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4

Redundancy and diversity: do they influence optimal management?

BOBBI LOW, ELINOR OSTROM, CARL SIMON, AND JAMES WILSON

> The command-and-control approach, when extended uncritically to treatment of natural resources, often results in unforeseen and undesirable consequences. A frequent, perhaps universal result of command and control as applied to natural resource management is reduction of the range of natural variation of systems – their structure, function, or both – in an attempt to increase their predictability or stability.
>
> (Holling and Meffe, 1996: 329).

4.1 Introduction

In many fields, there are fashions in favored approaches – what is assumed to be 'best.' A recurrent theme in American academia – particularly among students of public administration, policy analysis, and resource economics – has been to criticize 'redundancy' in government, decrying the number of governments that exist in the USA and the competition that exists among them. Consider education policy: beliefs that large numbers of schools were inefficient and that massive consolidation would be effective led to the reduction of 'redundant' school districts in a massive campaign during the first half of the twentieth century. In 1932, there were almost 130 000 school districts in the USA. This number was halved by 1952 and quartered by 1962, and halved once again by the early 1970s. The massive consolidation of school districts has slowed down during the past two decades. However, today we have around 15 000 school districts in the USA for a population that has almost doubled since the campaign to consolidate schools was initiated (see Ostrom, Bish, and Ostrom, 1988). During the heat of this policy reform, research was almost non-existent on the effect of school size, number of schools in a region, and related issues. Since the 1970s, considerable research on the effects of these variables on school performance has provided contrary evidence to the implicit theory used by policy makers to support the school consolidation movement. A recent study for the National Bureau of Economic Research, for example, finds that having a larger number of schools in a metropolitan area is associated with higher average student performance (as measured by students' educational attainment, local wages, and test scores). These areas were also characterized by lower per-pupil spending (Hoxby, 1994; see also Pritchett and Filmer, 1999). Now, after years of trying to increase size and reduce numbers of schools, policy makers are reconsidering the consequences of these past reforms and recommending new efforts to create more responsive schools through a variety of structural reforms.

Similarly, earlier empirical studies of redundancy in public services found that redundancy did not have the adverse consequences frequently attributed to it and that improvements (rather than reductions) in performance were frequently associated with redundant arrangements.[1] During the 1960s and 1970s, the 'Metropolitan Reform' movement was the dominant way of thinking about urban government (see Hawley and Zimmer, 1970). The existence of many units of government, seen as redundant and inefficient, was thought to cause many problems. Multiple units of government were further viewed as competitive, and providing a means whereby the rich could escape without contributing to the provision of public services needed by the poor and disadvantaged living in the central city (reviewed in Stephens and Wikstrom, 1999; Hawkins and Ihrke, 1999).[2] But fashions change. In the 1990s, scholars called for the elimination of all of the redundant suburbs by creating one city for a metropolitan area (Rusk, 1993), at the same time as other problems were seen as best solved by extensive stakeholder analyses.

Fashions have influenced the management of ecosystems as well. Over time, ecological 'redundancy,' of multiple similar species, was seen as buffering an ecosystem from stresses. Yet, in contrast, because ecosystems were seen as complex and because of actors' ignorance and self-interest, centralized rules were seen as necessary to restrain local actions that were injurious to the interests of the broader society. This reasoning influenced the formation of important national laws (in the USA the Clean Air Act, Clean Water Act, Fisheries Conservation and Management Act) and international protocols (e.g., Kyoto). All of these initiatives were designed to address large-scale ecological problems; all tend toward the creation of 'one-size-fits-all' rules. It is no surprise that such attempts have problems: both scale and conflicting self-interest of actors can be difficult. Nation-states might attempt to subvert international plans so they may continue to pollute their neighbors; states and provinces argue against national rules so that they might pass their environmental costs on to their neighbors, and so on. Although the perceived need for centralization may be softened in clear instances of local heterogeneity (see below), redundancy among local units is, in some circles, viewed as giving rise to and encouraging collective dilemmas.

These examples raise a puzzle for anyone interested in establishing effective governance arrangements. The systems are complex, and it is difficult to imagine how to test for efficiency in appropriate ways. We know little about what *level of redundancy*, from zero to complete, would be optimal. Common-sense arguments have frequently been used as the foundation for policy: some relationships are thought to be self-evident. Action is proposed on the basis of these self-evident truths – but without testing the 'self-evident' hypotheses. When reforms are based on self-evident 'truths' that do not have a solid empirical and theoretical foundation, they can generate counterproductive results – as they have with American schools.

We suggest that it is short-sighted and ineffective to derive policy from untested assumptions. Both the 'redundancy is inefficient' and the countervailing 'local decisions are best' approaches seem too often to be prescriptions, rather than decisions arising from analysis of function. Here we examine redundancy as a widespread attribute of many types of systems: genetic, human engineered, complex adaptive, ecological, and governance systems. We define functionally different kinds of redundancy, and suggest a path for deciding the optimal level of redundancy in particular systems.

4.1.1 Challenged policy assumptions

No single model describes governance of ecological resources, and often there is debate. However, many important contemporary environmental policies rest on critical assumptions we wish to challenge. These include:

- Ecological organization is characterized by high levels of connectivity over large spatial scales. Hence, 'management over the range' (of connectivity) is necessary.
- Local users of natural resources cannot really be trusted to take a long-term perspective and to pay attention to the externalities they cause, because their short-term interests are seldom the same as those of the greater group or the ecosystem itself. Local users, trapped in dilemmas, will overuse or even destroy valuable resources unless they are prevented from doing so by government action.
- It is possible to plan for the efficient and equitable use of resources covering a large region – to design an optimal one-size-fits-all management system – by doing systematic analysis for a region as a whole. This assumes that existing variability within the region is irrelevant to efficient design.
- Organization or order is generated by centralized direction, generally through hierarchical systems of superior–subordinate relationships.
- The presence of a large number of governance regimes is a sign of inefficiency.

Under these assumptions, ideal management would involve a single governmental unit devising rules for managing local resources, and ensuring that these rules are monitored and enforced. Redundancy or diversity of resource-governance units would be inefficient. However, many natural resource regimes are locally self-organized and quite robust and functional, in contrast to the assumptions above (e.g., Ostrom, 1990; Baland and Platteau, 1996). In the Maine lobster fishery, for example, self-organizing groups tend to arise in local fishing areas (Acheson, 1993; Wilson, 1997). They probably number up to a hundred along the coast. Such actors seldom all use the same rules for either organization or resource utilization. Knowledge about how these local systems operate – and sometimes even their existence – often does not exist in a state or regional center, let alone the national capital. We think there are conditions in which redundancy and diversity at a local level enhance performance – as long as there are also overlapping units of government that can: (1) resolve conflicts, (2) aggregate knowledge across diverse units, and (3) insure that when problems occur in smaller units, a larger unit can temporarily step in if needed.

4.1.2 Is it time to reconsider redundancy?

Rather than prescriptions, which often arise from over-generalizing specific results, we seek to define and analyze redundancy across systems (see Low *et al.*, 1999, Costanza *et al.*, 2001). We examine redundancy not as *always costly*, or *absolutely required*, but simply as one attribute of a system, with consequences for the way a system performs – under some conditions improving, under other conditions decreasing, overall system performance. Costs are always associated with redundancy, because building more than one unit involves the use of energy, materials, and time that could be used for other purposes. System performance can, in turn, be measured along multiple dimensions, e.g., capacity to cope with risk and uncertainty; adaptation to exogenous change; error reduction through repetitive learning or through learning from others; matching system responses to local conditions; and ability to reduce the probability of system failure. Whether the benefits (of improved system performance) are worth the costs (of added time, effort, and resources used to build multiple units) of redundancy depends on: (1) the type of problems faced in governing a system, (2) how the particular kind of redundancy copes with these problems, and (3) the cost of the particular type of redundancy. In any system, we should be able to calculate an *optimal level of redundancy*.

Many natural systems – genetic, ecological, physiological, and behavioral – exhibit considerable redundancy, of various types. The existence of apparently profitable redundancy in natural systems suggests that it is time to re-examine the effects of redundancy in policy decisions. Consider, for example: most ecosystems exhibit some biodiversity – much of which constitutes functional redundancy from the perspective of the entire ecosystem (see below). Examine the trophic structure of most healthy ecosystems, and you will find numerous herbivores whose diets are not identical, but similar. This 'redundancy' renders the system relatively robust in the face of exogenous changes. From a manager's perspective, redundancy, and resulting robustness, mean many management decisions are relatively safe, unlikely to precipitate ecological crises. (We note, however, that from a genetic diversity perspective, or that of a conservation biologist, similar species are not, in fact, redundant.)

Here we examine redundancy in several systems. In genetic systems, there has been substantial recent research to determine why genomes appear so redundant. In engineering and information systems there has been a self-conscious effort to understand the importance of redundancy. We examine the role of redundancy in contemporary theory of complex adaptive systems. Redundancy in ecological systems challenges several assumptions: that most resource systems are so thoroughly interconnected that they must be considered as one large system governed by one large, administrative entity. We then examine governance systems, in which it appears that redundancy can buffer the system in the face of decision errors. We conclude that, despite the complexity and superficial diversity, in all these systems: (1) there is some optimum level of redundancy, depending on a variety of conditions (e.g., ecological, technological, institutional, informational); and (2) redundancy arises, is maintained, or disappears in different systems, as a result of its benefits and costs to actors at different levels.

4.2 The meanings of redundancy

'Redundancy' is defined by the *Oxford English Dictionary* (OED) as 'the state or quality of being redundant; superfluity, superabundance;' 'redundant' is further defined as 'excessive, abounding too much.' The word, paradoxically, has substantially different meanings in the fields we survey, yet most, like the definition from the OED, carry a negative connotation. We argue that understanding function would change our view of redundancy as 'superfluity.' This has happened in some fields already. In cybernetics dictionaries, redundancy is defined as one minus the ratio of the actual uncertainty to the maximum uncertainty. That is, redundancy does not increase the amount of information actually transmitted, but is essential to combat noise, to assure reliability, and to maintain communication (e.g., http://pespmc1.vub.ac.be/ASC/REDUNDANCY.html).

In most of our discussions, we refer to redundancy of multiple *units* (building blocks) within some larger *system*. The units may be genes in an individual, individuals in a community, physical parts in an engineered object, jobs in a political or social organization, firms in an industry – any organized subunits (themselves composed of other units or parts), or anything that is itself part of a larger system. The functional form of the units differs and so must the appropriate level of focus. We identify the following kinds of redundancy (Table 4.1).

4.2.1 Redundancy within a level of a multi-level system

1. *Multiple identical in-use copies (of rules or units).* This is common in genetic systems and human-designed systems, for example, and can serve two functions:
    (a) *Encounter rates.* The existence of multiple exits in a commercial airliner means that, in emergencies, any passenger, regardless of seat location, is likely to find an exit quickly. In city police departments, the assignment of numerous foot-patrolmen in local neighborhoods has been considered redundant – but the probable encounter rate (of children needing directions, small break-ins) is increased. One might argue that there are 'too many' gas stations – but the more gas stations, the better the encounter rate for consumers.
    (b) *Dosage–response* curve. If each unit contributes similar strength of response, multiple copies confer increased total strength. The evolution of pesticide resistance in mosquitoes, discussed below, exemplifies this kind of redundancy: identical copies of a resistant allele confer additive resistance. Similarly, local riot control effectiveness is, over some range, a function of the number of police assigned.
2. *Multiple similar in-use copies.* The production of similar – but not identical – antibodies means that, as a pathogen counters the currently most-effective antibody, new variations exist to confer immunity to the host. At a slightly different level, the evolution of gametic sex is a device that produces novel genetic combinations in new offspring: meiosis 'scrambles' genetic material, to produce haploid 'samples' of genetic combinations in egg and sperm, for combining with gametes of another individual. The resulting diversity of genetic combinations in offspring is advantageous in changing environments (e.g., see Williams, 1975; Maynard Smith, 1978). Economic competitors faced with a heterogeneous consumer environment develop a variety of differentiated products to cope successfully with changing and heterogeneous tastes. Chess and checkers strategies proliferate as slight variants on standard ploys.

Table 4.1 *Kinds of redundancy in selected systems*

		Kind of system			
	Proposed advantages	Genetic	Genetic algorithms	Designed physical systems	Governance
Within 'level'	Identical multiple in-use copies Encounter rates	R	R	R	R, L
	Multiple in-use copies Dose response	Ch		Ch, R	R, L
	Nonidentical multiple in-use copies	L	L, Exp, Err	L, Exp	L, Err
	Many rules → one outcome	R, Ch	L	Ch, R	Err
	Spare tires	——	——	R, Ch	Ch, R
	Reduced margin of error in designed systems			Ch, R	R, Ch, Err
Horizontal units at 1 level	Multiple nonidentical units	L, Ch, Exp, R	L	(?)	Ch, Exp
Multi-level	High-level rules general Low-level rules specific	L, Ch	Ch, R	Ch, R	Ch, R, Rec
	Duplication of rules low and high		(?)		R, C, Rec
	Occasionally high replaces low		(?)	R, C	R, C, Rec

L = matching local conditions ('requisite variety') – nonuniform response to nonuniform conditions; Ch = response to exogenous change – large stresses (pesticides–mosquito, acts of God), – nonuniform responses to nonuniform stresses; Exp = experimentation (from L) (and learning from others) – V-notch (Newfoundland) – municipal associations and their communities, – faster exploration of solution space; R = Risk reduction – backup systems within unit; C = Reducing cost of institutional failure – high/low (Nixon grand jury), – low/high (Segregation, Spotted Owl); Err = Error reduction through repetitive learning – repetitive learning; Rec = Recombination to find appropriate scale – joint powers agreement, V-notch (Mass).

3. *Many rules, one outcome.* In genetic coding systems, considerable redundancy exists (e.g., Hurst, 1996; Freeland and Hurst, 1998). For example, there are 16 amino acids – but 3^3 ways of coding for them. This means that a deleterious mutation in one of the coding sites does not result in loss of the (essential) amino acid – a sort of insurance policy to avoid the risk of mistakes in one-to-one coding.
4. *Backup systems not currently in use ('spare tires').* Such devices, as with point 3, function to reduce risk of failure. John Doyle (see below) has estimated that a few hundred systems could run a Boeing 777 if no uncertainties were faced; instead, there are some 150 000 systems.
5. *Redundant strength to reduce margin of error.* An example of this is common, initially costly insurance against potential extreme conditions and unforeseen changes. For example, gaps in bridges are often larger than apparently necessary, to accommodate later expansion and contraction in hot and cold conditions. Daily and Ehrlich (1995: 55) stress that 'Society should no more assume abundant functional redundancy among population and species and exterminate them *ad lib* than a pilot should pop rivets from the wing of an aircraft and sell them based on a similar redundancy assumption.'

4.2.2 Redundancies across multiple levels

6. *General high-level rules, specific low-level rules.* This is a common design in genetic algorithm systems, as well as in many governance systems. A constitution, for example, provides general powers to specific government units. Within these constitutional rules, the units establish public policies that specify general rights and duties for participants in the polity. Participants, in turn, create many operational rules about specific activities that are consistent with public policies and constitutional rules. Thus, there are always at least three levels of rules operating in governance systems.
7. *Duplication of high-level and low-level rules.* The criminal codes of lower jurisdiction frequently duplicate some of the criminal code of a higher-level jurisdiction. If the one level does not prosecute a suspected criminal, the other system is potentially available. (In American jurisprudence, a person does not have to stand trial in both jurisdictions, so the potential double jeopardy is eliminated once proceedings are completed by one level.)
8. *Occasional replacement of rules at one level by rules at another level.* In engineered systems, this reduces the risk of failure or human error (e.g., ABS braking systems). In federal systems, the national government may decide to regulate some area of activity due to previously nonexistent 'spillovers.' The regulation of banking in the USA was largely handled at the state level until Congress allowed banks to cross state lines – opening up the need for much more regulation at the national level (Polski, 2000).

These examples may seem diverse and unconnected; in fact, there are real homologies. Particular functional kinds of redundancy occur in systems not usually thought of as related – yet the function of redundancy is similar in the different systems. Many of the statements about redundancy in governance systems, for example, have parallels in the immune system's antibodies (see Farmer, Packard, and Perelson, 1986).

Several points are important here.

1. In genetic, ecological, political, and market systems, redundancy is likely to arise from the self-interest of the redundant units (e.g., Ostrom 1987, 1991, 1997). It may continue to exist even when it has no positive effect on the entire system, and will be lost only if it creates such severe costs that the entire system fails. In contrast, in such human-designed phenomena as engineered systems, there is strong selection on the entire system's coherence, and redundancy may be designed in for the sake of functionality of the entire system.
2. Repetition of identical or similar units may, or may not, fit the OED explanation of 'superfluity,' depending on whether they have functional importance.
3. Governance systems show parallels to other systems in many kinds of redundancy (Table 4.1) – but in many cases we have as yet insufficient information about the associated costs and benefits to define optimal levels of redundancy.

4.2.3 Redundancy in genetic systems

Geneticists have puzzled for a long time over the existence of repetitions – redundancies – and apparent nonsense genes in genomes. Organisms have many genes: the smallest known genome in nature is almost twice the size of best estimates for the minimal necessary genome (Maniloff, 1996), and genetic redundancy appears to be common (e.g., Goldstein and Holsinger, 1992; Tautz, 1992; Thomas, 1993; Brookfield, 1997). However, clues exist: for example, 'despite the apparent redundancy in the yeast genome, more than half of all yeast genes contribute detectably to competitive fitness' (Smith *et al.*, 1996: 2073). Although a duplication can arise and become fixed through drift, clearly the rate of fixation results from the relative advantage (or disadvantage) of the duplication for the organism (e.g., as a buffer: Clark, 1994). Nowak *et al.* (1997) modeled four cases that explain the commonness of genetic redundancy; in three of the four cases, redundancy is stable. Wagner (2000) noted that, along with overlapping gene function, 'one or more genes with similar functions' (redundancy) is a principal mechanism protecting an organism's physiological and developmental processes from the deleterious effects of mutation.

Gene duplications arise spontaneously at high rates in bacteria, bacteriophages, insects, and mammals. They are generally viable (Fryxell, 1996), but only a small fraction of all duplicated genes is retained, and an even smaller proportion evolves new functions, because the probability of 'nonfunctionalization' is comparatively high. Nonetheless, in very large populations, there may be a significant probability of a duplicated gene evolving a new function (Walsh, 1995; Nadeau and Sankoff, 1997).

As we examine genomes more closely and learn more, we discover that many duplicate genes and apparent 'nonsense' genes are in fact functional. Clearly duplication may serve the interests of the duplicated unit. It is more interesting to ask when duplication serves the interests of the whole genome – the organism. Clark's (1994) models show clearly that any duplication can only invade when it provides a *direct advantage to the organism*. Invariant repetitions (redundant copies) of gene sequences may occur when some threshold level of a genetic product is important. This type of redundancy is advantageous (and common) when there exists a metabolic need to produce large quantities of specific RNAs or proteins (Ohno, 1970). An increase in the number of genes can occur quite rapidly under selection for increased amounts of a gene product. Some spectacular examples include the evolution of resistance to organophosphorous insecticides in aphids (Field and Devonshire, 1998), mosquitoes, and *Drosophila* (Mouchès *et al.*, 1986; Maroni *et al.*, 1987; Callaghan *et al.*, 1998). Each gene contributes some amount of resistance, and repeated genes mean increased resistance.

Genes that are spatially separated from other genes that work with them are more likely than nearby genes to become duplicated as a form of risk reduction. Because genetic material can 'cross over' in replication, a gene can become further separated from its necessary co-genes (and, after meiosis to form egg or sperm, it may end up in a different sex cell – with loss of function). Loss of a single-copy gene is usually deleterious. There are two solutions: spatial clustering ('supergenes') of genes that work together, or duplication of separated genes.

Frequently, a nonfunctional (silent) pseudogene arises from a duplicate allele. Perhaps because these are typically harmless (duplicates exist), they may be maintained. Many have been documented: the human pseudogene *yh* in the β-globulin family contains numerous defects. Chimpanzees and gorillas, our closest relatives, have the same number of genes and pseudogenes as humans, suggesting that the pseudogene arose before the species diverged. Here is a redundancy that may have no positive benefit, but does not appear to cost the organism. Even when duplicates have no advantage, they may go to fixation, suggesting that costs are low (Clark, 1994). We should be cautious, however. Wagner (1999) calculated mean equilibrium redundancy (which depends on fitness effects of mutations); he noted that while selection will slow the 'decay' of redundancy caused by mutation and genetic drift, some mutations may only be 'neutral' because their effects on gene products are absorbed by the epigenetic system.

Novel function can arise after duplications; when this occurs, the original redundancy disappears. Some complex genes may have arisen this way: ovomucoid gene, $\alpha 2$ allele of haptoglobin, antifreeze glycoprotein genes (Graur and Li, 2000: 259–63, Table 6.1). 'Variant repeats' are copies with small differences (multiple nonidentical copies), as in the knirps and knirps-related genes in *Drosophila* (González-Gaitán *et al.*, 1994). The repeats occasionally come to perform new or different functions (e.g., thrombin and trypsin, lactalbumin and lysozyme). Differentiation typically requires a large number of substitutions, so one would think this sort of duplication-leading-to-new-function would be rare. However, sometimes surprisingly few substitutions after duplication can give rise to novel functions. For example, lactate dehydrogenase can be converted into malate dehydrogenase by replacing just one of 317 amino acids (Graur and Li, 2000: 264). This kind of redundancy allows rather cheap experimentation. We could view the evolution of pleiotropy and divergence in function over time as a trade-off between two countervailing forces: mutation, which tends to add diversity, and selection for robustness and resilience (Wagner, 1998, 2000).

Larger-scale redundancies are more complicated to understand. A well-known deleterious example is Down's syndrome, a type of polysomy (duplication of a complete chromosome) called trisomy 21. Repetition of whole chromosomes seems to be disadvantageous, and this kind of redundancy is rare.

At an even larger scale, polyploidization is the addition of one or more complete sets of chromosomes to the original set. When genetically distinct sets of chromosomes are combined (as is common in plants), the condition is called allopolyploidy. Autopolyploidy (especially autotetraploidy) occurs in many organisms (Nagl, 1990). However, tetraploids seem to have survived rarely: they suffer prolonged division time, increased nucleus volume, increased chromosomal disjunctions, and other difficulties. In these cases, redundancy gives rise not only to slower function, but also to internal dysfunctions. A few cases of fully functional tetraploidy are known, in which the duplication has no effect on the phenotype (e.g., the flowers *Chrysanthemum* and *Rosa*, the leptodactylid frog *Odontophrynus*, and goldfish).

In some plants, polyploidy reduces inhibitions to selfing and hybrid infertility, so that individual plants isolated at the edge of a habitat can reproduce by selfing (e.g., Stebbins, 1974) – an advantage. In those cases in which polyploidy 'works,' an ancient polyploid is no longer distinguishable today from a diploid (Cavalier-Smith, 1985). Thus, the large size of some genomes may reflect assimilated genetic redundancy.

The bottom line is that certain generalities hold for a variety of (otherwise apparently unrelated) cases of genetic redundancy: redundancy typically serves the interests of the duplicated unit; and redundancy may or may not serve the interests of any larger unit in which it is embedded. In genetic systems, the persistence and/or proliferation of replicated subunit depends in part on the relative *efficiency* of large units with replicated subunits, compared to those without. This may involve efficiency of communication and ability to respond to stimuli (see Tautz, 1992; Clark, 1994; Wagner, 1998, 2000).

When will replication serve the interests of both the replicator and the larger group? We can think of several conditions: when conditions differ for subunits ('experimental' nonidentical units); when replication increases the total response possible (as in the development of pesticide resistance in mosquitoes). In contrast, there are cases in which what is ideal from the point of view of the replicated unit may be costly from the viewpoint of the larger unit (e.g., 'outlaw' genes, driving Y chromosomes). In these cases, persistence of the replicated unit will depend on the relative ability of the replicated subunit to protect itself from elimination or consolidation by the whole group.

4.2.4 Redundancy in engineering systems

Genetic systems (and their mimic, genetic algorithms: Holland, 1995) begin with some elements of randomization; then the relative survival and reproduction of the elements result from differential performance. Indeed, in some complex manufacturing problems, this approach has been used with great success (Norman and Bean, 1999). In most engineered systems, however, the intent is to design in optimality from the start.

Redundancy, because it has costs, might seem suboptimal, but many systems must function in a variety of environments. Further, when failure would be very costly (e.g., engine failure in an airplane), the expense of redundant elements may be worthwhile. The 'robust integration of systems of systems' (Carson and Doyle, 1999) can provide reliable performance in changing and uncertain environments. Consider the Internet, the portable compact disk player, VLSI design, the Boeing 777, and the Mars Pathfinder as examples of the robust integration of systems of systems. As John Doyle (1999) noted:

> The Boeing 777 has millions of parts, mostly rivets, but 150,000 distinct subsystems, many of which are themselves highly complex components . . . What's important, though, is that the overwhelming proportion of the millions of parts in a modern commercial aircraft or the thousands of genes in biological organisms, is there purely for robustness and uncertainty management. For the 777, some uncertainties are flight timing, weather, routing, other traffic, turbulence in the boundary layer, payload size and location, uncertainty in components due to manufacturing and aging, and so on . . . Now imagine an idealized laboratory setting in which uncertainty is greatly reduced or eliminated . . . For the case of the idealized 777, a working vehicle could probably be built with a few hundred subsystems, rather than 150,000 . . . This interplay between complexity and robustness . . . is both the most essential issue in complex systems, and the least understood . . . Major success stories, such as . . . the Boeing 777, have been the result of highly structured and systematic processes, with an almost obsessive attention to robustness.

Computer design follows similar principles. Consider the following, from an Intel Application Note (Intel LXT332 Redundancy Applications; http://developer.intel.com):

> The primary concern in most high speed data networks is reliability. Redundancy is one way to protect and ensure reliability in the event of catastrophic failure. At low data rates, redundancy may not make sense, but as the number of lower data ports are multiplexed to the higher bit streams, it begins to play a major role. Because of this, most major network multiplexers and bandwidth managers use redundancy techniques to ensure data integrity.

In this industry, also, are some of the most developed procedures for analyzing the costs and benefits of redundancy (e.g., Hampson, 1997).

4.2.5 Redundancy in ecological systems

In ecosystems, 'redundancy' raises questions of biodiversity and ecosystem function (e.g., Frank and McNaughton, 1991; Naeem and Li, 1997; Grime, 1998). Here, redundancy is typically of the 'multiple nonidentical copies' sort within ecosystems, or across ecosystems. Ecology has a history of postulating that species diversity enhanced primary productivity, stability, resistance to invaders (e.g., MacArthur, 1955; Margalef, 1969; Frank and McNaughton, 1991; McGrady-Steed, Harris, and Morin 1997; Naeem and Li, 1997), and resilience. The reality is much more complicated (e.g., Tilman, 1996; McGrady-Steed *et al.*, 1997; Symstad *et al.*, 1998; Naeem, Hahn, and Schuurman, 2000; Lehman and Tilman, 2000), and still in dispute (e.g., Finlay, Maberly, and Cooper, 1997; Grime, 1997; Wardle, Bonner, and Nicholson, 1997; Bengtsson, 1998; Hodgson, Thompson, and Wilson, 1998 (and the commentary that follows); Andren and Balandreau, 1999).

Does species, or functional, redundancy influence how ecological systems react to external and internal changes? Scholars today suggest that, within ecosystems, functional redundancy (different species occupying roughly the same niches) can, if co-dependencies are not too developed, often afford resiliency to the ecosystem (e.g., Risser, 1995; Tilman, 1996; Grime, 1998; Naeem *et al.*, 2000; Lehman and Tilman, 2000). Greater temporal stability appears to be afforded by higher productivity at higher diversity, and competitive interactions. The relative importance of each varies at different levels of diversity (Lehman and Tilman, 2000), and few broad generalizations are possible. Scale is very important (e.g., Pankhurst *et al.*, 1996; Groffman and Bohlen, 1999), and empirical results can support either the 'null' or the 'resilience' hypothesis. For example, in rangeland ecosystems, it is the communities with greater species diversity (and thus presumed redundancy) that are most easily and often invaded by new colonizer species (Levine, 2000)!

It used to be fashionable in environmental circles to repeat the mantra 'everything is connected to everything else.' Perhaps this was once a useful caution, even if untrue (Budiansky, 1995: 56–64). But we are better served by real understanding, rather than rhetoric, as Levins (1992) noted:

> All things are indeed connected if we follow chains of causation through their devious twists and turns. But everything is not strongly, directly or significantly connected to everything else. The analogy between an ecosystem and an individual organism simply does not hold up. The relation between, say, the liver and the heart is not the same as the relation between gazelles and gnus. The relative autonomy of linked subsystems is as important in understanding nature as their connectedness – we can in fact change some things without changing others – thus ecosystems are best understood not as harmoniously balanced wholes but as loosely coupled semi-autonomous sub-systems.

In other words, while there are important connections within ecosystems, they tend to be relatively important at local, rather than larger, levels. It is the *un*connectedness, or lack of critical dependence, that is important in analyzing redundancy. Most ecological 'connections' are spatially restricted and weak; further, their directions are unpredictable. If ecological systems were, in fact, unitary and fully connected, succession should indeed be (as early ecologists believed) a unitary phenomenon in any ecosystem, with a single endpoint. Rather, we find that (1) there is a significant element of chance in what species might arrive, (2) natural selection operates, so that (3) what particular species succeed depends on the specific local conditions. Thus, oak-hickory succession is not a singular phenomenon, but a multiply-replicated event, the outcome of which depends on local conditions. Yet oak-hickory successions are also recognizably similar, although the general relationships play out slightly differently depending on local conditions. The result is redundancy (multiple nonidentical in-use copies) of local, loosely connected ecological subunits.

In these important regards, ecosystems are qualitatively different from genetic systems, in which natural selection operates on the complex of genes carried in the organism (at the 'system' level), and engineering and political systems in which design for efficiency is deliberate. Natural selection affects the relative survival and reproduction of organisms most strongly; effects at the ecosystem level are, for the most part, simple epiphenomena. So, while managers may care about redundancy effects for our human ends, we have no evidence that redundant ecosystems always are, or are not, better in any way than simpler systems. This is the source of the complexity in the ecological literature (above).

In ecological systems, our desire for biodiversity as a contributor to stability in the face of fluctuations may rely more on the 'nonidentical' aspect of species redundancy than we have typically considered (references above). Ives, Klug, and Gross (2000), modeling complex communities from modular 'subcommunities' with random characteristics, found that it was not species diversity *per se* that generated stability, but rather the existence of species groupings with different characteristics – that community-level stability arises when species with a diversity of characteristics, sometimes overlapping, exist. Griffiths *et al.* (2000), in an empirical study, fumigated soil communities, progressively reducing soil microbial species diversity. There was no direct relationship between diversity and function: some functions (decomposition) were enhanced by reduced diversity, while others (nitrification) were compromised. Our concepts of species diversity may be enhanced by asking about the possible *kinds* of redundancy (see above) represented by examples of biodiversity.

Spatial redundancy (lesser-connected spatial repetitions) can benefit managers. It is precisely the relative independence of areas or subsystems that allows them to persist as natural areas near inhabited areas. A world in which everything *were* tightly connected to everything else would be a world in which wilderness areas, parks, greenways, and so on, might well disappear – small mistakes could have grave consequences. Very tightly connected systems are typically fragile and show little resilience (e.g., Drayton and Primack, 1996), which can be important as we increase the rate of disturbances. Systems with redundant and loosely connected subsystems, on the other hand, may change in many ways (particular species composition, exact spatial boundaries), yet persist relatively well. Had the natural areas been 'an inseparable part of the whole,' it is quite likely we would have lost much more biological diversity than we have.

From the perspective of human use, management, and exploitation of ecosystems, there is clearly some range of redundancy and connectedness that is optimal. But two things mean we cannot expect any particular level of redundancy – especially the level we desire – to eventuate. First, redundancy arises from interests of the redundant units, not the system as a whole. Second, there is no, or weak, feedback from ecosystem 'function' or 'health' on redundancy, except through failure of some ecosystems while others persist – and this process is not only slow, but has large random components. This suggests that ecosystem managers should not be sanguine in relying on ecosystem 'rules' inferred from whole ecosystem 'function.'[3] The optimal level of redundancy in any ecosystem is a managerial concept, not an evolved characteristic at the ecosystem level.

Two kinds of redundancy are especially important to managers. First, there is the redundancy of many similar (but not identical) subsystems (e.g., Ives *et al.*, 2000). Second, there is redundancy arising from the functional overlap of closely related species (functional redundancy of nonidentical species; cf. Naeem, 1998; McGrady-Steed and Morin, 1998; Griffiths *et al.*, 2000).[4] Both constitute risk reduction (cf. Walker, 1992; Walker, Kinzig, and Langridge, 1999) and multiple nonidentical in-use copies in our terms (see above). Both forms of redundancy may (or may not) contribute to an ecosystem's persistence in the face of external perturbations. Spatial redundancy of subsystems provides source populations for recolonization after local extinctions in nearby areas. The redundancy of species within functional groups means that, in the same area, the decline of one species may be 'compensated' (from a manager's point of view) by an increase in a different but functionally similar species. (Again, note that this does not speak to issues of biodiversity and genetic resources in any way.) Here is a further caution. Metapopulations may also exemplify a form of spatial redundancy. Relatively closely spaced populations (e.g., of fish species) may be reproductively independent.[5] Yet, as Wilson *et al.* (1999) note, this may not contribute to resilience; it can, in fact, present a danger if managers do not recognize the fact that populations have this spatially redundant structure. If we assume a single, large population, when in fact many small populations exist, we may inadvertently exterminate one after another of the small populations – we assume that recolonization will be swift (not true for a metapopulation). Under modest pressure, the redundancy is protective – but great pressure can collapse even very large systems.

Sometimes the redundancy of ecosystems, as in engineered and genetic systems, can buffer the systems – and us – from failures arising from our ignorance (e.g., of threshold effects). Perhaps because of this protection, some environmental policies tend to ignore the smaller-scale, subsystem aspects of ecosystems. This may not matter under many circumstances and for long periods of time (Low *et al.*, 1999, Wilson *et al.*, 1999); our errors may have relatively little effect in a redundant system. However, as human actions continue to erode any system (i.e., remove or degrade the subsystems that provide redundancy), there comes a point where the buffering capacity of the system is lost (Ames, Watson, and Wilson, 2000). At this point we are confronted with sudden, surprising – and usually undesirable – changes in the system.

As we noted above, sometimes we fail to recognize any impact until there are significant losses (e.g., species loss or dramatic declines in abundance). It is, in fact, hard to discern the difference between normal variability and changes that might be precursors of system collapse. For example, as some local or relatively independent fish populations are fished down, other nearby populations (often of a similar but not identical species) may grow and/or shift distribution to take advantage of newly available food sources. Compensation of this sort is common and expected, especially because large swings in species abundance are themselves common. As long as 'enough' redundant subsystems remain, 'normal' system patterns may still appear. Beyond a certain point, however, the ability of remaining subsystems to compensate (from a manager's point of view) for the loss or functional impairment of others reaches its limit. Then the view from the top is a view of a sudden and surprising decline, or even a catastrophic shift in system state (Carpenter, Ludwig, and Brock, 1999); whereas the view from below is of progressive loss of redundancy, leading to a threshold and sudden decline.

We are beginning to recognize that these subsystem losses (not only whole-system collapses) are important for issues of biodiversity. We suggest that policies and institutions that recognize, and respond to, the inherent redundancy of ecosystems are much less likely to be surprised by cumulative erosive actions. Further, there is a good possibility that institutions organized in ways that parallel the structure of the ecosystem are more likely to receive accurate and timely information about the state of the system, and to be able to respond in constructive ways (Costanza *et al.*, 2001). In other words, in multiscale systems a multiscale management hierarchy should be best suited to detect the onset of system-wide decline if change is buffered by local redundancies of some sort (Wilson, 2002).

4.3 Can redundancy reduce error and increase fit between preferences and outcomes in human decisions?

Contemporary public policy analysis assumes an individual knows all relevant options, has full information about the probability of particular outcomes of alternatives (given the actions of others), and has completely ordered preferences for outcomes. Yet such conditions are rare. The important work of Simon (1947) and Cyert and March (1963) assumed that humans have *limited* rationality that is *constrained* – constrained by the level of information present in a situation, by the limited attention that any individual can give to a myriad of potentially relevant facts, and by limits on the way that information is processed. These early arguments have been supported by considerable empirical research, especially by psychologists. We repeatedly find that decision makers overestimate their understanding of a problem, and underestimate the risk and uncertainty surrounding a problem. Kinder and Weiss (1978: 723), for example, note that 'decision-makers [are] more confident that they understand the problem and more satisfied that their policies will achieve the predicted ends than the evidence really justifies' (cited in Bendor, 1985: 292). If individuals behave with limited rationality, are organizational systems as unreliable as the individuals working within them?

Martin Landau (1969: 349), drawing on Von Neumann's (1956) work on reliability theory, argued that 'it makes a good deal of sense to regard a large-scale organization as a vast and complicated information system. It is, after all, necessarily and continuously engaged in the transmission and reception of messages.' Thus, within an administrative system, minor errors by one individual can be amplified as information is relayed, leading to major errors in final decisions. Error magnification is particularly problematic in systems or organizations that are strictly 'serial:' all subordinates report to a single supervisor who, in turn, reports to another supervisor. Yet exactly this type of system has been the favorite design of many scholars – particularly those teaching public administration. The logic of the preferred system of bureaucratic organization culminates in a central control point. 'The model which represents this dream is a linear organization in which everything is arrayed in tandem' (Landau, 1969: 354). Landau warned, however, that 'Organization systems of this sort are a form of administrative *brinksmanship*. They are extraordinary gambles. When one bulb goes, everything goes. Ordering parts in series makes them so dependent upon each other that any single failure can break the system' (*Ibid.*). Bendor (1985: 293) further analyzed the flaws in the conventional public administration advice to create streamlined decision-making systems:

> Thus, the proverb 'a chain is only as strong as its weakest link' is overly optimistic; a chain or series system is *weaker* than its weakest link. If, for example, the probability of completing acts A, B, and C is 0.9, 0.8, and 0.9, respectively, then the probability of completing the whole chain is, assuming statistical independence, $0.9 \times 0.8 \times 0.9 = 0.648$. This is less than its weakest link unless the probability of completing all the other links is one.

Landau proposed that adding 'sufficient' redundancy in administrative organization would make possible organizations that were more reliable than their individual human parts. Later, he noted that if the probability of failure in a particular system is 1 in 100, the probability of error if there were two duplicate systems would be 1 in 10 000, and if there were three such systems, it would be 1 in 1 million. Thus, 'the probability of failure decreases exponentially with arithmetic increases in duplication' (Landau, 1973: 187). Drawing on reliability theory, he cautioned that for the redundant parts of an administrative system to decrease the risk of serious errors, they need to operate independently and in such a manner '*that they cannot and do not impair other parts*' (Landau, 1969: 350). If the redundant parts were not independent, then redundancy would be not only a waste, but a dangerous addition. Note the homologies here with redundancy in natural and engineered systems.

Independence, however, does not imply a lack of overlap (cf. genetic systems, above). Drawing on the concept of equipotentiality derived from the early cybernetic analysis of biological systems (Ashby, 1960), Landau also encouraged thinking about the kinds of overlap that enable some systems to 'take over' the functions of other parts that may have been damaged. 'It is this overlap that permits the organism to exhibit a high degree of adaptability, i.e. to change its behavior in accordance with changes in stimuli' (Landau, 1969: 351). Complementary earlier work (Tiebout, 1956; Ostrom, Tiebout, and Warren, 1961) looked afresh at the multiple units of government found in many metropolitan areas. Considering a *system* of governance units in a metropolitan area, they asked whether multiple units influenced potential competition and consequent performance among these governance units.

Several mechanisms potentially increase performance because of the presence of competitive units. On the citizen-consumption side, Tiebout (1956) argued that residents could 'vote with their feet' and move to the jurisdiction that most fitted their own preferences in terms of a service/tax package. Ostrom *et al.* (1961) made a key analytical distinction between decisions to *provide* public services and decisions to *produce* these services. Once a community had decided that a service was to be provided, having multiple producers allowed public officials an opportunity to search out the most efficient set of producers for the mix of services desired by the citizens of a community. Some services would be produced by a local unit; other services would be produced by larger or other small units. Thus, competition among multiple units would generate considerably more *information about alternatives*; it would also increase the pressure to seek out the most efficient combination for a particular locality.

Substantial research on public service economies supports these analyses of redundancy (summarized in Oakerson, 1999; McGinnis, 1999a, 1999b, 2000). In 80 metropolitan areas, for example, the most efficient urban policing is found in metropolitan areas with 21 or more police departments, and the least efficient in metropolitan areas with seven or fewer departments (Parks and Ostrom, 1999). Further, efficiency is enhanced by differentiation in the services provided: by small, immediate response services, and by overlapping larger agencies that provide services such as radio communications and major homicide investigations (Parks and Ostrom, 1999). A very recent survey of over 70 empirical studies of fragmentation of urban governance found little support for the presumption that suburbs represented a costly form of redundancy: 'The extant empirical literature is scarcely a strong endorsement of the view that suburbs damage cities' (Hawkins and Ihrke, 1999: 119). More than two-thirds of the studies challenged the dominant view that suburbs were harmful; several other studies were supported only with anecdotal evidence. 'It appears that the suburban exploitation thesis has been sustained principally by studies that do not investigate benefits; that overlook evidence of benefits; or that assent to reformist claims about suburban fragmentation, commuters, and growth without systematically weighting the evidence available to test those claims' (Hawkins and Ihrke, 1999: 188, 120).

Bendor (1985) analyzed duplication (or its absence) in the planning and operation of large transportation systems, providing systematic evidence from in-depth studies of three metropolitan areas. The conclusions, while focused on urban transportation, are quite instructive for our interest in resource regimes. In general, Bendor concluded that redundancy in public services can provide higher service levels (in those public services in which it is relatively easy to measure performance and behavior can be observed) due both to the increased level of competition and to the increased reliability of such redundant systems. At the same time, there is a tendency to try to remove redundancy. Bendor argued these conditions would increase redundancy's feasibility and advantages:

1. The probability of a premature quashing of redundancy is diminished if overlapping agencies use different technologies . . . [D]ifferent technologies promote a (possibly false) expectation of functional specialization, that is, the different technologies will be deployed for different ends, whereas identical technologies make redundancy highly visible and vulnerable (p. 279).
2. If bureaus overlap rather than exactly duplicate each other's functions, redundancy is more tolerable politically (p. 280).
3. A well-established agency can mobilize its political resources to bar newcomers to its policy field. It is not accidental that both redundant cases in this study involved agencies that started almost simultaneously (p. 280).
4. Redundancy is more stable, and therefore more practical, if overlapping bureaus do not have a powerful superior close at hand.[6] For this reason, redundancy is probably more feasible among special districts than among

regular line departments because districts are less commonly embedded in hierarchies (p. 281).
5. [R]edundant agencies must retain some diversity in order to produce the full fruits of duplication. The probability of parallel agencies remaining independent is the knottiest problem in the pragmatics of redundancy theory (p. 282).

An important lesson from Bendor's research is that having multiple *non-identical* jurisdictions yields greater diversity and more flexible responses and less risk of being destroyed.

4.4 Complex adaptive systems: reducing risk through redundancy

Contemporary scholars of complex adaptive systems have integrated much earlier work. Complex adaptive systems are composed of a large number of active elements whose rich patterns of interactions produce emergent properties – which are not easy to predict by analyzing the separate system components. Holland (1995: 10) viewed complex adaptive systems as 'systems composed of interacting agents described in terms of rules. These agents adapt by changing their rules as experience accumulates.' Complex adaptive systems 'exhibit coherence under change, via conditional action and anticipation, and they do so without central direction' (Holland, 1995: 38–9). Levin (1995, 1999) successfully used complex adaptive systems to understand fragile ecosystems.

Holland pointed out that complex adaptive systems differ from physical systems that are not adaptive and that have been the foci of most scientific effort – yet, inappropriately, the physical sciences have been the model for many aspects of contemporary social science. We find it odd that social scientists have traditionally drawn more on physical analogies in developing an approach to scientific explanation than on biology and ecology. The concepts needed to understand the behavior of complex systems are not yet well developed by social scientists.

All systems face challenges that may lead them to falter or fail. Complex adaptive systems are not immune to risks, but they may have unique ways of coping with risks. In complex information systems, redundancy is seen as a major source of stability and strength as such systems are buffeted by uncertain and new events (see Axelrod and Cohen, 2000). In most information systems, such as the Internet or local area networks, current technology has only been invented within the last few decades. Thus, few precise assessments can be made of the risks they face. Innovation keeps the systems undergoing enough change for it to be hard to predict the specific risks they will face. When the sources of risk to a system are relatively independent, redundancy is a major structural attribute that reduces the overall risks to the survival of a system. As Axelrod and Cohen (2000: 107) suggest:

> The primary method of risk management for independent failures is to build redundancy into the system . . . [R]edundancy makes possible reliable traffic flows through information networks by channeling traffic around nodes that fail. In addition to redundancy, a useful design feature to deal with local failures is to avoid having any one element of the system be essential to its overall performance. This is typically achieved by making the system highly decentralized like the Internet.

In his own recommendations for devising adaptive forms of environmental management for fragile and at risk ecosystems, Simon Levin (1999: 198–206) presents 'eight commandments of environmental management.' In direct contrast to earlier views of scientific environmental management, one of Levin's 'commandments' is to 'preserve redundancy.' Not surprisingly, a second commandment is to 'maintain heterogeneity,' given that natural selection acts only on existing variability, and if we reduce variability, we reduce options for responding to future environmental changes. He stresses the close connection between the importance of redundancy and that of heterogeneity, but points out, as we have above, that the value of spare parts may only be understood when other parts are lost (Levin, 1999: 202–3):

> Redundancy is the immediate source of replacement of lost functions; heterogeneity provides the materials for adaptive responses over longer time scales . . . The essential element to understanding the importance of redundancy is to elucidate the functional substitutability of one species for another, the ecological complement to economic substitutability.

Levin is primarily concerned with redundancy of populations, but his commandment is also important for ecological subsystems (above) and for social systems. Thus, *two of the initial assumptions underlying much of modern policy are profitably contradicted in resilient complex adaptive systems.* Further, in addition to simple redundancy, having diverse structures within a complex adaptive system also helps to insure against known and unknown risks. If subunits are diversely structured, they are less likely all to be swamped by the same external risk (Holling, 1978; Gunderson, Holling, and Light, 1995).

4.4.1 Redundant resource regimes: an example

In the USA, many examples exist of dynamic resource governance systems characterized by redundancy, in which there is strong evidence of high performance.

One example is the Maine lobster fishery, which is noteworthy because of the long-term, complementary roles adopted by both local and state governance systems. Maine is organized into riparian territories along most of its coast (Acheson, 1988). Boundary rules and many of the day-to-day fishing regulations are organized by harbor gangs:

> In order to go fishing at all, one must become a member of a 'harbor gang,' the group of fishermen who go lobstering from a single harbor. Once one has gained admittance into such a group, one can only set traps in the traditional territory of that particular harbor gang. Members of harbor gangs are expected to obey the rules of their gang concerning fishing practices, which vary somewhat from one part of the coast to another. In all areas a person who gains a reputation for molesting others' gear or for violating conservation laws will be severely sanctioned. Incursions into the territory of one gang by fishers from another are ordinarily punished by surreptitious destruction of lobster gear. There is strong statistical evidence that the territorial system, which operates to limit the number of fishers exploiting lobsters in each territory, helps to conserve the lobster resource.
>
> *(Acheson, Wilson, and Steneck, 1998: 400)*

At the same time, the state of Maine has long-established formal laws that protect the breeding stock and increase the likelihood that regeneration rates will be high. 'At present, the most important conservation laws are minimum and maximum size measures, a prohibition against catching lobsters with eggs, and a law to prohibit the taking of lobsters which once had eggs and were marked – i.e. the "V-notch" law' (Acheson *et al.*, 1998: 400). Neither the state nor any of the harbor gangs has tried to limit the quantity of lobster captured. The state does not make any effort to limit the number of fishers, because this is already done at a local level. However, the state has been willing to intercede when issues exceed the scope of control of local gangs. In the late 1920s, for example, when lobster stocks were at very low levels and many local areas appear to have had substantial compliance problems, the state took a number of steps – including threats to close the fishery – that supported informal local enforcement efforts. By the late 1930s, compliance problems were largely resolved and stocks had rebounded.

In response to changes that were breaking down the harbor gang system, this was recently formalized by dividing the state into zones with democratically elected councils. Each council has been given authority over rules that have principally local impacts (e.g., trap limits, days and times fished). This formalization of local zones was followed almost immediately by the creation of an informal council of councils to address problems at higher levels. It is expected that the council of councils will be formalized soon (Wilson, 1997). Today, the state needs only about six patrol officers on the water to police the activities of 7100 lobstermen, all other fisheries, and boating, shipping, and coastal environmental laws. Clearly this is a relatively efficient redundancy. Further, the ecological impacts appear positive. During the 1990s, the fishery has grown substantially, with increased yields (Maine Department of Marine Resources, 2000). Further, the increase in yields appears to be due to an increase, not a 'mining down,' of the population.

4.5 Conclusion

We have tried to move beyond prescriptions and normative statements to some analytic considerations of how, in different systems, redundancy arises and is maintained or disappears, as a result of its benefits and costs at different levels. This is a complicated question, and so far we have no easy, singular 'answer.' The systems we described all have redundant elements, but the sources and impacts of redundancy may differ. In genetic systems, redundancy arises because alleles, in their own self-interest, manage to get duplicated. In fact, this is probably a major source of redundancy in many systems. In genetic systems, whether such duplications persist, are suppressed, or are multiplied, depends on the impact of redundancy on the functioning of the entire genome – there is some optimum level of redundancy in any particular case. In engineering systems, redundancy is designed in, typically as a risk-reduction strategy, *for the sake* of the whole system. In self-organizing systems, redundancy arises because of the self-interest of local actors. In systems of governance, additional layers of complication exist.

When will redundancy in governance enhance the efficiency of the 'whole' system? We suggest that the following conditions make redundancy advantageous. When transfer of information or actors across subsystems is inefficient or slow, redundant local systems are likely to be efficient. Similarly, when a large system or geographic region is spatially (ecologically) heterogeneous, redundant local systems may work well. In general, local systems may be best able to verify local information, address locally specific conditions, and respond rapidly. At the same time the checks and balances on local interests may work best at greater-than-local levels. The fact that 'redundant' local variations exist may mean that system-level responses can be more potent and rapid than otherwise, and/or that local variations may be able to meet unforeseen contingencies.

Further, individuals who interact with others frequently on a face-to-face basis, and know that future interactions are likely, are more apt to build trust and adopt forms of reciprocity than when interactions are more anonymous and infrequent. We note that this may work either to the advantage or to the disadvantage of the larger system (e.g., such as in Spotted Owl (*Strix occidentalis*) conservation). More experimentation can occur when local units have some autonomy to create their own rules and policies. Some experiments (each in only a small segment of a larger system) will fail, but others can learn from both the good and bad experiences.

Conversely, when a governance system is large and faces conditions that are relatively homogeneous and stable (and/or predictable), and when information and actors can be transferred rapidly, redundant local systems will be relatively inefficient. If competition among parallel units turns to destructive strategies, or if the interests of local decision makers are at sharp odds with the interests of those at other levels (e.g., Spotted Owl conservation), redundancy may escalate conflict rather than increase performance. In such cases, redundancy may be destructive unless it is embedded within larger jurisdictions with effective conflict resolution arenas.

Some tensions and trade-offs will always remain. Proponents of central or dispersed systems frequently fail to recognize these trade-offs in a relevant way. Consider the recurring debates about whether Bureau of Land Management (BLM) stocking rates should be set by Washington BLM personnel or by local BLM representatives. Both sides have some validity in their arguments; both have hidden agendas. Local, on-the-ground managers know local conditions better, can respond to them efficiently, and have more locally relevant information at hand for making decisions. On the other hand, the ability of local managers to focus only on the large-scale, long-term interests of the BLM, when these might conflict with the interests of local landowners, may be limited.

One issue that needs further clarification is the trade-off between different types of errors that can be made by governance systems. Bendor (1985: 50), for example, argued:

> Modern reliability theory distinguishes between a type one error, failing to stop an undesired event, and a type two error, failing to effect a desired one. Organizational redundancy theory has not yet incorporated this point. Landau did not discuss the question in his 1969 essay and though he subsequently (1973) discussed redundancy in the context of constitutional design, that a different kind of error is involved was not made explicit. Yet many policy sectors exhibit both types of errors. Recall, for example, that a welfare program may overlook an eligible person (error of omission) or aid an ineligible one (error of commission). A perfect welfare system would be completely reliable in both respects, but there may be trade-offs between these two kinds of reliability. Does guarding against unwanted actions nullify or vitiate efforts to ensure that desired actions occur?

Decisions about the relative impact of central, versus dispersed, decisions in any system may be difficult. Here we hope to highlight (1) the fact that not all redundancies are equivalent; (2) the relative costs and benefits of redundancy depend on political and ecological conditions; and (3) conflicts of interest exists in most systems. We need, urgently, to develop a grounded theoretical approach to the study of redundancy, for efficient and responsive management depends on matching optimal levels of redundancy to the appropriate conditions.

The presence of larger, overlapping jurisdictions is an important complement to the work of parallel, smaller-scale units. Larger units can back up smaller units in several ways: (1) providing support at times of natural disasters; (2) addressing corruption or gross inefficiency; (3) providing scientific and technical skills to complement local knowledge; (4) providing conflict resolution arenas for conflicts among parallel units; and (5) taking on functions that are generally more efficiently undertaken by larger units.

It is time to leave behind the prescriptive approach to redundancy. Instead, it is crucial to analyze the level of diversity, types of risk, and location of important information in diverse locations before making any judgment about the impact of specific kinds of redundancy in a governing system.

Notes

1. See, for example, Ostrom, Tiebout, and Warren (1961); Hirsch (1970); Ostrom, Parks, and Whitaker (1973); Niskanen (1975); Kaufman (1977); Meier (1980); Bendor (1985); Ostrom *et al.* (1988); Miranda and Lerner (1995); Bish (2001).
2. Stephens and Wikstrom, (1999: 5–6), for example, state: 'In the United States, urban regions are layered onto one of the world's most complex federal systems, with a national government, fifty states . . . 87,453 local governments as of 1997, with the number increasing over time . . . In addition, local public institutions are divided into both discrete and layered segments when it comes to how the system affects individuals and groups of citizens. Public policy is similarly fragmented. Confusion abounds. It's fair to say that this situation all too often leads to distrust and disgust with the performance of government(s).'
3. The cellular automaton 'Life' (sometimes seen as a computer screen saver) may help clarify this concept. The rules are extremely simple: depending on how neighboring pixels are occupied, a pixel will 'behave' in a certain way, generating a set of 'organisms' (agents). The original pixels are randomly scattered; over time, a stable array of agents exists. If you know the rules and watch the process, it appears delightfully clear. But if, as ecologists must, you could only consider the end arrays in all their diversity, inferring the rules would be a nightmare! Thus, it is easy for us to derive reasonable rules that we later discover are either wrong or limited in their effects. Consider the maxim that 'diversity causes stability' in ecosystems, popular a few years ago. Our favorite counter-example is the *Spinnifex* systems of central Australia. Much to managers' chagrin, this is an economically useless, very simple, non-diverse, and extremely stable ecosystem. The vast majority of the plant biomass comprises two species of *Spinnifex*, and the vast majority of animal biomass, three genera of termites. The system is extreme, with high temperatures, low soil nutrients, and very low moisture. Unless water and nutrient subsidies are applied, nothing else can persist under these conditions. Indeed, a moment's reflection suggests that while diversity (redundancy) almost certainly enhances stability, as in the examples noted, systems do not spring into existence full-blown and diverse. In fact, stability of climate, combined with moderate climatic conditions, allows diversity to grow. If one wants to posit causality, this is the direction.
4. Note that we are talking about two separate kinds of redundancy in ecological systems: (1) spatial redundancy of similar subsystems; and (2) redundancy of species within a functional group. Both allow the system to respond to an external perturbation, but in different ways. Spatial redundancy of subsystems may provide source populations for recolonization after local extinctions nearby, depending on the connectedness of subsystems. The redundancy of species within functional groups means that, in the same area, the decline of one species may be 'compensated' (from a manager's point of view) by an increase in a different but functionally similar species. Levin (1999) notes, as we do in Table 4.1, that some redundancies are simple repetitions, while others (e.g., species redundancy in a functional group) are very close to heterogeneity/diversity. We suspect there are trade-offs between connectivity and independence. Probability of permanent local extinction increases with isolation (less connectivity), but for patchy subsystems to exist in human-dominated environments, independence is an essential characteristic. Isolated independent systems may be depauperate (unable to benefit from recolonization) compared with original (no human impact) systems, but they may still be able to function. Further, we see that redundancy contributes to function – but Walker (1992), for example, argues convincingly that maintaining ecosystem function is an excellent way to maintain species diversity (redundancy). Thus we have a positive feedback system.
5. This also raises an issue more difficult in analyzing ecosystems than, for example, engineered or genetic systems: the issues of scale in measurement and inference of redundancy (see Peterson, Allen, and Holling, 1998).
6. Bendor points out in a footnote that the proposition does not necessarily hold if there is more than one powerful superior.

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Part II

Building resilience in local management systems

In dealing with multiple-scale systems, a useful place to start is local management systems. In the development of common property theory in the 1980s and the 1990s, the local or the community level received by far the greatest part of research attention. This was not because the local level was necessarily perceived as the most important scale of organization, but because social–ecological systems at this level provided a 'laboratory' in which principles can be generated, before they can be tested in the real world of external drivers and cross-scale interactions.

When analyzing resilience, again it makes sense to address the local level and build linkages to other scales. This approach helps simplify the analysis of change and the response to change. For example, it is easier to deal with the response and adaptation to one kind of perturbation (e.g., major hurricane), than to a perturbation complicated by an external driver (e.g., the collapse of commodity markets that previously supported an agricultural society). Also, it is easier to deal with the comparison, for example, of two local–regional forest management systems subject to the same forces of social and economic change over a period of time, than a larger system that may have come under other stresses as well. Resilience thinking helps the researcher to look beyond the static analysis of social systems and ecological systems, and to ask instead questions regarding the adaptive capacity of societies and their institutions. One way to approach these questions is to look for co-existing property rights systems, and to analyze their performance and adaptation (Chapter 5). Another way may be to investigate a given social–ecological system holistically, and to tease out the details of different kinds of adaptations that confer resilience to the system as a whole (Chapter 6). A third way is to search out cases in which there is periodic perturbation in the system (e.g., annual flood), and look specifically at how societies build resilience to enable them to live with disturbance (Chapter 7).