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REDUNDANCY AND DIVERSITY IN GOVERNING AND MANAGING COMMON-POOL RESOURCES

by

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> '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)

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Abstract

In many fields, policymakers seem to have an increasing preference for simple, large, nonredundant systems of analysis and governance. To address this question, we examine several definitions of redundancy as well as several fields in which scholars have studied the costs and benefits of different levels of redundancy. These include: genetics, engineering, ecological systems, decision sciences, and complex adaptive systems. Both empirical data and models suggest that a simple prescription is, at best, premature—bigger and less redundant may not always be "better." We find that several kinds of costs and benefits must be considered. We suggest that a better approach is to ask: For any system, what is the optimal level of redundancy?

Keywords: fisheries, governance, risk, error correction

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A recurrent theme in American academia—particularly among students of public administration, policy analysis, and resource economics—is to criticize redundancy in government especially the number of governments that exist in the United States and the competition that exists among them. During the 1960s and 1970s, the "Metropolitan Reform" movement was the dominant way of thinking about urban government. The cause of many problems was posited to be the presence of many units of government that were seen as redundant and inefficient. In addition, multiple units of government were viewed as competitive and providing a means whereby the rich could escape their contribution to the provision of public services needed by the poor and disadvantaged members of society (see Hawley and Zimmer, 1970 and literature summarized in Stephens and Wikstrom, 1999).[1]

In the field of education, for example, the belief in the inefficiency of large numbers of schools and the efficacy of massive consolidation led to the reduction of "redundant" school districts in a massive campaign during the first half of this century. In 1932, there were almost 130,000 school districts in the United States. This number was halved by 1952 and quartered by 1962. The over 30,000 school districts of the early 1960s were halved once again by the early 1970s. The massive consolidation of school districts has slowed down during the past two decades and we currently have around 15,000 school districts in the United States for a population that has almost doubled since the campaign to consolidate schools was initiated (see V. Ostrom, Bish, and E. Ostrom, 1988). The research on the effect of school size, number of schools in a region, and related issues were almost nonexistent during the heat of this policy reform.

Since the 1970s, considerable research on the effects of these variables on school performance has provided contrary evidence to the implicit theory used by policymakers 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) while also being 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, policymakers are reconsidering the consequences of these past reforms and recommending new efforts to create more responsive schools through a variety of structural reforms. Further, earlier empirical studies of redundancy in public services also 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.[2]

The example of the schools is meant to raise a puzzle for those interested in how to establish effective governance arrangements. Common-sense arguments have frequently been used as the foundation for policy. Some relationships are thought to be self-evident and action is proposed on the basis of these self-evident truths. When reforms are based on self-evident truths that do not have a solid empirical and theoretical foundation, reforms can generate counterproductive results—as they have with American schools. That is, we suggest that it is short-sighted and frequently ineffective to derive policy from untested assumptions.

Assumptions Underlying Current Policies

Underlying contemporary policies are several rather critical assumptions that affect that way policy reforms are articulated. Among these assumptions are the following:

1. Local users 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 identical to the good of the greater group. Local users are trapped in dilemmas. In regard to resources, this means that local users will overuse or even destroy valuable resources unless they are prevented from doing so by government action.

2. It is possible to plan for the efficient and equitable use of resources for a large region. In other words, it is possible to design an optimal management system by doing systematic analysis for a region as a whole. This assumes that any existing variability is irrelevant to efficient design.

3. Organization or order is equated with the presence of hierarchical systems of superior-subordinate relationships.

4. The presence of a large number of governance regimes is a sign of inefficiency.

5. Ecological organization is characterized by high levels of connectivity over large spatial scales (i.e., Simon's nearly decomposable sub-systems are not a spatial characteristic of the ecology or water resource or whatever). Hence, "management over the range" is necessary.

Therefore, it is expected that a single governmental unit should devise the optimal rules for managing local resources and should make sure these are monitored and enforced. There is no room for redundancy or diversity of resource governance units in such a vision.

Many existing regimes created to govern and manage natural resource do not conform to these assumptions. First, some users of natural resources do seem to be willing to organize themselves in order to avoid the overuse or destruction of local resources (Ostrom, 1990; Baland and Platteau, 1996). Second, there are many of these self-organized systems. In the Maine lobster fishery, for example, these self-organizing groups tend to arise in most localized fishing areas and probably number in the hundreds along the coast. Third, they do not all use the same rules for how to organize themselves and how to use the resource itself. Fourth, knowledge about how these local systems operate and sometimes even their existence is often not present in a state or regional center let alone the national capital. We think there are sound reasons for encouraging redundancy and diversity—so long as there are also overlapping units of government that can bring capabilities for conflict resolution, for aggregating knowledge across diverse units, and for ensuring that when problems occur in smaller units that a larger unit can temporarily step in if needed.

Reconsidering Redundancy

There are problematic aspects of all five of the assumptions listed above. We cannot in this paper discuss them all in depth, so we plan to focus somewhat more on the fourth and fifth assumptions (see Low et al., 1999; Ostrom, 1990 for a challenge to the others). Instead of viewing redundancy as always *bad* or *costly*, we would rather view redundancy as an attribute of a system. As a system attribute, redundancy has consequences for the way an overall system performs—sometimes leading to increases in performance and sometimes leading to decreases. And, there are costs associated with redundancy. If there are no increases in performance and only costs, obviously redundancy is not desirable. But, as we discuss below, there are many instances where redundancy does lead to increased performance of a system as a whole. Whether the benefits are worth the costs of redundancy depends very much on the type of problems faced in governing a system, how redundancy may cope with these problems, and the cost of particular types of redundancy. We will focus on the question: under what circumstances does redundancy of information or function enhance the efficiency of a system? Our eventual goal is to develop a better understanding of the benefits and costs of building in various kinds of redundancy in the governance of local resources. This paper represents a step in that direction.

In the paper, we will first discuss the meaning of redundancy as it is used in various fields. Then, we will turn to the puzzle of redundancy in genetic systems since there has been substantial research in recent times trying to determine why the human genome is characterized by so much redundancy. Then, we will examine the role of redundancy in engineering systems since a selfconscious effort to understand the importance of redundancy exists in this literature. Next we will turn to an analysis of redundancy of ecological systems which challenges the fifth assumption that resource systems are not separable and must be treated as one large system of closely interconnected local systems. Then, we will turn to the problem of how redundancy may help to off set some of the problems faced in all human decision-making. All humans face cognitive limits and make errors. The question to be explored is whether some kinds of redundancy in governance systems reduces some of these errors. Also addressed is the role of redundancy in increasing the fit between citizen preferences and governance outcomes. Then, we will examine the role of redundancy in contemporary theory of complex adaptive systems. We conclude by stressing that the optimum level of redundancy depends on a variety of conditions (e.g., ecological, social, economic, technological, institutional, informational) and that redundancy tends to arise, is maintained, or disappears in different systems, as a results of its benefits and costs to actors at different levels.

The Meaning of Redundancy

It is somewhat paradoxical that there are multiple concepts used in diverse fields for the meaning of redundancy. In general, redundancy refers to the relationships of multiple units (building blocks) to some larger system of which the units are a part. The units may be individuals, physical parts, jobs, genes, 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 across various meanings of redundancy. At least four things are referred when the term redundancy is used:

(1) Multiple in-use copies of the same unit. Here are some examples.

[a] *dosage-response*: if each copy contributes some response, multiple copies yield greater response (e.g., as in multiple copies of an allele for pesticide resistance in mosquitoes);

[b] *many-to-one coding*: in the genetic code, the same allele may be coded for in multiple ways (Freeland and Hurst, 1998) (there are 16 amino acids and 3^3 ways to code for them);

[c] *multiple exact copies*: in biological or genetic algorithm systems. For example, in regard to antibodies—the more copies of a particular antibody there are, the better the chance that an invading pathogen that matches these antibodies will be thwarted;

[d] *many nonexact copies*: among antibodies, variations of the antibody that is currently the most successful are functionally desirable because sooner or later the antigen will evolve to a slightly different form against which the earlier successful antibodies will have limited success. When there is some variation in effectiveness with regard to variations in antigens, having both multiple exact copies as well as variation is highly effective). In Holland's classifier (or rule-based) models, one would want variants of successful rules because when the environment changes the best response to a given situation may vary also;

(2) **Backup functional or informational copies of units** ("spare tires"). Functionally, this is one mechanism of risk reduction—if the unit in use becomes lost or dysfunctional, an immediate replacement exists.

(3) **Redundant strength.** By building in greater strength or larger allowances, a higher margin of error in performance is achieved (e.g. larger supports than needed or gaps in bridges,

allowing greater expansion and contraction than would probably be needed under the region's temperature patterns). This meaning parallels several of (1) above.

(4) **Redundant governance units.** Multiple units that govern and manage public goods or common-pool resources. We are primarily interested in governance units that are responsible for diverse types of natural resources such as inshore fisheries, local forests, grazing areas, irrigation systems, air sheds, etc.

[a] Parallel systems involve multiple governance units at the same level in a governance hierarchy. These would be repeated similar or identical structures and functions carried out at different locations with regard to different resources.

[b] Overlapping systems that involve more general governance structures that have a larger geographic domain and some responsibility for holding smaller units responsive to their citizens and accountable for performance according to legal rules.

Although these examples seem diverse and unconnected, in fact there are some real homologies. Nearly any statement about redundancy in governance systems has a parallel in the immune system's antibodies (Farmer et al., 1986).

<u>Redundancy in Genetic Systems</u>

Redundancy, the duplication of units or functions, can be advantageous or disadvantageous in genetic systems. Geneticists have been puzzled for a long time by the existence of apparent repetitions—redundancies—and apparent nonsense genes, in the genome. Organisms have a lot of genes: the smallest known genome in nature is almost twice the size of best estimates for the minimal necessary genome (Maniloff, 1996). Gene duplications arise spontaneously at high rates in bacteria, bacteriophages, insects, and mammals, and are generally viable (Fryxell, 1996). However, only a small fraction of all duplicated genes are 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 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 in fact are functional.

Clearly duplication may serve the interests of the duplicated unit; a more interesting question is: when does apparently redundant duplication serve the interests of the whole genome and the organism? One of the best-known deleterious effects of genetic redundancy in humans is that of Down's syndrome, a type of polysomy (duplication of a complete chromosome) called trisomy 21. Repetition of whole chromosomes seems to be disadvantageous. In contrast, invariant repetitions (redundant copies)of gene sequences may occur when some threshold level of a genetic product is important. This advantageous type of redundancy is common when a metabolic need exists to produce large quantities of specific RNAs or proteins (Ohno, 1970). An increase in number of genes can occur quite rapidly under selection for increased amounts of a gene product. Some spectacular examples of these involve the evolution of resistance to organophosphorous insecticides in aphids (Field and Devonshire, 1998), mosquitos and Drosophila (Mouchès et al., 1986; Maroni et al., 1987; Callaghan et al., 1998).

Genes that are in some way separated spatially from other genes that work with them are more likely to become duplicated. In this condition a gene can become separated (and after meiosis to form egg or sperm, end up in a different sex cell—with loss of function). Loss of a single-copy gene is usually deleterious and unlikely to be fixed, so spatially separated genes that become duplicated are advantageous not only to the gene, but its organism.

A frequent happening is the origination of a nonfunctional (silent) pseudogene from a duplicate allele. Perhaps because these are typically harmless (because duplicates exist), these may be maintained; the human pseudogene yh in the b-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 these species diverged.

Novel function can arise after duplications (complex genes may have arisen thus; ovomucoid gene, a2 allele of haptoglobin, antifreeze glycoprotein gene (see also Graur and Li, 2000: 263, table 6.1). Variant repeats are copies with small differences—surprisingly, the repeats can sometimes do very different functions (e.g., thrombin and trypsin, lactalbumin and lysozyme). Differentiation typically requires a large number of substitutions—but sometimes surprisingly few 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).

An additional, global sort of redundant duplication exists in the world of genetics: polyploidization: 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 almost all organisms (Nagl, 1990). However, tetraploids seem to have survived rarely, for tetraploids 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 to internal dysfunctions. A few cases of fully-functional tetraploidy are known, in which the duplication has no effect on the phenotype (flowers Chrysanthemum and Rosa, the leptodactylid frog Odontophrynus, and goldfish. In fact, 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). In these case 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.

Certain generalities appear to 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 the replicated unit is embedded. The genetic case is simpler than the other examples we discuss (below). In genetic systems, the persistence and/or proliferation of replicated subunits will depend on a number of things: 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); and the relative power of the subunits to protect its replications. When will replication serve the interests of both the replicator and the larger group? We can think of several conditions: when communication is slow or inefficient; when conditions differ for sub-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 ("outlaw" genes, driving Y chromosomes?). In these cases, persistence of the replicated unit will depend of the relative ability of the replicated subunit to protect itself from elimination or consolidation by the whole group.

Redundancy in Engineering Systems

In engineered systems, in contrast to genetic systems, optimal performance of the designed system is an a priori goal. Genetic systems (and their mimic, genetic algorithms; Holland, 1995) begin with some elements of randomization; then the relative survival and reproduction of the elements results from differential performance. Indeed, in some complex manufacturing problems, this approach has been used successfully (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 sub-optimal, but many systems must function in a variety of environments. Further, when failure has very high costs (e.g., engine failure in an airplane), the costs of redundant elements may be perceived as worthwhile. Thus the "robust integration of systems of systems" (Doyle http://www.cds.caltech.edu/~doyle/notes/1.html; see also 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 (Doyle http://www.cds.caltech.edu/~doyle/notes/1.html):

> 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. (Doyle, 1999)

Redundancy in Ecological Systems

Still another way of looking at redundancy in complex systems is to consider how ecological systems react to external and internal changes. It used to be fashionable in environmental circles to repeat the mantra "everything is connected to everything else." In a trivial sense this is true but as a practical matter it is probably the case that most of those connections are very, very weak almost to the point of nonexistence. The connections that are important are those that are proximate.

This is fortunate for the environment, for a world in which everything was tightly connected to everything else would be a world in which wilderness areas, parks, greenways, and so on, could not exist. It is the relative independence of these kinds of areas or sub-systems that allows them to persist as natural areas. Over the long haul the existence of relatively independent natural areas may assure the preservation of biological diversity and allow, perhaps, its eventual regeneration into larger or more numerous areas. Had the natural areas been "an inseparable part of the whole," it's quite likely we would have no natural areas today and would have lost much more biological diversity than we have. Tightly connected systems are fragile and show little resiliency to change. Systems with large numbers of redundant and loosely connected sub-systems, on the other hand, roll with the punches much better.

As in engineering situations, the redundancy of these systems buffers them and us from failures emanating from our ignorance or willful actions. Yet, or maybe because of this, many of our environmental policies tend to ignore the smaller scale, subsystem aspects of ecosystems and attempt to treat them as if they were tightly unified wholes. This ignorance tends not to matter under many circumstances and for long periods of time (Wilson et al., 1999), because a redundant system can compensate for our errors. However, as human actions continue to erode the system (i.e., remove or degrade the subsystems that provide redundancy), there comes a point where the buffering capacity of the system is lost and we are confronted with sudden, surprising and usually undesirable changes in the state of the system.

For example, as some local or relatively independent fish populations are fished down, other populations may grow to take advantage newly available food sources. From within the system these changes might be viewed as the of substitution of one species for the fished species or a shift in the geographical location of the fished species. Viewed from the top, "as if" the fishery were a unified system, little change in the normal variability of the system might be noticed. So long as "enough" redundant subsystems remained, the system as a whole might be able generate its normal patterns even in the face of rather abusive behavior by humans. But beyond a certain point the ability of subsystems to compensate for the loss of other subsystems reaches its limit and 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).

The other side of this somewhat problematical aspect of redundancy is that policies and institutions that recognize and organize around the inherent redundancy of ecosystems are much less likely to be surprised by cumulative, erosive actions. In other words, institutions organized in ways that parallel the redundant structure of the ecosystem are more likely to receive accurate and timely information about the state of the system and because of that are more likely to be able to adapt in ways that are constructive.

Redundancy as a Means of Reducing Error and Increasing the Fit between Preferences and Outcomes in Human Decisions

While the model of the individual that is frequently used in contemporary analysis of public policies is of an individual who knows all of the alternatives that need to be considered, has full information about the probability of particular outcomes resulting from choosing an alternative (given the actions of others), and has a complete preference ordering over outcomes, few decision situations enable individuals to approximate this model closely. The important work of Simon

(1947) and Cyert and March (1963) was based on an assumption that humans have limited rationality that is 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 speculations have been supported by considerable empirical research—especially by psychologists. A repeated finding is that decision makers tend to 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 in a manner that is closer to a model of limited rationality, an important question is whether organizational systems must be as unreliable as the individuals working within them.

This question was addressed in an important theoretical analysis by Martin Landau (1969) drawing on Von Neumann's (1956) work on reliability theory. Landau 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" (1969: 349). Landau points out that within an administrative system it is quite possible for minor errors made by one individual to be amplified as information is relayed to lead to major errors in making final decisions.

The problem of error magnification is particularly acute in systems that are arrayed in a strict serial fashion whereby all subordinates report to a single supervisor who, in turn, reports to another supervisor and the serial nature of information flow and decision making is repeated throughout the organization.   It is exactly this type of system, however, that 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 points out (1969: 354). He warns, 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 further analyzes 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 x 0.8 x 0.9 = 0.648. This is less than its weakest link unless the probability of completing all the other links is one. (Bendor, 1985: 293)

Landau proposed that by adding "sufficient" redundancy in the way that administrative system are organized that it would be possible to build organizations that were more reliable than their individual human parts. In a later article, Landau noted that if the probability of failure in a particular system is 1 in a hundred, 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 a million. Thus, "the probability of failure decreases exponentially with arithmetic increases in duplication" (1973: 187). Drawing on reliability theory, he cautions 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 there is not independence among the redundant parts, then redundancy would be not only a waste, but a dangerous addition.

Independence, however, does not imply a lack of overlap. Drawing on the concept of equipotentiality derived from the analysis of biological systems, he also encourages thinking about the kinds of overlap that enables 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).

Landau's work complemented the earlier work of Tiebout (1956) and Ostrom, Tiebout, and Warren (1961) that looked afresh at the multiple units of government found in many metropolitan areas. Instead of focusing on each unit, they focused on a system of governance units in a metropolitan area and asked whether having multiple units increased 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, Tiebout, and Warren (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 themselves and other services would be produced by larger or small units for other services arranged through a contract. Thus, competition among multiple units would generate considerably more information about alternative benefit-cost packages as well as increasing the pressure to seek out the most efficient combination for a particular locality.

Considerable research on urban services has generated substantial research in support of these analyses of redundancy (see work summarized in McGinnis, 1999a, 1999b). In a study of 80 metropolitan areas, for example, Parks and Ostrom (1999) find that the most efficient producers of urban policing are found in metropolitan areas with 21 or more police departments and the least efficient producers are found in metropolitan areas with seven or less departments. Further, efficiency is enhanced by a 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).

The comparative study of transportation systems characterized by duplication or its absence in the planning and operation of large scale system undertaken by Jonathan Bendor (1985) provides evidence about both of these theoretical analyses of the potential benefits of redundancy. His conclusions, while related to urban transportation, are quite instructive for our own interest in resource regimes. In general, Bendor concludes that redundancy in public services can provide higher service levels (in those public services where it is relatively easy to measure performance and where behavior can be more easily observed) due both to the increased level of competition and to the increased reliability of such systems. But, at the same time, there is a tendency to try to remove redundancy and he concluded his analysis with a set of condition that he argued would increased redundancy's feasibility:

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.[3]. . . 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).

Thus, one of the important lessons one learns from Bendor's research is that having multiple jurisdictions that are not strictly identical yields greater diversity, more flexible responses and less risk of being attacked.

Redundancy in Reducing Risk in Complex Adaptive Systems

These early findings have now been integrated into the work of contemporary scholars on complex adaptive systems. Complex adaptive systems are composed of a large number of active elements whose rich patterns of interactions produce emergent properties that are not easy to predict by analyzing the separate parts of a system. Holland (1995:10) views 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: 38-39). Holland points out that complex adaptive systems differ from physical systems that are not adaptive and that have been the foci of most scientific effort. It is the physical sciences that have been the model for many aspects of contemporary social science. Thus, the concepts needed to understand the adaptivity of systems are not yet well developed by social scientists.

All systems face challenges that may lead them to falter or fail. A complex adaptive system is not immune to risks, but there may be ways of coping with risks that differ from the ways used in simple systems. In recent analyses of 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: 107). In most information systems, such as the Internet or local area networks, the technology in use has only been invented within the last few decades. Thus, few precise assessments can be made of the type of risks they face. Further, innovation keeps the systems undergoing enough change that it is hard to assess what are 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) indicate:

> 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.

Thus, two of the initial assumptions underlying much of modern policy are broken in resilient, complex, adaptive systems. Further, in addition to simple redundancy, having diverse structures within a complex adaptive system also helps to ensure against known and unknown risks. If subunits are diversely structured, they are less likely to all be swamped by the same external risk.

Redundant Resource Regimes: An Example

In the United States, many examples of dynamic, resource governance systems characterized by redundancy exist where 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 the coast. Boundary rules and many of the day-to-day fishing regulations are organized by harbor gangs (Acheson, 1988).

> 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, Wilson, and Steneck, 1998: 400). Neither the state nor any of the harbor gangs have tried to limit the quantity of lobster captured. Until recently the state did not make any effort to limit the number of fishers. 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.

Recently, in response to changes that were breaking down the harbor gang system, the state has formalized the system by dividing the state into zones with democratically elected councils.

Each council has been given authority over rules that have principally local impacts—trap limits, days and times fished, etc. Interestingly, the formalization of local zones was followed, almost immediately, by the creation of an informal council of councils to address problems at a greater than local scale. It is expected the council of councils will be formalized soon (Wilson, 1997).

Today the state needs only about six to ten patrol officers on the water at any time to police the activities of 6,800 lobstermen, all the other fisheries, and coastal environmental laws. During the 1990s, the fishery has been growing substantially with increased yields (Acheson, 1993). At the same time, there is strong evidence that the number of reproductive age females in the Maine waters is very large and that the recruitment levels are continuing at a high level.

Conclusion

In this paper, we have tried to move beyond normative statements to some considerations of how, in different systems, redundancy arises and is maintained or disappears, as a result of its benefits and costs to actors at different levels. This is a complicated question, and so far we have no easy, singular "answer." The systems we have described all may 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 likely a major source of redundancy in many systems. Whether such duplications persist, are suppressed, or multiplied, depends on the impact of redundancy on the functioning of the entire genome—there is some optimum level of redundancy in a particular case. In engineering systems, redundancy is designed in, typically as a risk-reduction strategy, *for the sake* of the whole system. In systems of governance, additional layers of complication exist.

When will redundancy in governance regimes 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 may be more efficient. Similarly, when a large system or geographic region is spatially (e.g., ecologically, socially, economically) heterogeneous, redundant local systems may work better. In general, local systems may be better able to verify local information, address locally specific conditions, and respond rapidly. The fact that "redundant" local variations exist may mean that responses may be more potent and rapid than otherwise possible, and/or that local variations may be able to meet unforeseen contingencies and local diversity. Further, individuals who interact with others more 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 antonymous and infrequent. Finally, more experimentation can occur when local units have some autonomy to create their own rules and policies. Some experiments will fail. Participants can learn from the both the good and bad experiences of others. And, failure occurs in a segment of a larger system rather than in the entire system.

Conversely, when a system to be governed is large and relatively homogeneous, and information and actors can be transferred rapidly, redundant local systems may be relatively inefficient. This is especially the case if there is only one good or resource involved and where substantial economies of scale exist. The advantage of repeated face-to-face interactions, however, remains missing in large-scale, single-unit governance.

Redundancy through various degrees of overlap may improve performance if competition among parallel units turns to destructive strategies and conflict escalation processes ensue. Further, the presence of larger, overlapping jurisdictions is an important complement to the work undertaken by parallel smaller-scale units. Larger units can back up the smaller units in several ways: (1) at times of natural disasters, (2) if there is corruption or gross inefficiency that needs to be addressed, (3) providing scientific and technical skills that complement the local knowledge present in smaller systems, (4) providing conflict resolution arenas for conflicts that may occur among parallel units, and (5) taking on those functions that are generally more efficiently undertaken by larger units.

Proponents of central or dispersed systems frequently fail to recognize the tradeoffs 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 some 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 remain focused only on the large-scale, long-term interests of the BLM, when these might conflict with the interests of local landowners, may be limited. Clearly, much remains to be done.

One issue that needs further clarification is the tradeoff 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. Thus, instead of presuming that all redundancy is inefficient (or, on the other hand, that large, centralized systems are always inefficient), it is crucial to analyze the level of diversity, types of risk, and location of crucial information in diverse locations prior to making any judgment about the results of adding specific kinds of redundancy to a governing system. It is an urgent question 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.

Notes

1. 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)."

2. See, for example, V. Ostrom, Tiebout, and Warren, 1961; Hirsch, 1970; E. Ostrom, Parks, and Whitaker, 1973; Niskanen, 1975; Kaufman, 1977; Meier, 1980; Bendor, 1985; V. Ostrom, Bish, and E. Ostrom, 1988; Miranda and Lerner, 1995.

3. Bendor points out in a footnote that the propositions does not necessarily hold if there are more than one powerful superiors.

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