Ecosystems (2001) 4: 390–405
DOI: 10.1007/s10021-001-0101-5

ECOSYSTEMS

MINIREVIEWS

Understanding the Complexity of Economic, Ecological, and Social Systems

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ABSTRACT

Hierarchies and adaptive cycles comprise the basis of ecosystems and social-ecological systems across scales. Together they form a panarchy. The panarchy describes how a healthy system can invent and experiment, benefiting from inventions that create opportunity while being kept safe from those that destabilize because of their nature or excessive exuberance. 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. The whole panarchy is therefore both creative and conserving. The interactions between cycles in a panarchy combine learning with continuity. An analysis of this process helps to clarify 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," thus refers to the goal of fostering adaptive capabilities and creating opportunities. It is therefore not an oxymoron but a term that describes a logical partnership.

Key words: hierarchy; adaptive cycles; multiple scales; resilience; sustainability.

INTRODUCTION

The ecological status of nations and regions is a current item for assessment and action on the agenda of several organizations. In the United States, the National Academy of Sciences and the Heinz Center have issued guidelines to identify sustainability indicators. Internationally, the Species Survival Commission of the World Conservation Union (IUCN) has stated that sustainability, either in a region or of a species, depends on interactions among internal and external factors. The internal factors may be social, political, ecological, or economic; the external factors include foreign debt, structural poverty, global environmental problems, and social/political/economic conflicts. Indicators of sustainability have been identified for all the internal factors, while issues of concern have been suggested for the external ones. One unpublished report cited 76 specific sustainability indicators for the internal factors and a more diffuse set of attributes for the external factors.

All of these indicators and all of the attributes make sense. The problem is not that they are wrong, or that they are not useful. They are, if anything, incomplete. Rather, they suggest a complexity that can overwhelm understanding, even when, in specific situations, only a subset of these entities are relevant. There are two approaches to complexity.

One of them, which has been explored thoroughly and incisively by Emory Roe (1998), views complexity as anything we do not understand, because there are apparently a large number of inter-

This paper has been adapted from Gunderson and Holling (2001), with permission of Island Press.
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acting elements. The appropriate approach, according to Roe, is to embrace the complexity and resulting uncertainty and analyze different subsets of interactions, each of which seem relevant from a number of fundamentally different operational and philosophical perspectives. A recent article in *Conservation Ecology* offered a review of this thesis from four different disciplinary and policy perspectives and a commentary on the reviews by the author (*www.consecol.org/Journal/vol4/iss2/index.html*).

An alternative view (Holling 2000; Gunderson and Holling 2001) suggests that the complexity of living systems of people and nature emerges not from a random association of a large number of interacting factors rather from a smaller number of controlling processes. These systems are self-organized, and a small set of critical processes create and maintain this self-organization. ("Self-organization" is a term that characterizes the development of complex adaptive systems, in which multiple outcomes typically are possible depending on accidents of history. Diversity and the individuality of components, localized interactions among components, and an autonomous process that uses the outcomes of those local interactions to select a subset of those components for enhancement are characteristics of complex adaptive systems [Levin 1999]). These processes establish a persistent template upon which a host of other variables exercise their influence. Such "subsidiary" variables or factors can be interesting, relevant, and important, but they exist at the whim of the critical controlling factors or variables. If sustainability means anything, it has to do with the small set of critical self-organized variables and the transformations that can occur in them during the evolutionary process of societal development.

But these two views of complexity require alternative perspectives and competing models and hypotheses. The goal of each approach is to mobilize evidence that can distinguish among competing explanations so that multiple lines of evidence begin to define what is known, what is uncertain, and what is unknown. We are always left with best judgments, not certainties.

The view presented here argues that there is a requisite level of simplicity behind the complexity that, if identified, can lead to an understanding that is rigorously developed but can be communicated lucidly. It holds that if you cannot explain or describe the issue of concern using at least a handful of causes, then your understanding is too simple. If you require many more than a handful of causes, then your understanding is unnecessarily complex. That level of understanding is built upon a foundation of adequate integrative theory, rigorously developed. This theory is rooted in empirical reality and communicated with metaphor and example. The first requirement is to begin to integrate the essence of ecological, economic, and social science theory and to do so with the goal of being, in Einstein's words, "as simple as possible but no simpler."

The purpose of this paper is to summarize a theoretical framework and process for understanding complex systems. This concept has recently been developed and expanded into a book-length thesis (Gunderson and Holling 2001). In its expanded version, it provides a means of assessing information about the internal factors and external influences that interact to determine systemic sustainability. To be useful, such a framework and process must satisfy the following criteria:

- Be "as simple as possible but no simpler" than is required for understanding and communication.
- Be dynamic and prescriptive, not static and descriptive. Monitoring of the present and past is static unless it connects to policies and actions and to the evaluation of different futures.
- Embrace uncertainty and unpredictability. Surprise and structural change are inevitable in systems of people and nature.

An Integrative Theory

Background

The theory was developed under the auspices of the "Resilience Project", a 5-year collaboration among an international group of ecologists, economists, social scientists, and mathematicians. The project was initiated to search for an integrative theory and integrative examples of practice. Its goal was to develop and test the elements of an integrative theory that had the degree of simplicity necessary for understanding but also the complexity required to develop policy for sustainability. The results of that project are summarized in the final report to the MacArthur Foundation found at http://www.resalliance.org/reports.

The heart of the work has now been amplified in *Panarchy: Understanding Transformations in Human and Natural Systems* (Gunderson and Holling. 2001). This book expands the theory and explores its implications for ecological, political, institutional, and management systems. It was intended to deepen our understanding of linked ecological/economic/decision systems through the use of a set of interactive models, several analyses of institutions that

Table 1. Table of Contents for Panarchy: Understanding Transformations in Human and Natural Systems

Part I. Introduction
- Chapter 1. In Quest of a Theory of Adaptive Change. C.S. Holling, L.H. Gunderson, and D. Ludwig

Part II. Theories of Change
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- Chapter 3. Sustainability and Panarchies. C.S. Holling, L.H. Gunderson, and G.D. Peterson
- Chapter 4. Why Are Systems of People and Nature not just Ecological or Social Systems? F. Westley, S.R. Carpenter, W.A. Brock, C.S. Holling, and L.H. Gunderson
- Chapter 5. Back to the Future: Ecosystem Dynamics and Local Knowledge. F. Berkes and C. Folke
- Chapter 6. The Dynamics of Political Discourse in Seeking Sustainability. L. Pritchard Jr. and S.E. Sanderson

Part III. Myths, Models, and Metaphors
- Chapter 7. Collapse, Learning, and Renewal. S.R. Carpenter, W.A. Brock, and D. Ludwig
- Chapter 8. Dynamic Interaction of Societies and Ecosystems: Linking Theories from Ecology, Economy, and Sociology. M. Scheffer, F. Westley, W.A. Brock, and M. Holmgren
- Chapter 9. A Future of Surprises. M. Janssen
- Chapter 10. Resilience and Sustainability: The Economic Analysis of Non-Linear Dynamic Systems. W.A. Brock, K.G. Mäler, and C. Perrings

Part IV. Linking Theory to Practice
- Chapter 11. Resilient Rangelands — Adaptation in Complex Systems. B. Walker and N. Abel
- Chapter 12. Surprises and Sustainability Cycles of Renewal in the Everglades. L.H. Gunderson, C.S. Holling, and G.D. Peterson
- Chapter 13. The Devil in the Dynamics: Adaptive Management on the Front Lines. F. Westley
- Chapter 14. Planning for Resilience: Scenarios, Surprises, and Branch Points. G. C. Gallopin

Part V. Summary and Synthesis
- Chapter 15. Discoveries for Sustainable Futures. C. S. Holling, S. R. Carpenter, W. A. Brock, and L. H. Gunderson
- Chapter 16. Towards an Integrative Synthesis. R. Yorque, B. Walker, C. S. Holling, L. H. Gunderson, C. Folke, S. R. Carpenter, and W. A. Brock

link people and nature, and an extensive exploration of two prototypical systems, the savannas and grasslands of Australia and the Everglades of Florida. Table 1 summarizes the book's contents.

"Panarchy" is the term we use to describe a concept that explains the evolving nature of complex adaptive systems. Panarchy is the hierarchical structure in which systems of nature (for example, forests, grasslands, lakes, rivers, and seas), and humans (for example, structures of governance, settlements, and cultures), as well as combined human–nature systems (for example, agencies that control natural resource use) (Gunderson and others 1995) and social-ecological systems (for instance, co-evolved systems of management) (Folke and others 1998), are interlinked in never-ending adaptive cycles of growth, accumulation, restructuring, and renewal. These transformational cycles take place in nested sets at scales ranging from a leaf to the biosphere over periods from days to geologic epochs, and from the scales of a family to a sociopolitical region over periods from years to centuries. If we can understand these cycles and their scales, it seems possible to evaluate their contribution to sustainability and to identify the points at which a system is capable of accepting positive change and the points where it is vulnerable. It then becomes possible to use those leverage points to foster resilience and sustainability within a system.

The idea of panarchy combines the concept of space/time hierarchies with a concept of adaptive cycles. I will deal with each in turn and then show the consequence of combining them in a synthesis.

Hierarchies

Simon (1974) was one of the first to describe the adaptive significance of hierarchical 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/spatial attributes). Each level communicates a small set of information or quantity of material to the next higher (slower and coarser) level. Figure 1 shows an example for a forested landscape, Figure 2 shows a wetland system, and Figure 3 shows a social system.

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 integ-

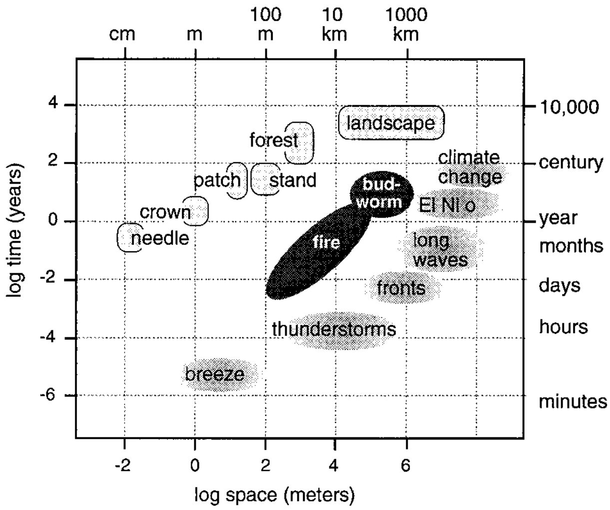

Figure 1. Time and space scales of the boreal forest (Holling 1986) and the atmosphere (Clark 1985) and their relationship to some of the processes that structure the forest. Contagious meso-scale processes, such as insect outbreaks and fire, mediate the interaction between faster atmospheric processes and slower vegetation processes. (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

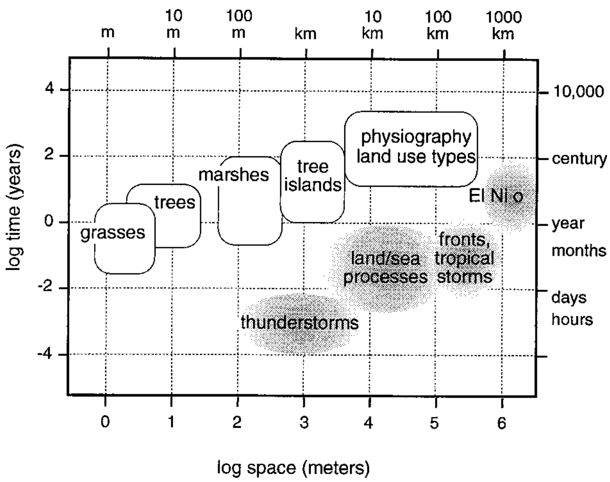

Figure 2. Time and space scales of levels of a hierarchy in the Everglades. (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

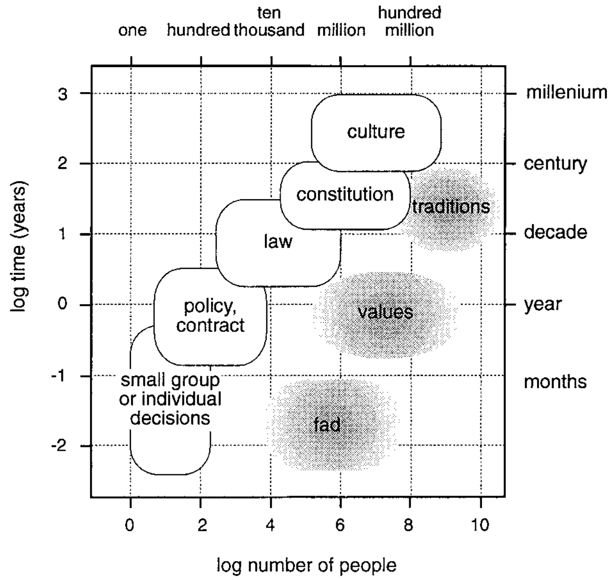

Figure 3. Institutional hierarchy of rule sets. In contrast to ecological hierarchies, this hierarchy is structured along dimensions of the number of people involved in rule sets and approximate turnover times (Gunderson and others 1995; Westley and others 2001). (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

rity. As a consequence, this structure allows wide latitude for experimentation within levels, thereby greatly increasing the speed of evolution.

Ecologists were inspired by Simon's seminal article to apply 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 and others (1986) stimulated 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 re-enforcing relationships over distinct ranges of scale. More recently, Levin (1999) has expanded that representation of cross-scale dynamics in a way that greatly deepens our understanding of the self-organized features of terrestrial ecosystems.

Simon's key arguments are that each of the levels of a dynamic hierarchy serves two functions. One is to conserve and stabilize conditions for the faster and smaller levels; the other is to generate and test innovations by experiments occurring within a level. It is this latter, dynamic function we call "an adaptive cycle" (Holling 1986). It is a heuristic model, a fundamental unit that contributes to the understanding of the dynamics of complex systems from cells, to ecosystems, to societies, to cultures.

The Adaptive Cycle

There are three properties that shape the adaptive cycle and the future state of a system:

- The inherent potential of a system that is available for change, since that potential determines the range of future options possible. This property can be thought of, loosely, as the "wealth" of a system.

- The internal controllability of a system; that is, the degree of connectedness between internal controlling variables and processes, a measure that reflects the degree of flexibility or rigidity of such controls, such as their sensitivity or not to perturbation.
- The adaptive capacity; that is, the resilience of the system, a measure of its vulnerability to unexpected or unpredictable shocks. This property can be thought of as the opposite of the vulnerability of the system.

These three properties—wealth, controllability, and adaptive capacity—are general ones, whether at the scale of the cell or the biosphere, the individual or the culture. In case examples of regional development and ecosystem management (Gunderson and others 1995), they are the properties that shape the responses of ecosystems, agencies, and people to crisis.

Potential, or wealth, sets limits for what is possible—it determines the number of alternative options for the future. Connectedness, or controllability, determines the degree to which a system can control its own destiny, as distinct from being caught by the whims of external variability. Resilience, as achieved by adaptive capacity, determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control.

A stylized representation of an adaptive cycle is shown in Figure 4 for two of these properties—potential and connectedness. The trajectory alternates between long periods of slow accumulation and transformation of resources (from exploitation to conservation, or r to K), with shorter periods that create opportunities for innovation (from release to reorganization, or Ω to α). That potential includes accumulated ecological, economic, social, and cultural capital as well as unexpressed chance mutations and inventions. During the slow sequence from exploitation to conservation, connectedness and stability increase and capital is accumulated. Ecosystem capital, for example, includes nutrients, biomass, and physical structure. Although this accumulated capital is sequestered for the growing, maturing ecosystem, it also represents a gradual increase in the potential for other kinds of ecosystems and futures. For an economic or social system, the accumulating potential could as well derive from the skills, networks of human relationships, and mutual trust that are developed incrementally

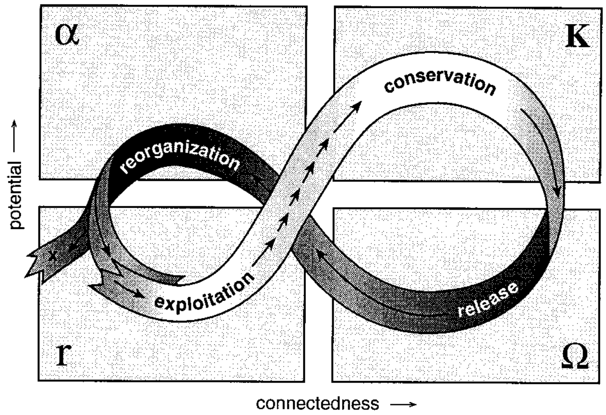

Figure 4. A stylized representation of the four ecosystem functions (r, K, Ω, α) and the flow of events among them. The arrows show the speed of the flow in the cycle. Short, closely spaced arrows indicate a slowly changing situation; long arrows indicate a rapidly changing situation. The cycle reflects changes in two properties: the y axis (the potential that is inherent in the accumulated resources of biomass and nutrients) and the x axis (the degree of connectedness among controlling variable). The exit from the cycle indicated at the left of the figure suggests, in a stylized way, the stage where the potential can leak away and where a flip into a less productive and less organized system is most likely (Holling 1986). (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

and integrated during the progression from r to K. They also represent a potential that was developed and used in one setting but could be available in transformed ones.

As the progression to the K phase proceeds in an ecosystem, for example, the accumulating nutrient and biomass resources become more and more tightly bound within existing vegetation, preventing other competitors from utilizing them. The potential for other use is high, but it is expropriated and controlled by the specific biota and processes of the ecosystem in place. That is, the system's connectedness increases, eventually becoming overconnected and increasingly rigid in its control. It becomes an accident waiting to happen.

The actual change is triggered by agents of disturbance, such as wind, fire, disease, insect outbreak, and drought. The resources accumulated and sequestered in vegetation and soil are then suddenly released and the tight organization is lost. Human enterprises can exhibit similar behavior, as, for example, when corporations such as IBM, AT&T, or General Motors accumulate rigidities to the point of crisis and then attempt to restructure (Hurst and Zimmerman 1994; Hurst 1995; Holling and others 2001). The Soviet Union is a societal example of accumulated rigidities that precipitate a sudden collapse. The proximate agents of disturbance in these cases can be stakeholder revolts, public-interest attacks through the legal system, or more extreme societal revolts.

The phase from Ω to α is a period of rapid reorganization during which novel recombinations can unexpectedly seed experiments that lead to innovations in the next cycle. The economist J. A. Schumpeter (1950) appropriately called this phase "creative destruction." Initially, the "front loop" of the trajectory, from r to K, becomes progressively more predictable as it develops. In contrast, the "back loop" of the adaptive cycle, from Ω to α, is inherently unpredictable and highly uncertain. At that stage, the previously accumulated mutations, inventions, external invaders, and capital can become reassorted into novel combinations, some of which nucleate new opportunity.

It is as if two separate objectives are functioning, but in sequence. The first maximizes production and accumulation; the second maximizes invention and reassortment. The two objectives cannot be maximized simultaneously but only occur sequentially. And the success in achieving one inexorably sets the stage for its opposite. The adaptive cycle therefore embraces two opposites: growth and stability on the one hand, change and variety on the other.

Figure 5 adds the third dimension, resilience, to the adaptive cycle. The appearance of a figure 8 in the path of the adaptive cycle, as in Figure 4, is the consequence of the projection of a three-dimensional object onto a two-dimensional plane. We can view that three-dimensional object from different perspectives, emphasizing one property or another. Figure 5 rotates the object to expose the resilience axis.

This orientation of the figure shows that as the phases of the adaptive cycle proceed, a system's ecological resilience expands and contracts. The conditions that occasionally foster novelty and experiment occur during periods in the back loop of the cycle, when connectedness, or controllability, is low and resilience is high (that is, during the α phase). The low connectedness, or weak control, permits novel reassortments of elements that were previously tightly connected to others in isolated sets of interactions. The high resilience allows tests of those novel combinations because the system-wide costs of failure are low. The result is the condition needed for creative experimentation. This recognition of resilience varying within a cycle adds an element that can reconcile the delicious paradoxes of conservative nature vs creative nature; sustainability vs creative change.

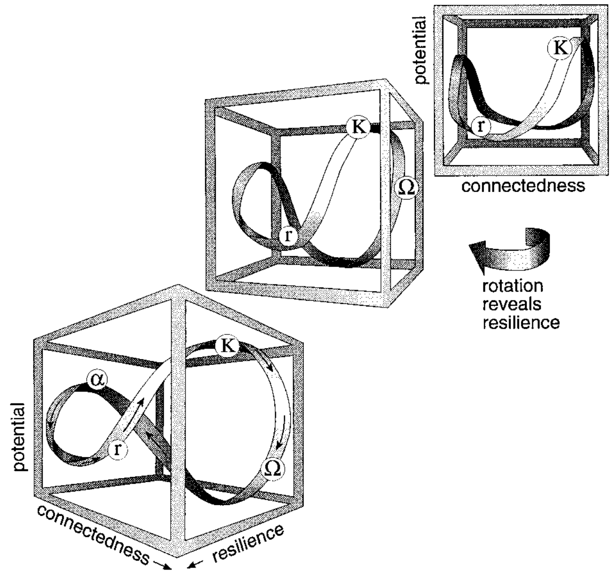

Figure 5. Resilience is another dimension of the adaptive cycle. A third dimension, resilience, is added to the two-dimensional box of Figure 4 to show how resilience expands and contracts throughout the cycle. Resilience shrinks as the cycle moves towards K, where the system becomes more brittle. It expands as the cycle shifts rapidly into a back loop to reorganize accumulated resources for a new initiation of the cycle. The appearance of a figure 8 in Figure 4 is the consequence of viewing a three-dimensional object in a two-dimensional plane. (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

The α phase is the stage that is least examined and the least known. It is the beginning of a process of reorganization that provides the potential for subsequent growth, resource accumulation, and storage. At this stage, ecological resilience is high, as is potential. But connectedness is low and internal regulation is weak. There is a wide stability region, with weak regulation around equilibria, low connectivity among variables, and a substantial amount of potential available for future options. Because of those features, it is a fertile environment for experiments, for the appearance and initial establishment of entities that would otherwise be outcompeted. As in good experiments, many will fail, but in the process, the survivors will accumulate the fruits of change. It is a time of both crisis and opportunity.

In summary, there are four key features that characterize an adaptive cycle, with its properties of growth and accumulation on the one hand and of novelty and renewal on the other. All of them are measurable in specific situations:

1. Potential (that is, wealth as expressed in ecosystem structure, productivity, human relationships, mutations, and inventions) increases incrementally in conjunction with increased efficiency but also in conjunction with increased rigidity. This is the phase from r to K in Figure 4.
2. As potential increases, slow changes gradually expose an increasing vulnerability (decreased resilience) to such threats as fire, insect outbreak, competitors, or opposition groups. The system becomes an accident waiting to happen. A break can trigger the release of accumulated potential in what the economist Schumpeter called "creative destruction" (1950). The trajectory then moves abruptly into a back loop from K to Ω.
3. Innovation occurs in pulses or surges of innovation when uncertainty is great, potential is high, and controls are weak, so that novel recombinations can form. This is the phase of reorganization represented in α (Figure 4) where low connectedness allows unexpected combinations of previously isolated or constrained innovations that can nucleate new opportunity.
4. Those innovations are then tested. Some fail, but others survive and adapt in a succeeding phase of growth from r to K.

Not All Adaptive Cycles Are the Same

Efforts to find exceptions that might invalidate the preceding representation have identified different classes of systems that represent distinct variants of, or departures from, that cycle. Examples of these exceptions include:

- Physical systems where the lack of invention and mutation limits the potential for evolutionary change. Examples: tectonic plate dynamics, and Per Bak's (1996) sand pile experiments demonstrating "organized criticality" from K to Ω).
- Ecosystems and communities of plants and animals that are strongly influenced by uncontrollable or unpredictable episodic external inputs and have little internal regulation and highly adaptive responses to opportunity. Examples: exploited arid rangelands, pelagic biotic communities. These systems tend to remain largely in the lower left quadrant of the cycle, oscillating in the α and r phases, dominated by trophic dynamics (Walker and Abel 2001).
- Ecosystems and human organizations with predictable but variable inputs and some significant internal regulation of external variability over certain scale ranges. For example, productive temperate forests and grasslands, large bureaucracies. These systems represent the full cycle of boom-and-bust dynamics shown in Figure 4 (Holling and Gunderson 2001).
- 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. This is an example of local control that can release external opportunity and variability at a different scale—a transfer of the full adaptive cycle to the larger arena of a higher level in the hierarchy.
- Human systems with foresight and active adaptive methods that stabilize variability and exploit opportunity. Examples: entrepreneurial businesses, futures markets and resource scarcity, some traditional cultures. The high variability of the adaptive cycle can be transferred from the society to an individual entrepreneur or, in a traditional culture, to a "wise person" (Westley and others 2001; Berkes and Folke 2001).

The Panarchy: A Synthesis

Because the word "hierarchy" is so burdened by the rigid, top-down nature of its common meaning, we decided to look for another term that would capture the adaptive and evolutionary nature of adaptive cycles that are nested one within each other across space and time scales. Our goal was to rationalize the interplay between change and persistence, between the predictable and the unpredictable. We therefore melded the image of the Greek god Pan as the epitoma of unpredictable change with the notion of hierarchies across scales to invent a new term that could represent structures that sustain experiment, test its results, and allow adaptive evolution. Hence, "panarchy".

A panarchy is a representation of a hierarchy as a nested set of adaptive cycles. The functioning of those cycles and the communication between them determines the sustainability of a system. That synthesis will be explored in this section.

The adaptive cycle, as shown in Figures 4 and 5, transforms hierarchies from fixed static structures to dynamic, adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the Ω phase) and the transition from reorganization to rapid growth (the α phase). At 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.

However, the structural, top-down aspect of hierarchies has tended to dominate theory and application, reinforced by the standard dictionary definition of hierarchy as a system of vertical authority and control. Therefore, the dynamic and adaptive nature of such nested structures has tended to be lost.

It is certainly true that slower and larger levels set the conditions within which faster and smaller ones function. Thus, a forest stand moderates the climate within the stand to narrow the range of temperatures experienced by its individuals constituents. Similarly, cultures of different people establish norms that guide the actions of human individuals. But this representation has no way of accounting for the dynamics of each level as symbolized in the four-phase cycle of birth, growth and maturation, death, and renewal.

This adaptive cycle captures in a heuristic fashion the engine that periodically generates the variability and novelty upon which experimentation depends. As a consequence of the periodic, but transient, phases of creative destruction (Ω stage) and renewal (α stage), each level of a system's structure and processes can be reorganized. This reshuffling in the back loop of the cycle allows the possibility of new system configurations and opportunities utilizing the exotic and entirely novel entrants that had accumulated in earlier phases. The adaptive cycle opens transient windows of opportunity so that novel assortments can be generated.

For organisms, those novel entrants are mutated genes or, for some bacteria, exotic genes that are transferred occasionally between species. For ecosystems, the novel entrants are exotic, potentially invasive species or species "in the wings" waiting for more appropriate conditions. For economic systems, these novel entrants are inventions, creative ideas, and innovative people. The adaptive cycle explicitly initiates a slow period of growth during which mutations, invasions, and inventions can accumulate, followed by a briefer period when they undergo rearrangements. This process can occur periodically within each hierarchical level, in a way that partially isolates the resulting experiments, reducing the risk to the integrity of the whole structure.

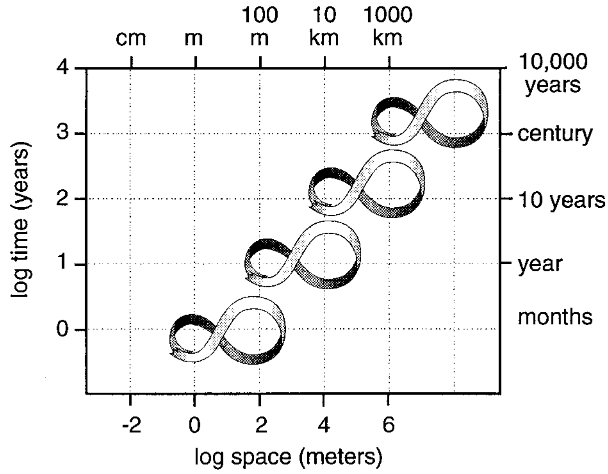

Figure 6. A stylized panarchy. A panarchy is a cross-scale, nested set of adaptive cycles that indicates the dynamic nature of structures depicted in the previous plots. (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

The organization and functions that form biological, ecological, and human systems can therefore be viewed as a nested set of four-phase adaptive cycles. Within these cycles, there are opportunities for periodic reshuffling within levels, which maintain adaptive opportunity, while simple interactions across levels maintain integrity. One major difference among biological, ecological, and human systems is the way that inventions are accumulated and transferred over time. But more on that later.

There are two features that distinguish the panarchical representation from traditional hierarchical ones. The first, as discussed earlier, is the importance of the adaptive cycle and, in particular, the α phase as the engine of variety and the generator of new experiments within each level. The various levels of the panarchy can be seen as a nested set of adaptive cycles (Figure 6).

The second feature is the connections between levels. There are potentially multiple connections between phases at one level and phases at another level. But two of these connections are particularly significant to our search for the meaning of sustainability. They are labeled as "revolt" and "remember" in Figure 7, where three levels of a panarchy are represented. The revolt and remember connections become important at times of change in the adaptive cycles.

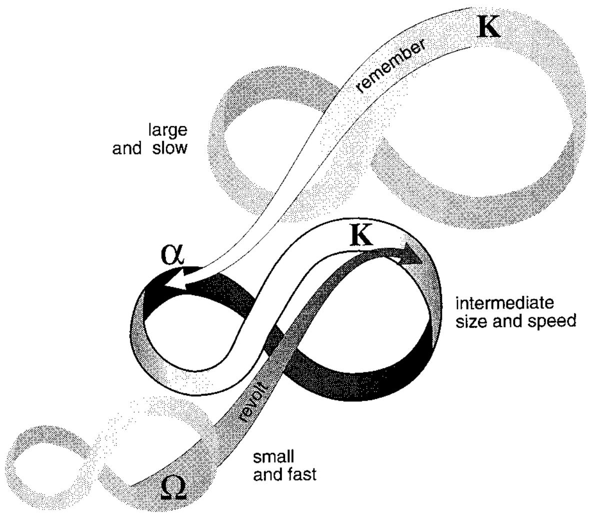

Figure 7. Panarchical connections. Three selected levels of a panarchy are illustrated to show the two connections that are critical in creating and sustaining adaptive capability. One is the "revolt" connection, which can cause a critical change in one cycle to cascade up to a vulnerable stage in a 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. An example of the sequence from small and fast through larger and slower and thence to largest and slowest for a boreal forest ecosystem includes needles, tree crowns, and patches. For institutions, those three speeds might be operational rules, collective choice rules, and constitutional rules (Ostrom 1992); for economies, they might be individual preferences, markets, and social institutions (Whitaker 1987); for developing nations, they might be markets, infrastructure, and governance (Barro 1997); for societies, they might be allocation mechanisms, norms, and myths (Westley 1995); for knowledge systems, they might be local knowledge, management practice, and world view (Gadgil and others 1993; Berkes 1999; Holling and others 2001). (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

When a level in the panarchy enters its Ω phase of creative destruction, the collapse can cascade to the next larger and slower level by triggering a crisis. Such an event is most likely if the slower level is at its K phase, because at this point the resilience is low and the level is particularly vulnerable. The "revolt" arrow in Figure 7 suggests this effect, one where fast and small events overwhelm slow and large ones. Once triggered, the effect can cascade to still higher, slower levels, particularly if those levels have also accumulated vulnerabilities and rigidities.

An ecological version of this situation occurs when conditions in a forest allow a local ignition to create a small ground fire that spreads first 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 version occurs when local activists succeed in their efforts to transform regional organizations and institutions, because the latter have become broadly vulnerable. Such a change occurred in New Brunswick, Canada when a few small groups opposed to spraying insecticide over the forest were able to transform this region's vulnerable forest management policies and practices (Baskerville 1995).

The arrow labeled "remember" in Figure 7 indicates a second type of cross-scale interaction that is important at times of change and renewal. Once a catastrophe is triggered at one level, the opportunities for, or constraints against, the renewal of the cycle are strongly influenced by the K phase of the next slower and larger level. After a forest fire, for example, the processes and resources that have accumulated at a larger level slow the leakage of nutrients that have been mobilized and released into the soil. At the same time, the options for renewal include the seed bank, physical structures, and surviving species, which comprise biotic legacies (Franklin and MacMahon 2000) that have accumulated in the course of the forest's growth. Similarily, for its reorganization and renewal, a coral reef hit by a storm draws on its own legacies and the memory of the seascape of which it is a part (Nyström and Folke 2001). It is as if this connection draws on the accumulated wisdom and experiences of maturity; hence, the word "remember."

In a similar vein, Stewart Brand, in his marvelous meditation on buildings (1994), described them as adaptive, hierarchical entities. Buildings of enduring character are a reflection of seasoned maturity—the culmination of a series of idiosyncratic, wise, and thought-provoking experiments in the form and content of a mature, evolved structure. In *The Clock of the Long Now*, Brand (1999) extends these ideas and generalizes the concept of fast and slow processes to society as a whole. His work resonates with features reminiscent of panarchy theory. Similarly, Levin's *Fragile Dominion* (1999) is an accessible and effective disquisition on self-organization as it characterizes adaptive, complex ecological systems.

The panarchy is a representation of the ways in which a healthy social-ecological system can invent and experiment, benefiting from inventions that create opportunity while it is kept safe from those that destabilize the system because of their nature or excessive exuberance. 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. The whole panarchy is therefore both creative and conserving. The interactions between cycles in a panarchy combine learning with continuity.

This process can serve to clarify 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", therefore refers to the goal of fostering adaptive capabilities while simultaneously creating opportunities. It is therefore not an oxymoron but a term that describes a logical partnership.

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 the sustaining properties of panarchies, destroying levels, and triggering destructive cascades down the successive levels of a panarchy. The cataclysmic loss of biological diversity that occurred some 65 million years ago, destroying about 70% of Earth's species; Jablonski 1995), for example, is likely to have been caused by the impact of an asteroid (Alvarez and others 1980). That event, which may also be associated with massive volcanic eruptions that occurred around the same time, unraveled the web of interactions within and between panarchical levels over scales from biomes to species.

Since recovery from these events is so delayed, it is likely that mass extinction events eliminate not only species but also ecological niches. For their continued existence, species depend on an environment that is created by life. Because they destroy most species, mass extinction events concomitantly eliminate many ecological niches. The recovery of biodiversity from such cataclysmic events requires the reconstruction of these niches, as new species evolve to fill them.

Notably, different families, orders, and species dominated the new assemblages after recovery; novel inventions and new ways of living emerged. The dinosaurs became extinct during the collapse that occurred 65 million years ago; the mammals, inconspicuous before that time, 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, a long view of human history reveals not regular change but spasmodic, catastrophic disruptions followed by long periods of reinvention and development. In contrast to the sudden collapses of biological panarchies, there are long periods of ruinous reversal, followed by slow recovery and the restoration of lost potential. Robert Adams's magnificent reconstruction of Mesopotamian societies (1966, 1978) and a later review of other archaeological sequences at regional or larger scales (R. M. Adams unpublished) led him to identify two trends in human society since the Pleistocene. The first is an overall increase in the 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 second trend is defined by the occurrence of rapid discontinuous shifts, interspersed by much longer periods of relative stability. A number of scholars have focused on the study of such societal dynamics in more recent history. For example, Goldstone (1991) examined the wave of revolutions that occurred in Eurasia after a period of calm in the 17th century. He hypothesized that political breakdown occurs when there are simultaneous crises at several different organizational levels in society. In other words, adaptive cycles at different levels in a panarchy become aligned at the same phase of vulnerability. Thus, he explicitly posits a cascading, panarchical collapse.

In *The Great Wave*, David Fischer (1996) presents a somewhat similar model of political breakdown that focuses less on social stratification and revolutionary dynamics than on empirical price data and inflation. According to Fischer, at least three waves of social unrest swept Eurasia, first in the 14th century and later in the 17th and late 18th centuries. He argues that currency mismanagement and the outbreak of diseases aggravated the destabilizing effects of an inflation that in turn was driven by population growth.

In effect, both of these models of societal change propose that slow dynamics inform social organization. Periods of success carry the seeds of subsequent downfall, because they allow stresses and rigidities to accumulate. Organizations and institutions often fail to cope with these slow changes either because the changes are invisible to them, or they are so complex and highly contested that no action can be agreed upon.

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

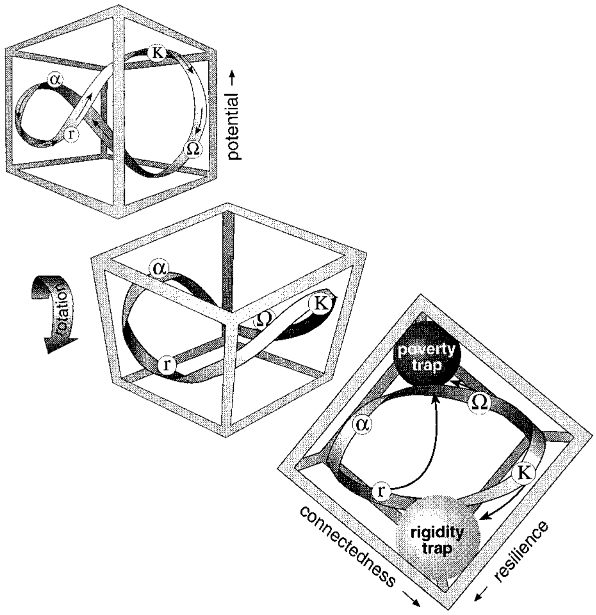

Figure 8. Maladaptive systems. A poverty trap and a rigidity trap are illustrated as departures from an adaptive cycle. If an adaptive cycle collapses because the potential and diversity have been eradicated due to misuse or an external force, an impoverished state can result, with low connectedness, low potential, and low resilience, thus creating a poverty trap. A system with high potential, connectedness, and resilience is represented by the rigidity trap. It is suggestive of the maladaptive conditions present in hierocracies, such as large bureaucracies (Holling and others 2001). (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

change through periodic political elections. So long as there is a literate and attentive citizenry, the painful lessons learned from the episodic collapses of whole societal panarchies can be transferred to faster learning at smaller scales. Various designs in business, from the creation of "skunk works" to the introduction of total quality management, serve the same purpose.

Poverty Traps and Rigidity Traps

Collapsing panarchies begin to decline within specific adaptive cycles that have become maladaptive. Earlier, I described the path of an adaptive cycle as oscillating between conditions of low connectedness, low potential, and high resilience to their opposites. Could there be systems with other combinations of those three attributes in which variability is sharply constrained and opportunity is limited? We suggest two such possibilities in Figure 8. If an adaptive cycle collapses because the potential and diversity have been eradicated through misuse or due to an external force, an impoverished state can result, with low connectedness, low potential, and low resilience, thus creating a poverty trap.

This 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, beginning with sparse vegetation. Thereafter, subsequent drought precipitates further erosion, and economic disincentives maintain sheep production. The same persistent collapse might also occur in a society traumatized by social disruption or conflict, so that its cultural cohesion and adaptive abilities are lost. In such a situation, the individual members of the society would be able to depend only on themselves and perhaps their immediate family members.

Some such societies might continue to exist in this degraded state of bare subsistence, barely able to persist as a group, but unable to accumulate enough potential to form the larger structures and sustaining properties of a complete panarchy. Others might simply collapse into anarchy. Berkes (1999) and Folke and others (1998) tried to determine how far such erosion must progress before recovery becomes impossible. When recovery is possible, it would be useful to know what critical attributes need to be reinvented and reestablished from the residual memory stored in slowly fading traditions and myths to recreate a new, sustaining panarchy.

Figure 8 also suggests that it is possible to have a sustainable but maladaptive system. Imagine a situation of great wealth and control, where potential is high, connectedness great and—in contrast to the phase where those conditions exist in an adaptive cycle—resilience is high; that is, a wealthy, tightly regulated, and resilient system. The high resilience would mean that the system had a great ability to resist external disturbances and persist, even beyond the point where it is adaptive and creative. It would have a kind of perverse resilience, preserving a maladaptive system. The high potential would be measured in accumulated wealth or abundant natural capital. The high connectedness would be created by efficient methods of social control, in which any novelty is either smothered or its inventor ejected. It would represent a rigidity trap.

We see signs of such sustained but maladaptive conditions in great "hierocracies," such as societies that operate under rigid and apparently immutable caste systems. Other examples occur in regions of the developing world that have abundant natural resources but are subject to the rigid control of corrupt political regimes. But all such systems are likely to have the seeds of their own destruction built in, as was the case with the totalitarian bureaucracy of the now defunct Soviet Union (Levin and others 1998).

What Distinguishes Human Systems?

Human systems exhibit 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. Human foresight and intentionality can dramatically reduce or even 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 issue in debates about sustainability. The economist R. Solow (1973) provided 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 in the real economic world. This forward-looking process functions through futures markets and the strategic purchase and holding of commodities. They provide very large incentives for some people 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; thus, this process transmits information to the market as a whole.

But there limits to this process, as described by Carpenter and others (1999, 2001). These limits are illustrated in specific examples of models that combine ecosystem simulations with economic optimization and decision processes. These models suggest that even when knowledge is total, a minimally complex ecosystem model, together with stochastic events, can thwart the forward-looking economic and decision-making capacity to eliminate booms and busts. These minimal requirements for the system are the same ones that characterize the ecosystem panarchy—that is, at least three speeds of variables, separation among those speeds, and nonlinear, multistable behavior.

That analysis is the source of our conclusion that ecosystems have a minimal complexity we call the "Rule of Hand" whose features make linear policies more likely to produce temporary solutions and a greater number of escalating problems. Only an actively adaptive approach can minimize the consequences.

Finally, how can we explain the common tendency for large organizations to develop rigidities, thus precipitating major crises that initiate restructuring in a larger social, ecological, economic setting? Or, the many examples of long-term, ruinous reversals in the development of societies? These collapses seem to be more extreme and require much longer recovery than the 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 rather than to further larger societal goals. The foresight that maintains creativity and change when connected to an appropriate economic market can lead to rigid organizations that are maintained even when that particular market no longer exists. The market in these cases is a market for political power of the few, not a free market for the many (Pritchard and Sanderson 2001). Foresight and intentionality can therefore precipitate ruinous reversals if they are not connected to a market with essential liberal and equitable properties.

Communication. Organisms transfer, test, and store experience in a changing world genetically. Ecosystems transfer, test, and store experience by forming self-organized patterns that repeat themselves. These patterns 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 out of a few such sets that establish a reproducing, discontinuous template to provide niches for species diversification and the adaptation of individual organisms.

In human systems, the same self-organized patterns are strongly developed, but humans uniquely add the ability to communicate ideas and experience. As they are tested, these ideas can become incorporated into slower parts of the panarchy, such as cultural myths, legal constitutions, and laws. Many sources of information, including television, movies, and the Internet, are global in their connectedness and influence. These media are contributing to a transformation of culture, beliefs, and politics at global scales.

Technology. The scale of the influence exerted by every animal other than humans is highly restricted. But technology amplifies the actions of humans so that they affect an astonishing range of scales from the submicroscopic to global and—however modestly at the moment—even extend beyond Earth itself.

As human technology has evolved over the last hundred thousand years, it has progressively accelerated, changing the rules and context of the panarchies in the process. The specialized tools, habitation, and weapons of hunter-gatherers, for example, together with the domestication of canines for use as hunting companions, created opportunities over wide scales. The use of fire by early humans made them part of the ecological structuring process. In temperate North America and Australia, for example, they became capable of transforming mosaics of grasslands and woods into extensive regions of contiguous grasslands or forests (Flannery 1994).

Progressively, the horse, train, automobile, and aircraft have extended the ambit for human choices from local to regional and thence to planetary scales, but the time allotted for each of these choices has changed little, or even 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 hundred kilometers by commuter aircraft. The slope of the decision panarchy for humans, if plotted in the same space as in Figures 1–3, now angles sharply upward, intersecting and dominating other panarchies of nature.

Assessing Sustainability

The current state of our understanding of panarchies is summarized in Table 2. The theory is sufficiently new that its practical application to regional questions or the analysis of specific problems has just begun. Panarchy theory focuses on the critical features that affect or trigger reorganization and transformation in a system. First, the back-loop of the cycles is the phase where resilience and opportunity is maintained or created, via "release" and "reorganization" (Figures 4 and 5). Second, the connections between levels of the panarchy are where persistence (via "remembrance") and evolvability (via "revolt") (Figure 7) are maintained.

These four phases or processes make up the four R's of sustainability and development: release, reorganization, remembrance, and revolt. They provide new categories that can be used to organize the more specific indicators and attributes discussed in documents aimed at finding ways to evaluate sustainability and development.

To summarize: The panarchy describes how a healthy socioecological system can invent and experiment, benefiting from inventions that create opportunity while it is kept safe from those that destabilize the system due to their nature or excessive exuberance. 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. The whole panarchy is therefore both creative and conserving. The interactions between cycles in a panarchy combines learning with continuity.

The four R's, then, represent the critical processes that manage the balance and tension between change and sustainability.

It is often useful to begin the analysis of a specific problem with a historical reconstruction of the events that have occurred, focusing on the surprises and crises that have arisen as a result of both external influences and internal instabilities. In essence, a sequence of adaptive cycles can be described, for the so-called natural system, the economy, management agencies, users, and politics. We think it is necessary to consider three scale ranges for each system, although the particular scales might be different for different subsystems. One of the principal aims is to define where in their respective adaptive cycles each of the subsystems is now. Actions that would be appropriate at one phase of the cycle might not be appropriate at other phases. Knowing where you are helps you to define what action needs to be taken.

In many instances, the motive for an assessment is a crisis or transformation that has already occurred or is anticipated. In these situations, the conditions of the back loop of the adaptive cycle (Figure 4) dominate. However, it is these times of greatest threat that offer the greatest opportunity, because many constraints have been removed. In an insightful analysis of local communities as seen from this perspective, Berkes and Folke (2001) showed that local societies often develop reserves that are necessary during back-loop restructuring. In the same book, Westley (2001) presented an equally incisive analysis of a sequence of decisions and actions taken in specific examples of problem solving by a resource manager. Figure 9 provides an example of the kind of analysis that is possible.

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

Because a unique combination of separate developments has to conspire to occur simultaneously, extreme events are rare. Some developments emerge within adaptive cycles during the back loop of the cycle, when recombinations and external

Table 2. Summary Findings from the Assessment of Resilience in Ecosystems, Economies, and Institutions

Statement	Brief Explanation
Multistable states are common in many systems.	Abrupt shifts among a multiplicity of very different stable domains are plausible in regional ecosystems, some economic systems, and some political systems.
The adaptive cycle is a fundamental unit of dynamic change.	An adaptive cycle that aggregates resources and that periodically restructures to create opportunities for innovation is a fundamental unit for understanding complex systems, from cells to ecosystems to societies to cultures.
Not all adaptive cycles are the same and some are maladaptive.	Variants to the adaptive cycle are present in different systems. These include physical systems (because of the absence of mutations of elements), ecosystems strongly influenced by external pulses, and human systems with foresight and adaptive methods to stabilize variability. Some systems are maladaptive and trigger poverty and rigidity traps.
Sustainability requires both change and persistence.	We propose that sustainability is maintained by relationships that can be interpreted as a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time—the panarchy.
Self-organization shapes long-term change.	Self-organization of ecological systems establishes the arena for evolutionary change. Self-organization of human institutional patterns establishes the arena for future sustainable opportunity.
There are three types of learning.	Panarchies identify three types of change, each of which can generate a different kind of learning: (a) incremental (r to K, Figure 4), (b) lurching, (Ω to α, Figure 4), and (c) transforming.
The world is lumpy.	Attributes of biological and human entities form clumped patterns that reflect panarchical organization, create diversity, and contribute to resilience and sustainability.
Functional diversity builds resilience.	Functional groups across size classes of organisms maintain ecosystem resilience.
Tractability comes from a "Rule of Hand."	The minimal complexity needed to understand a panarchy and its adaptive cycles requires at least three to five key interacting components, three qualitatively different speeds, nonlinear causation. Vulnerability and resilience change with the slow variables; spatial contagion and biotic legacies generate self-organized patterns over scales in space and time.
Emergent behavior emerges from integrated systems.	Linked ecological, economic, and social systems can behave differently from their parts. Integrated systems exhibit emergent behavior if they have strong connectivity between the human and ecological components and if they have key characteristics of nonlinearity and complexity as suggested in the "Rule of Hand."
Management must take surprise and unpredictability into consideration.	Managing complex systems requires confronting multiple uncertainties. These can arise from technical considerations, such as models or analytic frameworks. The examples suggest that as much complexity exists in the social dimensions as in the ecological ones and that managers must juggle shifting objectives.
Is adaptive management an answer?	For linked ecological/social/economic systems, slow variables, multistable behaviors, and stochasticity cause active adaptive management to outperform optimization approaches that seek stable targets.

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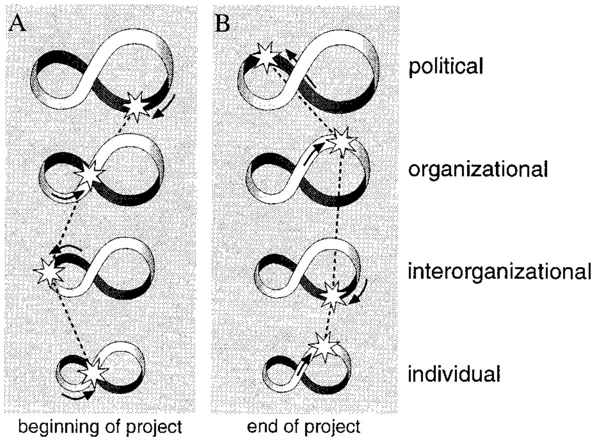

Figure 9. Separate adaptive cycles are used to depict phases of issues as interpreted in four systems—political, organizational, interorganizational, and individual. Managers' actions and solutions must account for these dynamics of these systems (Westley 2001). (Reprinted from Gunderson and Holling 2001 with permission of Island Press)

influences can generate unexpected new seeds of opportunity that can nucleate and modify the subsequent phase of growth. So long as connections are maintained with other levels, those innovations are contained and do not propagate to other levels.

But if these recombinations and inventions accumulate independently in a number of adjacent levels, a time will come when the phases of several neighboring cycles become coincident, and each becomes poised as an accident waiting to happen in a shift from Ω to α. Windows open that can then allow those independent inventions and adaptations to interact, producing a cascade of novel self-organized patterns across a panarchy and creating fundamental new opportunity. There is an "alignment of the stars." Such a coincidence in phases of vulnerability at multiple scales is quite rare. That is, true revolutionary transformations are rare, whether in systems of people or systems in nature.

Under conditions of crisis in a region, the elements of a prescription for facilitating constructive change are as follows:

- Identify and reduce destructive constraints and inhibitions on change, such as perverse subsidies.
- Protect and preserve the accumulated experience on which change will be based.
- Stimulate innovation and communicate the results in a variety of fail-safe experiments designed to probe possible directions in a way that is low in costs in terms of human careers and organizational budgets.
- Encourage new foundations for renewal that build and sustain the capacity of people, economies, and nature to deal with change.
- Encourage programs to expand an understanding of change and communicate it to citizens, businesses, and people at different levels of administration and governance, engaging them in the process of change.

A principal conclusion from the Resilience Project is that the era of ecosystem management via incremental increases in efficiency is over. We are now in an era of transformation, in which ecosystem management must build and maintain ecological resilience as well as the social flexibility needed to cope, innovate, and adapt.

ACKNOWLEDGMENTS

This paper draws extensively on Gunderson and Holling, (2001), particularly the three chapters I wrote with my colleagues Buz Brock, Steve Carpenter, Lance Gunderson, and Garry Peterson. Along with Carl Folke and Brian Walker, they served as the co-organizers of the Resilience Project, which provided the crucible for these ideas, models, and examples. I thank these marvelous friends and collaborators for their contributions, their inspiration, and their imagination. But all of the authors who contributed to the book were equally important to the development of these ideas. They comprised an international group of ecologists, economists, social scientists, and mathematicians whose depth of knowledge in their respective areas helped to produce a very real synthesis. In addition to those just mentioned above, they include Nick Abel, Fikret Berkes, Pille Bunnell, Gilberto Gallopin, Milena Holmgren, Marco Janssen, Don Ludwig, Karl-Göran Mäler, Charles Perrings, Rusty Pritchard, Steve Sanderson, Marten Scheffer, Frances Westley, and Ralf Yorque. Over the 5 years of the project, we became the best of friends and collaborators. Finally, I thank the MacArthur Foundation for the support of a grant and Dan Martin of the MacArthur Foundation for his sustained advice and help.

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