997) reviews his own influential work as well as that of some others, with the purpose of uncovering and measuring causal forces behind differential cross-country economic performance. He groups countries into economic lumps called "convergence clubs." Countries within a given club have economic growth performances that tend to converge. These patterns of growth performance across countries appear to be structured by movement toward a long-term target rate of growth for each country, where

the long-term target is determined by slow and medium time scale variables. Slow processes of governance establish the degree of flexibility, trust, and freedom of institutional/political structures. Medium-speed processes set the general level of public physical infrastructure and education.

This explanation and the nonlinear functions that support it (Durlauf and Quah 1999) seem very similar to those of the ecological panarchies. The great difficulty in moving nations from one lump or from one development pathway to another suggests the same conservative features of lumpy patterns in ecosystems. Both seem to be sustained by conservative, slow sets of variables forming the panarchy. Both the management of ecosystems and the development of nations require that attention be focused on the slow variables while encouraging experiments that engage fast ones. A critical number of levels of the panarchy need to be involved in order to satisfy minimal needs for understanding and action.

The attraction of scaling laws is that they emerge from simple physical and statistical processes and have astonishingly wide application (Brock 1999b). However, in this chapter, we argue that there are regular patterns of departures from or clustering along those scaling laws, and these lumps of attributes might have more ecological, economic, and social interest, and practical use, than the single laws or distributions themselves.

Specifically, these lumps seem to demonstrate how living systems of animals, plants, and human organizations develop self-organized interactions with physical processes over distinct ranges of scale. Just as pulses of resource acquisition over time by organisms increase efficiency of energy utilization, perhaps these "lumps" in the morphological, geometric, and behavioral variables of animals, plants, and people emerge from self-organizing properties that affect evolutionary change and development. They represent attractors, created by key biological and social processes, along a more continuous, physically defined template. Thus the measurable attributes of lumps and gaps, like body mass gaps in a distribution, are a transform of the potential that is discontinuously sustained across a panarchy.

In brief, physics sets the constraints around which life structures opportunity.

Cascading Change

The panarchy represents the dynamic interplay between processes and structures that sustain relationships on the one hand, and create and accumulate potential on the other. Some of the specifics are developed in more detail in subsequent chapters. We will close this chapter with a section on how whole panarchies can be transformed, either because productive novelty cascades up the levels, or because destructive catastrophes cascade down.

Novelty

Biological evolution is the one field of science where questions of how novelty is generated, selected, and spread have been most deeply and broadly

explored. It is a science that covers scales from the language of genes on chromosomes, to interactions of individual organisms in changing environments, to isolation and mixing of whole fauna as continents join, separate, and drift apart over geological time, to spasms of planet-wide extinction caused by asteroid impacts.

Simon Levin (1999) says it well in *Fragile Dominion*:

The combined weight of multiple small scale processes can accumulate to help shape other patterns of interaction, and hence the structure and function of ecosystems, from small scale to the biosphere. Natural selection, together with other drivers of evolutionary change such as mutation, recombination, environmental factors, and simple chance events, provides the central organizing principle for understanding how the biosphere came to be, and how it continues to change. No teleological principles are at work at the level of the whole system, or even at the local level. The biosphere is a complex adaptive system in which the never ending generation of local variation creates an environment of continual exploration, selection, and replacement.

But, despite the marvelous complexity and diversity of life, evolution is astonishingly conservative. In 1998, the nematode *Caenorhabditis elegans* became the first organized multicellular animal whose genes were completely unraveled and described (Hodgkin et al. 1998). An astonishing 19 percent of those genes and their 97 million bases in this multicellular animal correspond to those in yeast, a single-cell organism. Despite the billion years of evolution from some common ancestor, and the enormous transformations required to produce an organized multicellular organism, a remarkable number of the genes of the single-cell yeast and the multicellular nematode are shared. Similarly, despite the differences between chimpanzee and human, some 98.4 percent of their DNA is shared (Diamond 1992).

This suggests that the source of novelty lies not in single mutations alone, but also in novel, unpredictable combinations with existing genes that can suddenly establish new genetic domains of influence, opening an entirely new set of adaptive paths for selection. Similarly, the great sixty-year wave of technological innovation initiated in the nineteenth century was triggered not by the single invention of the steam engine, but by the context of a whole economy and society that had accumulated a set of rigidities and invented novelties that precipitated, synergized, and directed the transformation (Fischer 1996). That is what is happening with the Internet now.

Levi-Strauss (1962) used the word *bricolage* to describe this process of recombining existing elements and new mutations and inventions to form something novel that solves a newly emerged problem or creates new opportunity. It is the adaptive cycle that accumulates those elements as potential and then, for transient moments, rearranges them for subsequent testing in changing circumstances. Consequential rearrangements can nucleate new opportunity and accumulate further potential. If that accumulated potential

exceeds a threshold, it can cascade upward in the panarchy and create new panarchical levels. Think of the way the inventive circus Cirque du Soleil evolved in steps from individual street performers to a self-sustaining group, to a multitalented company in Montreal, to an international enterprise, accumulating capital, experience, organizational processes, and new skills in steps along the way.

Such transformations are qualitatively different from the incremental changes that occur during the growth phase of the adaptive cycle described in Chapter 2. They are also qualitatively different from the potentially more extreme changes and frozen accidents that can occur during the more revolutionary shift from creative destruction (Ω) to renewal (α). They are transformations that cascade and transform the whole panarchy and its constituent adaptive cycles.

Major transformations are rare and extreme because a unique combination of separate developments has to conspire together simultaneously. Some developments emerge within adaptive cycles during the back loop of the cycle, when recombinations and external influences can generate unexpected new seeds of opportunity that can nucleate and modify the subsequent phase of growth. So long as connections with other levels are maintained, those innovations are contained and do not propagate to other levels. But as such recombinations and inventions independently accumulate in a number of adjacent levels, a time will come when the phases of several neighboring cycles become coincident, when each becomes poised as an accident waiting to happen in a shift from Ω to α . Windows open that can then allow those independent inventions and adaptations to interact to produce a cascade of novel self-organized patterns across a panarchy, creating fundamental new opportunity. There is an "alignment of the stars."

In ecosystems, the period of those cycles differs between neighbors in the panarchy typically by an order of magnitude. Thus the frequency with which several cycles come simultaneously into the vulnerable phase decreases as the power of the number of cycles involved. Therefore, phases of vulnerability at multiple scales can be quite rare.

But what of human organizations and institutions, which operate on faster scales than biological/evolutionary ones? As a signal of that structure, studies of regional resource management and development show that policy and organizational changes also occur in spasmodic lurches of learning driven by crises precipitated by earlier myopic policy successes leading to larger failures (Chapter 12, Figure 12-1; Light et al. 1995).

That is what so often frustrates those of us who have been part of efforts to transform research, policies, and structures in rigid government agencies, universities, and research institutes. We learn that change in resource management agencies and policies, for example, requires much more than integrative scientific understanding of the uncertain and unpredictable features of linked natural and economic systems over different scales. While that understanding is often missing, it can usually be achieved by strategic analy-

sis and modeling by groups of scientists and scholars from different agencies, universities, and science-based NGOs. But such groups are effective only for short periods, and only if they act informally as a transient group that functions outside the constraints of its own organization and constituency. That is the assessment phase of the approach termed adaptive ecosystem management (Holling 1978; Gunderson et al. 1995a; Walters 1986, 1997).

It is the rest of the process, the implementation of adaptive policies, that frustrates because it encounters the reality of politics and power in societies where entrenched interests manipulate information for narrow purpose. Carl Walters beautifully summarizes his decades of such frustrations in a review (Walters 1997) that has triggered a series of responses and a special feature on adaptive management in the electronic journal *Conservation Ecology* (www.consecol.org).

In these situations, panarchical change can occur only when a triggering event unlocks the social and political gridlock of larger levels in the panarchy. In the case of the transformation of New Brunswick regional forest policy (Baskerville 1995), for example, the cycle of political elections allowed a new politician to emerge and become minister of the Department of Natural Resources at a time of unambiguous failure of earlier forest policies. Willing to admit the mistakes of predecessors, and wanting to place his own mark, he encouraged development of an integrative regional policy that could exploit the understanding that had accumulated in previous cycles of scientific experience, analysis, and communication. The person who created that opportunity, designed and implemented it was a "wise person"—a mix of scientist, politician, and manager, in this case Gordon Baskerville. Such a person is another critical ingredient for fundamental transformation. Transformation of forest fire policy in the U.S. national parks followed a similar history of frustrating resistance to accumulated integrative understanding, followed by a sudden lurch of policy transformation (Christensen et al. 1989). Frances Westley provides another example of resource management and intimate details of the events in Chapter 13. The reality of those situations is captured in the title of that chapter, "The Devil in the Dynamics." Truly transforming changes are panarchical ones that can cascade up a panarchy as a conscious act of wise, purposive design and implementation. Westley's example of regional policy change illustrates that cascade of decisions in Figure 13-2.

From a more distant perspective, the two great creative transformations in human progress were the agricultural revolution ten thousand years ago and the industrial revolution that began about 1750. Such panarchical, creative cascades are rare, "coming in great storms rather than occasional showers" of the kind that occur within adaptive cycles (Anon. 1999).

Collapsing Panarchies

Stochastic events external to a cycle can trigger spasmodic collapses, particularly if they encounter vulnerabilities within an adaptive cycle. Extremely

large events can overwhelm any sustaining properties of panarchies, destroying levels and triggering destructive cascades down levels of a panarchy. The great loss of biological diversity 65 million years ago (about 70 percent of Earth's species; Jablonski 1995), for example, is likely to have been caused by the impact of an asteroid (Alvarez et al. 1980). That event, perhaps associated with massive volcanic eruptions around the same time, unraveled the web of interactions within and between panarchical levels over scales from biomes to species. There have been five major spasms of biodiversity loss during Earth's history (Jablonski 1995), each probably precipitated by different causes (Donovan 1989). Each required at least 10 million years of evolutionary change to reestablish the lost diversity (Kirchner and Weil 2000).

Since recovery from these events is so delayed, it is likely that mass extinction events not only eliminate species, but also by doing so, eliminate ecological niches. That is, species depend upon an environment that is created by life. By eliminating most species, mass extinction events eliminate many ecological niches. The recovery of biodiversity from mass extinction events requires the reconstruction of these niches, before species can evolve to fill them.

Notably, different families, orders, and species dominated the new assemblages after recovery; new inventions and ways of living emerged. The dinosaurs became extinct during the collapse 65 million years ago; the mammals, inconspicuous before that, exploded in a diversification that created new opportunity. The conservative nature of established panarchies certainly slows change, while at the same time accumulating potential that can be released periodically if the "decks are cleared" of constraining influences, by large extreme events.

Similarly, human history has been one not of regular change but of spasmodic, catastrophic disruptions followed by long periods of reinvention and development. Unlike the sudden collapses of biological panarchies, there can be long periods of ruinous reversal, followed by slow recovery and restoration of lost potential. Robert Adams's magnificent reconstruction of Mesopotamian societies (1966, 1978) and his review of other archaeological sequences at regional or larger scales (Adams 2000) led him to identify two trends in human society since the Pleistocene. One is an overall increase in hierarchical differentiation and complexity of societies. That is, levels in the panarchy are added over time. If enough potential accumulates at one level, it can pass a threshold and establish another slower and larger level. The other trend Adams identifies is of discontinuous rapid shifts, interspersed by much longer periods of relative stability. Such irregularities, he remarks, "provide the framework for most archeological theory and synthesis, paralleling the long *durée* outlook with which Fernand Braudel has enriched the study of history."

Several scholars have focused on such societal dynamics in more recent history. Goldstone (1991) has attempted to understand why periods of revo-

lution appear across broad regions. In his book *Revolution and Rebellion in the Early Modern World*, he discusses how Eurasia experienced a wave of revolutions after a period of calm in the seventeenth century. He proposes that state breakdown occurs when there are simultaneous crises at several different organizational levels in society—i.e., adaptive cycles at different levels in a panarchy become aligned at the same phase of vulnerability (Box 3-3). That is, he explicitly posits a cascading, panarchical collapse.

Box 3-3. Revolution and Rebellion

G. Peterson

The breakdown of states in the seventeenth century (Goldstone 1991) provides an example of panarchical revolt. Revolutions occurred when a high potential for mass mobilization and conflict among elite groups intersected with a state in fiscal distress. Population growth, driven by increased agricultural productivity, produced stresses that intersected with rigid social institutions. These stresses came from a growing proportion of socially and economically marginalized people and produced a crisis when other social changes reduced the ability of the state to cope. That loss of social resilience occurred as inflation eroded the real value of taxes collected to support the state.

In the seventeenth century, population growth increased the demand for food without proportionally increasing food yields, leading to inflation in food and other prices. Institutional inflexibility prevented states from adjusting taxes to account for inflation. This loss of income reduced the ability of the state to respond to changes in society and increased the vulnerability of social organization to unusual events, such as a war, a bad harvest, or new policies. A less vulnerable society could cope with such events, but in these more vulnerable societies the events triggered larger crises.

As the state crises began, elite groups struggled for power and attempted to mobilize the general population for revolution. During a revolution, a new type of dynamic developed, as new ideas and ideologies of social reorganization were developed and spread. The period of state breakdown can be compared to a landslide, as the collapse of the state releases accumulated stresses, which then cascade, knocking down whatever lies in its path. The struggle for power that follows a state collapse is in many ways like an epidemic that becomes more virulent the faster it spreads.

continues

During the period of revolutionary mobilization, ideological varieties struggled for support, and in this intellectually competitive environment, moderate positions became radicalized. Radicalization was driven both by competition between ideas and by the underlying slow processes that brought about state breakdown in the first place. During this period of revolution, different groups desired different degrees of reform. Consequently, moderate policies were likely to be unsatisfying to most groups, as each sought more radical policies that suited their goals. The slow changes that brought about crises were not eliminated by state collapse, because the implementation of policies developed by moderates who initially gained power did not bring about social reform. Therefore, ideas calling for more radical change were able to proliferate.

This type of radical mobilization led to periods of revolutionary terror and mass political violence. In terms of the adaptive cycle, societal collapse had become so severe that it exceeded the society's capacity for renewal, moving a society into an alternative configuration. Terror was usually short term, as people left or were killed. However, this type of terror allowed an authoritarian group to seize power and establish order through force. Goldstone (1991) argues that once such a state was reached, it often took at least a political generation, or decades, before a more civil society began to emerge.

In *The Great Wave*, David Fischer (1996) presents a somewhat similar model of state breakdown that focuses much less on analysis of social stratification and revolutionary dynamics, and much more on analysis of empirical price data and inflation. He demonstrates that at least three waves of social unrest swept Eurasia in the fourteenth, seventeenth, and late eighteenth centuries. He demonstrates how currency mismanagement and diseases amplified inflation driven by population growth.

What unites these two models of societal change are their proposals that slow dynamics drove social organization. Periods of success brought about their own downfall, because stresses and rigidities slowly accumulated. Organizations and institutions failed to cope with these slow changes because either the changes were invisible to them, or they were so complex and contested that no action could be agreed upon. It is a view that Weber (1999) developed in the 1920s, when he argued that disintegration propagates among several levels of a monolithic culture into anarchic systems of competing ideologies. Those pave the way for a new synthesis by visionary or charismatic authority, which in turn becomes routinized into hierarchically complex and increasingly monolithic cultures.

Modern democratic societies are clearly vulnerable to the same process, but they have invented ways to diffuse large episodes of creative destruction by creating smaller cycles of renewal and change through periodic political elections. So long as there is a literate and attentive citizenry, that invention demonstrates that the painful lessons from episodic collapses of whole societal panarchies might be transferred to faster learning at smaller scales. Various designs in business make the same attempt—from creation of “skunk-works” to total quality management.

Such examples of collapsing panarchies start their collapse within individual adaptive cycles that have become maladaptive. We argued in Chapter 2 that the path of an adaptive cycle oscillates between conditions of low connectedness, low potential, and high resilience to their opposites. We argued that such an oscillation is inevitable in a system that persists and adapts in a changing environment. Its consequence is to probe the ever changing context of threat and opportunity, while accumulating and sustaining potential in the process.

Could we imagine systems in other combinations of those three attributes where variability is sharply constrained and opportunity is limited? We suggest two possibilities in Figure 3-12. If an adaptive cycle collapses because the potential and diversity have been eradicated by misuse or an ex-

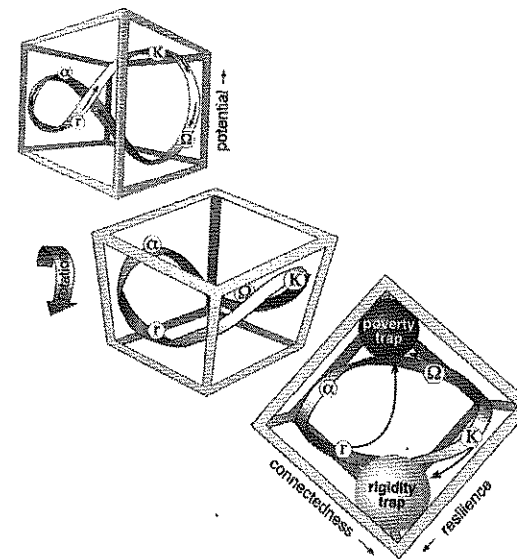


Figure 3-12. Maladaptive systems. A poverty trap and a rigidity trap are suggested as departures from an adaptive cycle. If an adaptive cycle collapses because the potential and diversity have been eradicated by misuse or an external force, an impoverished state can result, with low connectedness, low potential, and low resilience, creating a poverty trap. A system with high potential, connectedness, and resilience is represented by the rigidity trap, suggestive of maladaptive conditions present in hierocracies, such as large bureaucracies.

ternal force, an impoverished state can result with low connectedness, low potential, and low resilience, creating a poverty trap. That condition can then propagate downward through levels of the panarchy, collapsing levels as it goes. An ecological example is the productive savanna that, through human overuse and misuse, flips into an irreversible, eroding state with sparse vegetation, where subsequent drought precipitates further erosion, and economic disincentives maintain sheep production (Box 2-4, Chapter 2). An example of such a collapse occurs when a society is traumatized by social disruption or conflict, where cultural cohesion and adaptive abilities have been lost. Individuals can depend only on themselves and perhaps family members. In a sweeping analysis of poverty, Dasgupta (1993), for example, resolves the paradox of population growth at times of increasing impoverishment by explaining that children become needed for their work and minimum demands.

We could imagine that some such societies might exist in this degraded state of bare subsistence, barely able to persist but unable to accumulate enough potential to form the larger structures and sustaining properties of a panarchy. Still others might collapse in anarchy. That, in many ways, has been the history of both ecological and economic imperialism (Crosby 1986), following waves of human migration and expansion, initially from the Middle East and subsequently from Europe over the last seven centuries. If we have difficulties defining the conditions for sustainable, adaptive systems, we certainly have no difficulties in identifying the conditions for unsustainable, maladaptive ones.

The question raised in Chapter 5 by Berkes and Folke is how far such erosion can occur before recovery is impossible. When recovery is possible, what critical attributes need to be reinvented and reestablished from the residual memory stored in slowly fading traditions and myths in order to recreate a new, sustaining, panarchy? A specific example is described in Box 5-3 for the Cree Indians of northern Quebec and Labrador.

Figure 3-10 also suggests that it might be possible to have a sustainable but maladaptive system. Imagine a situation where potential is high, connectedness great, and, unlike the phase where those conditions exist in an adaptive cycle, resilience is high. The high resilience would mean a great ability for a system to resist external disturbances and persist, even beyond the point where it is adaptive and creative. The high potential would be measured in accumulated wealth. The high connectedness would come from efficient methods of social control whereby any novelty is either smothered or sees its inventor ejected. It would represent a rigidity trap.

We see signs of such sustained but maladaptive conditions in great "hierarchies," such as those that include rigid and apparently immutable caste systems. An example is described in Box 3-4 for the Hindu caste system. We are tempted to suggest, from our own frustrating experiences, that other examples might be found in present universities controlled by unchangeable, disciplinary departmental structures, or in agro-industry, where command

Box 3-4. The Hindu Caste System and the Hierarchy Trap

F. Berkes and C. Folke

The caste system in India has always fascinated students of human society. Indians marry according to their caste, and many professions are in the control of certain castes that have traditionally specialized in those tasks. Although discrimination by caste is against the law in contemporary India, many traces of the caste system are still visible. How did the caste system come about, and how did it become a "hierarchy trap"?

Gadgil and Malhotra (1983) hold the view that Indian society is analogous to a biological community made up of a number of cultural species or endogamous caste groups. They argue that the destruction of the ecological resource base and the effects of modernization have eventually rendered the caste system maladaptive.

Gadgil and Thapar (1990) trace the origins of the caste system to the breakdown of city-states and waves of migrations to the countryside in the Ganges plain after the fifth century, resulting in severe pressures on the rural land base and resources:

Indian society seems to have responded to the crisis through an elaboration of the caste system. The caste system divided society into innumerable endogamous groups within which most marriages and much social intercourse were restricted. The endogamous groups of caste society traditionally resembled tribal groups, from which they might in large part have been derived, in having a restricted geographical distribution, and in being self-governing. Each group tended to follow the customary pursuits of the group, a hereditary, rather well-defined mode of subsistence, and . . . several endogamous groups lived together. . . .

The modes of subsistence of such co-occurring groups tend to be diversified in ways that serve to minimize the competition between them. Thus in the Sirsi Taluka county of Karnataka State, for example, nine different endogamous groups use plant material to fabricate a variety of implements and structures. This resource use is highly diversified: for instance, only Christians employ cane to produce furni-

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ture, and only Chamagars use Phoenix palm to produce mats and brooms. While both Badigars and Acharis use *Careya arborea*, they fabricate different articles out of it. . . . These endogamous groups lived together in multi-caste village communities knit together in a web of reciprocity. It was, of course, an inegalitarian system with lower-status castes providing services far in excess of returns from higher-status castes.

Nevertheless, resource partitioning may have contributed to sustainable resource use and to the persistence of the caste system itself for some fifteen hundred years. However, according to Gadgil and Malhotra (1983):

The advent of British rule heralded the disorganization of this system. The British imposed high levels of demands on natural resources. They took over as government property vast resources which, until then, had been owned communally. . . . This led to considerable impoverishment [loss of social and ecological resilience] and often the complete collapse of the natural resource base. . . . The persistence of the caste, with loss of its traditional complementarity has, therefore, led to an increasing level of conflicts amongst different castes. . . rendering the once adaptive organization of caste society largely maladaptive. In fact, it has now become an impediment in coming to terms with new modes of resource utilization to which our society must adapt. But nurtured as it is by a long history. . . it is a very difficult task indeed to break out of the hold of this maladaptive system.

and control have squeezed out diversity and power, politics, and profit have reinforced one another. But all such systems might well have the seeds of their own destruction built in, much as in the case of the dictatorship of the bureaucracy in the now defunct Soviet Union. The speculation is interesting, maybe even useful, but we are now way beyond our own knowledge and conviction. We need enlightenment from political scientists and historians as described by Pritchard and Sanderson in Chapter 6.

Panarchy in Human and Ecological Systems

This effort of synthesis suggests that biological, ecological, and social systems exhibit properties of the four-phase adaptive cycle and of panarchy-

cal relationships across scales. These properties characterize all complex, adaptive systems. The adaptive cycle metaphor distinguishes the opposing forces operating between periods of gradual change and periods of rapid change, where long periods of accumulating potential alternate with briefer periods of creative opportunity. The panarchy distinguishes the influence of those cycles across scales in space and time. The interactions between cycles within a panarchy combine learning with continuity. The panarchy conserves the capacity to create, test, and maintain adaptive capability. The panarchy also preserves, accumulates, and transforms the potential created by that opportunity.

But this representation was largely formed from analyses of ecosystems and landscapes and the management agencies and activities developed to exploit those systems. The social science, economic, and ecological experience of authors of other chapters has helped challenge and deepen the concepts and their application. The resulting abstraction seems to identify events and sequences in human organizations and societies and to indicate the forces that might shape those sequences. But in the process, it becomes clear that human systems are different from ecological ones. Human systems show at least three features that are unique, features that change the character and location of variability within the panarchy, and that can dramatically enhance the potential of the panarchies themselves. Those three features are foresight, communication, and technology.

Foresight and Intentionality

As noted in Chapter 2 and further developed in Chapters 4, 5, 6, and 7, human foresight and intentionality can dramatically reduce or eliminate the boom-and-bust character of some cycles. Predictions of looming economic crises and collapses caused by resource scarcity, for example, are an important part of the debates about sustainability. The economist Solow (1973) provides a withering critique of such doomsday scenarios, pointing out that they ignore the forward-looking behaviors of people. These behaviors play a role in transmitting future scarcities into current prices, thereby inducing conservation behaviors seen today in the real economic world. This forward-looking process functions through futures markets and strategic purchase and holding of commodities. These provide very large incentives for some to forecast the coming scarcity better than the rest of the market, and to take a position to profit from it. But what one market participant can do, all can do, and this process transmits information to the market as a whole.

But there are limits to this process as described by Carpenter and Brock (Chapter 7) and Carpenter, Brock, and Hanson (1999). These are illustrated in specific examples of models that combine ecosystem models with economic optimization and decision processes. Both models suggest that even when knowledge is total, a minimally complex ecosystem model, together with stochastic events, can thwart the forward-looking economic and deci-

sion capacity to eliminate booms and busts. Those minimal requirements for the ecosystem characterize the ecosystem panarchy—at least three speeds of variables; separation among those speeds (lumpy, fast/slow dynamics, therefore); and nonlinear, multistable behavior. Such minimal models can create the reality of wide variability of an adaptive cycle and allow for exploration of actively adaptive approaches that minimize the consequence of transformational changes. An example is shown in Figure 7-9.

Finally, how can we explain the common tendency for large organizations to develop rigidities that precipitate major crises that initiate restructuring in a larger social, ecological, economic setting? Or of the long history of ruinous reversals in the development of societies? Such reversals seem to be more extreme and require much longer recovery than internally generated cycles of ecosystem panarchies. Certainly in management agencies, the exercise of foresight and intentionality is often brilliantly directed to protect the positions of individuals, not to further larger societal goals. The foresight that constructively maintains creativity and change when connected to an appropriate economic market can lead to rigid organizations that are maintained when there is no market with the same attributes. The market in these cases is a market for political power of the few, not a free market for the many (Chapter 6).

Communication: Transfer and Storage of Experience

Organisms transfer, test, and store experience in a changing world genetically. Ecosystems transfer, test, and store experience through forming self-organized patterns that repeat themselves. These are formed and refined by a set of interacting variables that function over specific scale ranges and form a mutually reinforcing core of relationships. In fact an ecosystem is developed from a few such sets, establishing a reproducing, discontinuous template that provides niches for species diversification and individual organism adaptation.

In human systems the same self-organized patterns are strongly developed, but humans uniquely add the power to communicate ideas and experience, which, as they are tested, can become incorporated into slower parts of the panarchy—from cultural myths (Chapter 5) to legal constitutions and laws (Chapters 4 and 13). Multiple sources of media, from television and movies to the Internet, are global in their connectedness and influence. These are contributing to a transformation of culture, beliefs, and politics at global scales. At smaller scales, the role of media is critical in the process of creating and disseminating the types of ecological crises described in Chapters 1 and 2. Subsequent chapters (6, 12, and 13) expand on the role that media and mass communication can play—from perpetuating myths to aggravating differences, to conducting forums that help resolve the crises.

Technology

The scale and influence of every animal but humans are restricted by its size. Such relationships were discussed in earlier sections, with regard to the identification of lumpy characteristics of body mass distributions and impacts on decisions made by animals. But technology transforms the actions of humans to influence an astonishing range of scales, from submicroscopic to planetary and, modestly at the moment, even a little beyond Earth itself.

This has evolved over a hundred thousand years, accelerating and changing the rules and context of the panarchies in the process. The specialized tools, habitation, and defense of hunters and gatherers, for example, together with the domestication of canines as hunting companions, opened opportunity over wide scales. The use of fire by early humans placed them as part of a structuring process capable, in temperate North America and Australia, for example, of transforming mosaics of grasslands and woods into extensive regions of contiguous grasslands or forests (Flannery 1994).

Progressively, the horse, train, automobile, and aircraft extended the ambit for human choices from local to regional to planetary scale, while the time for each of the sets of choices changed little, or decreased. Trips between home and work, for example, have always been largely limited to less than an hour or so, although the spatial scale has expanded from a maximum of a few kilometers by foot to potentially a few hundreds of kilometers by commuter aircraft. The slope of the decision panarchy of people, if plotted in that same space, as in Figure 3-11, now angles sharply upward, intersecting and dominating other panarchies of nature.

The characteristics that distinguish the self-organized patterns of ecological systems from those seen in social systems are developed in the next chapter and in Chapter 6. Chapter 4 addresses the question of why there is more than just disciplinary disunity between theories developed in social and ecological systems, and Chapter 6 addresses the particular dynamics of political systems linked to ecological dynamics.

Summary and Conclusions

Developing theory for sustainable futures requires a model of how human and ecological processes interact across space and time. The concept of panarchy provides an organizing framework for discussing these complex dynamics. Viewing sustainability from the perspective of panarchy yields five propositions:

1. Attributes of biological and human entities form clumped structures that reflect panarchical organization, create diversity, and contribute to resilience and sustainability.
2. Sustainability is maintained by relationships among a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time—the panarchy. The panarchy represents the dynamic inter-

play between processes and structures that sustains relationships on the one hand and accumulates potential on the other. The concept is sufficiently new that precise insights and prescriptions are just beginning to be made. Many of the alternative stable states mentioned above are situations in which panarchies are transformed, either because productive novelty cascades up the levels, or because destructive catastrophes cascade down.

3. Panarchies identify three types of change, each of which can generate a different kind of learning: incremental change and learning, abrupt change and spasmodic learning, and transformational learning.
4. Being as simple as possible, but no simpler than necessary, leads to the minimal complexity needed to understand a panarchy and its adaptive cycles. We propose that minimal complexity requires:
 - three to five key interacting components,
 - three qualitatively different speeds,
 - nonlinear causation and multistable behavior,
 - vulnerability and resilience that change with the slow variables,
 - biota that create structure that reinforces biota, and
 - spatial contagion and biotic legacies that self-organize over space and time.
5. Self-organization of ecological systems by interaction between the biota and physical variables establishes the arena for evolutionary change. Self-organization of human institutional patterns, by adding human activity to the set of interactions, establishes the arena for future sustainable opportunity.

The ideas summarized in the previous paragraphs are developed and tested in the second and third parts of this book. Part 2 develops quantitative representations of these dynamical systems, while Part 3 develops an integrated, more qualitative representation in applying these concepts to managing large complex systems. But before these tests appear, the next three chapters develop more theoretical underpinning, beginning with a chapter that explores ideas presented above on why ecological and social systems may not be similar.

CHAPTER 4

WHY SYSTEMS OF PEOPLE AND NATURE ARE NOT JUST SOCIAL AND ECOLOGICAL SYSTEMS

Frances Westley, Steven R. Carpenter, William A. Brock,
C. S. Holling, and Lance H. Gunderson

There are in nature no rewards or punishments, just consequences.
—Anon.

As we seek sustainable futures, we grapple with understanding complex systems of people and nature. Both the social and ecologic components of these systems have long histories of discipline-based scientific inquiries—replete with theories, methods, and findings. One way of understanding how these components interact is to link them in a common framework. This is a “systems” approach, in which a universal or common framework can be used to unite different components in the system. The previous chapters use this approach to address similarities in dynamics, properties, and structures between ecological and social systems by using the adaptive cycle heuristic. Other chapters (7, 8, and 9) expand on that approach and create mathematical models of linked systems that include economic, ecologic, and social components. We attempt something different in this chapter.

People in Ecosystems or Ecology of Social Systems

We would like to address at least two audiences, joined by a common interest in sustainability of people and their environment. The first group comprises those natural scientists interested in ecology who want to include in their world model a box called “people.” The second group comprises those social scientists interested in resource issues who wish to include in their model a box called “natural environment.” Our intention is to open up those two boxes to indicate the possible differences—i.e., the extent to which they deserve to be treated as two separate systems—and the possible similarities and relationships—i.e., the extent to which we can use conceptual