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Panarchy

Understanding Transformations in Human and Natural Systems

Edited by Lance H. Gunderson and C. S. Holling

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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 function that can be distilled into the following points:

- 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 are important in maintaining productivity and biogeochemical cycles.

- 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 behavior—i.e., to another stability domain (Holling 1973b). In this case

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, or, if other operating states exist, they can be avoided with appropriate safeguards, 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) has summarized in a masterful review of the empirical evidence. It has taken

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 ecological ones, is that resilience is not an ideal in itself. Moreover, it is not a fixed

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 of options possible;

- 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

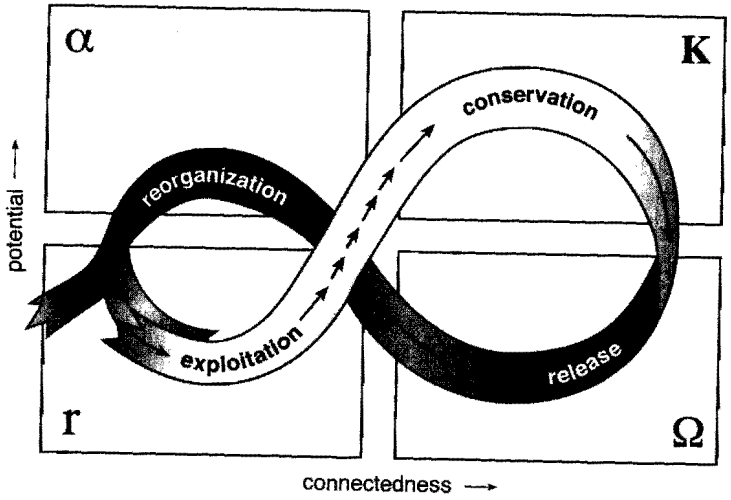

Figure 2-1. A stylized representation of the four ecosystem functions (r, K, Ω, α) and the flow of events among them. The arrows show the speed of that flow in the cycle, where short, closely spaced arrows indicate a slowly changing situation and long arrows indicate a rapidly changing situation. The 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 and where a flip into a less productive and organized system is most likely.

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, or escape.

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 Jeud 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 still lower potential in the Ω phase.

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 the nature of hierarchies will be explored in the next chapter.

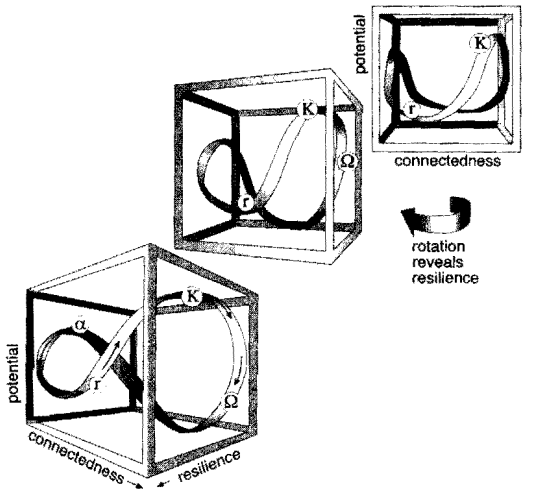

Figure 2-2. Resilience is another dimension of the adaptive cycle. A third dimension, resilience, is added to the two-dimensional box of Figure 2-1, showing that resilience expands and contracts throughout the cycle. Resilience shrinks as the cycle moves toward K, where the system becomes more brittle. 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 increase because facilitation and contest competition between species

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. Paleoecological 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 cycle and consolidated during the r and following phases. Subsequent sequences 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 reassortment. 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 all ecosystems, as we will shortly note for pelagic and semiarid grasslands.

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 instabilities gradually build up during "normal times" until fluctuations caused by those instabilities 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) because it adds a role for future expectations and the influence of future con-

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 that 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 traditional societies to sustainability.

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 the adaptive cycle. First, as sand is added to the pile, it reaches criticality (the

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.

We conclude that these arid grassland systems tend to stay in the lower quadrants of the adaptive cycle (Figure 2-1). That is where potential is low, 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 the natural parts of the linked economic/ecological system have nonlinearities

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).

continues

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 approach, not a predictive, optimizing one.

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 story-telling 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 certainly are some examples of the exercise of foresight potential and the exis-

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, disturbance processes, and species complexes involved in the regulation or

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 from the society to the individual entrepreneur.