

### 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  $\alpha$  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.

### CHAPTER 3

## SUSTAINABILITY AND PANARCHIES

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

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

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

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

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

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

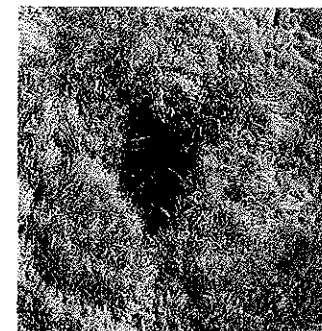
Over fifteen orders of magnitude separate a plant in the Everglades from the planet in space. Distinct regions of scale appear with unique objects and distinct processes in each. At the smaller scales, individual plants suggest the physiological processes of plant growth, nutrient exchange, and decomposition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

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

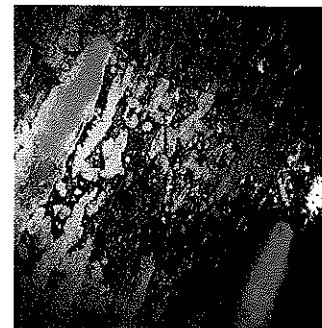
First, as scale increases, distinct objects appear and persist over distinct scale ranges and disappear, to be replaced by others that are aggregates of those objects. At each such range of scales, the objects have geometric properties of size measured as extent and grain. They also have temporal qualities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

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

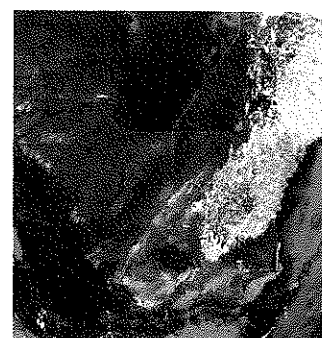
**Figure 3-1.** Everglades alligator hole. The linear extent of one side of the picture (or window size) is 10 meters. The alligator hole is the dark area of the water in the middle of the picture, surrounded by marsh plants, including sawgrass. The open water is kept free of plants by alligators. Small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

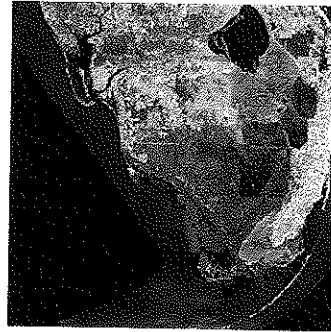


**Figure 3-2.** Everglades landscape. At a window size of 1 kilometer, plant communities are major features. Hardwood tree islands are the teardrop-shaped objects and are oriented with direction of water flow. The remaining matrix is comprised of sawgrass stands (lighter gray) and wet prairies (dark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

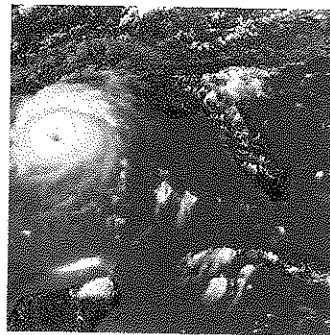


**Figure 3-3.** South Florida physiographic and land-use patterns. The major drainage feature of the southern Everglades (Shark River Slough) cuts a large swath through the frame that covers 100 kilometers. Water management structures (levees and canals) are the white straight lines cutting across the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

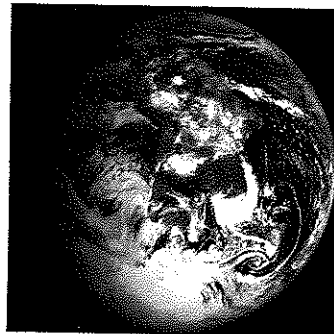




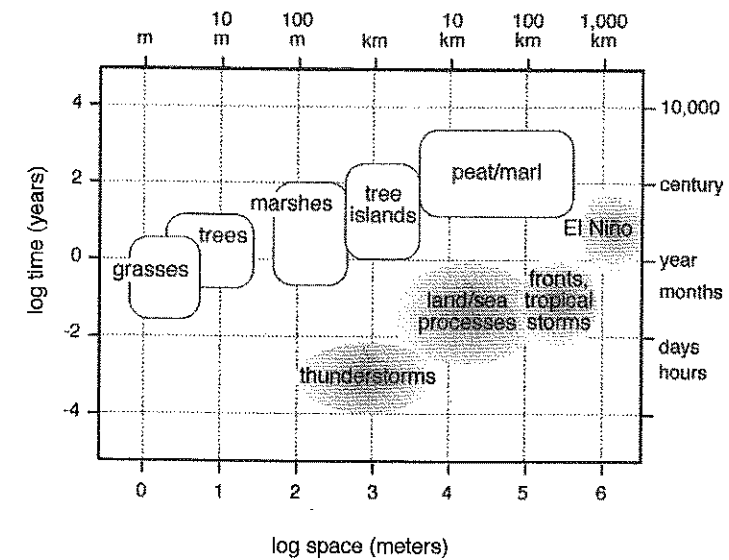
**Figure 3-4.** Southern Florida. The peninsula of Florida and the drainage basin of the Everglades are depicted in this satellite image that covers 300 kilometers on a side. The hydrologic unit is comprised of the Kissimmee River (north), Lake Okeechobee (central), and the Everglades. This is the scale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



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



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



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

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

Third, human impacts depend on the scale and on the medium affected—land, atmosphere, or water. Human influence on atmosphere occurs at all scales and has become planetary, as indicated by atmospheric  $\text{CO}_2$  accumulation and the greenhouse gas effect. Human influences on water are largely up to the scales of regions through construction of dams, dikes, and canals that allow water storage and transfers. Human influence on land, however, does not have that sweep; it is more local. For example, industrial agriculture homogenizes patterns at scales of fields within agricultural areas, but at coarser scales, human land-use patterns (agricultural area, park, and urban) largely reflect the existing landscape topography, formed by slow and extensive geomorphological processes. People farmed where soils exist; cities formed above flood-prone areas on the Atlantic ridge. And those utilization patterns change slowly. Humanity has yet to become the terraformers at the planetary scales suggested in science fiction.

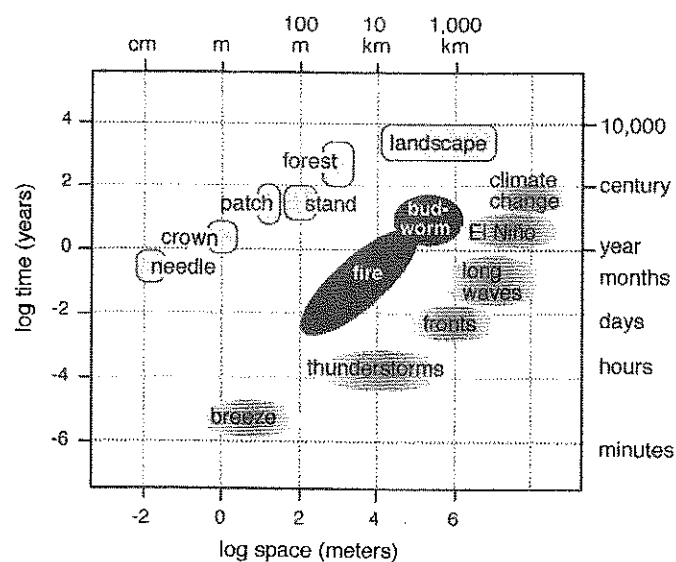
Finally, issues, problems, and opportunities are not just local; they can have integrated causes from processes at several scales. Some of those are local and are perceived locally. Some can originate half a world away, formed by geopolitical hemispheric policies, world trade, and climate change.

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

### Nested Cycles

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

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



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

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

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

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

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

### Box 3-1. Malaria and Adaptive Dynamics

M. Janssen and G. Peterson

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

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

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

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

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

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

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

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

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

### Hierarchies and Panarchies

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

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

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

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

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

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

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

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

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

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

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

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

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

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

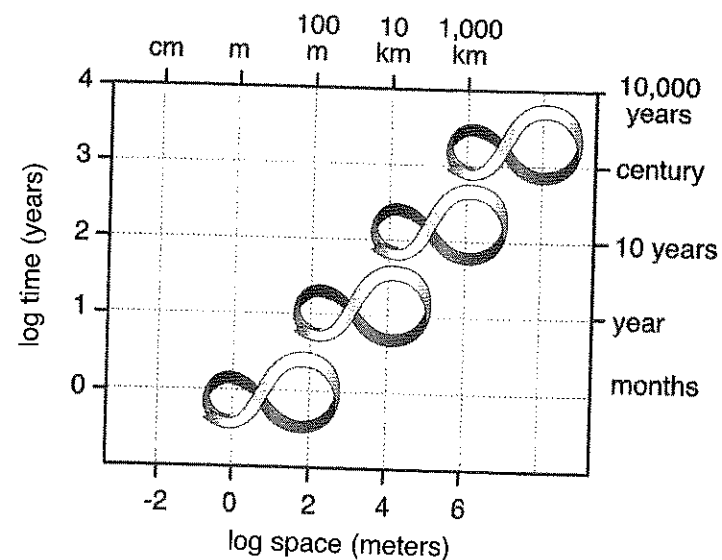


Figure 3-9. A stylized panarchy. A panarchy is a cross-scale, nested set of adaptive cycles, indicating the dynamic nature of structures depicted in the previous plots.

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

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

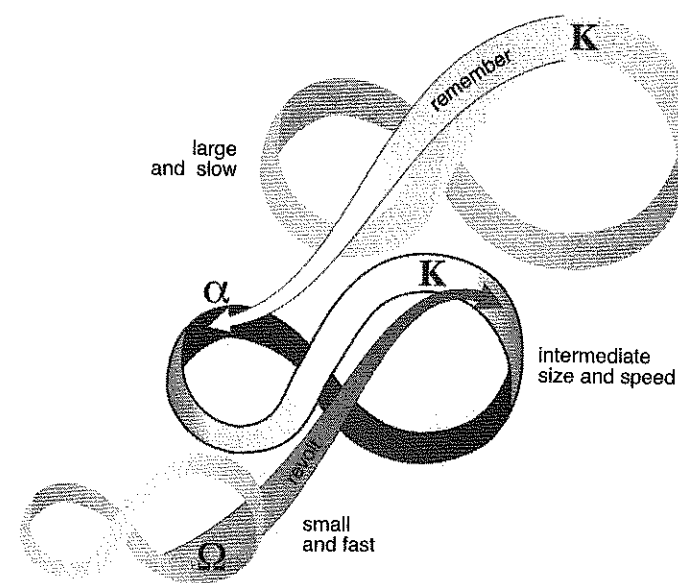


Figure 3-10. Panarchical connections. Three selected levels of a panarchy are illustrated, to emphasize the two connections that are critical in creating and sustaining adaptive capability. One is the “revolt” connection, which can cause a critical change in one cycle to cascade up to a vulnerable stage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

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

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

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

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

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

### Panarchies and Lumps

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

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

### Evidence for Panarchies

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

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

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



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

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

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

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

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

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

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

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

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

### Causes of Lumps

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

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

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

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

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

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

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

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

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

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

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

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

G. Peterson

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

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

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

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

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

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

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

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

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

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

### Significance of Lumps

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

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

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

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

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

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

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

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

### Decision Panarchies

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

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

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

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

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

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

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

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

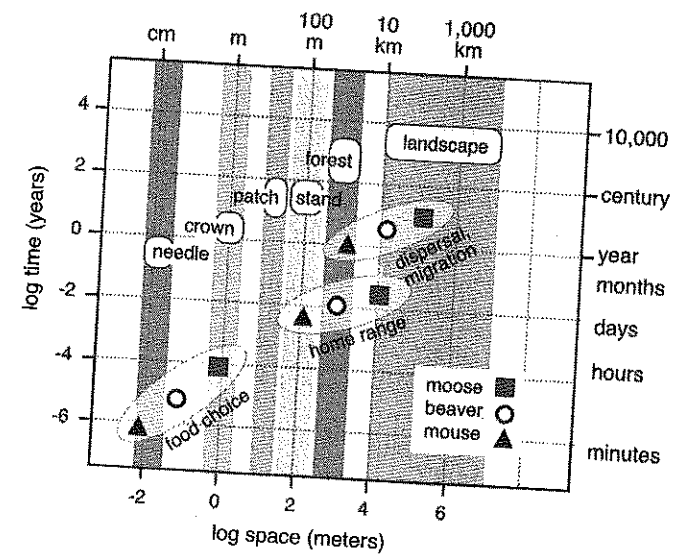


Figure 3-11. Decision hierarchies in the boreal forest. Shown are relative positions in the hierarchy for decisions about food choice, home range, or migration that would be made by each of three species from three different body mass lump categories. For example, a deer mouse establishes a home range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

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

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

### Lumps in Human Systems

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

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

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

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

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

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

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

### Cascading Change

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

### Novelty

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

### Collapsing Panarchies

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

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

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

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

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

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

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

### Box 3-3. Revolution and Rebellion

G. Peterson

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

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

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

*continues*



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

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

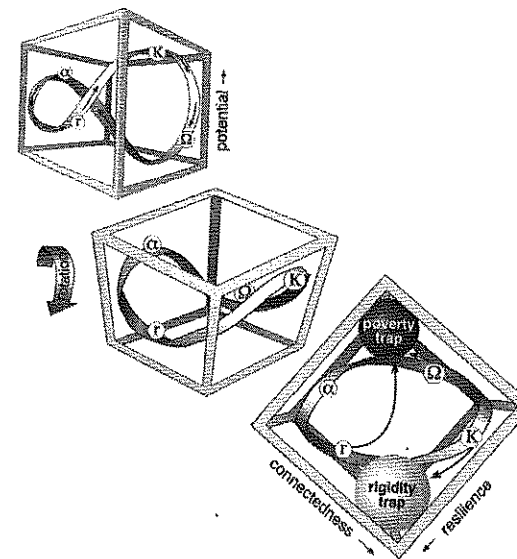
In *The Great Wave*, David Fischer (1996) presents a somewhat similar model of state breakdown that focuses much less on analysis of social stratification and revolutionary dynamics, and much more on analysis of empirical price data and inflation. He demonstrates that at least three waves of social unrest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

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

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

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

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



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

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

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

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

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

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

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

F. Berkes and C. Folke

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

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

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

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

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

*continues*

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

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

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

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

### Panarchy in Human and Ecological Systems

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

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

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

### Foresight and Intentionality

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

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

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

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

#### Communication: Transfer and Storage of Experience

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

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

#### Technology

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

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

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

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

#### Summary and Conclusions

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

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

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

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

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

## CHAPTER 4

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

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

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

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

#### People in Ecosystems or Ecology of Social Systems

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