Problem Solving: Complexity, History, Sustainability

Joseph A. Tainter
United States Department of Agriculture Forest Service

Sustainability or collapse follow from the success or failure of problem-solving institutions. The factors that lead to long-term success or failure in problem solving have received little attention, so that this fundamental activity is poorly understood. The capacity of institutions to solve problems changes over time, suggesting that a science of problem solving, and thus a science of sustainability, must be historical. Complexity is a primary problem-solving strategy, which is often successful in the short-term, but cumulatively may become detrimental to sustainability. Historical case studies illustrate different outcomes to long-term development of complexity in problem solving. These cases clarify future options for contemporary societies: collapse, simplification, or increasing complexity based on increasing energy subsidies.

KEY WORDS: collapse; complexity; problem solving; organizations; sustainability.

Organizational problem solving is typically addressed to the affairs of the moment, and we rarely consider its long-term consequences. Problems, of course, perennially confront human existence at scales from common challenges to the great dilemmas of nations and the world. Human institutions, including nations and empires, have disappeared because their members did not understand the development of problem solving (Tainter, 2000). The fields of organizational decision making (March & Simon, 1958; March & Olsen, 1986; Simon, 1997), organizational ecology (Aldrich, 1979, Hannan & Carroll, 1992; Baum & Singh, 1994a, 1994b), and learn-

Please address correspondence to Joseph A. Tainter, Rocky Mountain Research Station, 2205 Columbia SE, Albuquerque, NM 87106.

Population and Environment: A Journal of Interdisciplinary Studies
Volume 22, Number 1, September 2000

ing organizations (Senge, 1990) have done much in recent years to clarify why institutions thrive or stagnate. As Peter Senge (1990, pp. 23, 57) notes, decision-makers rarely foresee the full consequences of their actions. Problem solving can have pernicious effects, for a solution that is successful now can contribute to failure later on. It is important to understand how problem-solving systems develop over time periods stretching from decades to centuries. A science of institutional problem solving is above all a historical science. Regrettably, few studies of institutions extend beyond a few decades. The vast human experience of previous efforts at problem solving remain largely untapped in organizational research.

This essay mainly concerns problem solving by large institutions, of which the successes and failures of nations and empires provide some of history's most poignant examples. Three such cases, illustrating different trajectories of problem solving, are presented. Since the purpose is to understand general principles, the results can be (and have been) applied to other problem-solving institutions, such as businesses, agencies, or nongovernmental organizations (e.g., Tainter, 1997). The purpose is not to understand history per se, but to use history to formulate an understanding of problem solving that can clarify our situation today.

CONSTRAINTS TO ORGANIZATIONAL EFFECTIVENESS AND DURABILITY

Certain factors constrain all large institutions in their development and problem-solving effectiveness. These include the structure of an institution's environment (including other like institutions), the efficiency of internal transactions, and limits to human cognition and information processing.

The numbers of a type of organization tend to grow slowly at first, then accelerate until a point is reached beyond which further growth is not possible. Beyond this point the numbers will decline somewhat, then fluctuate. This process is regulated by two different mechanisms: legitimization and competition (Hannan & Carroll, 1992). Proliferation of a type of organization increases its legitimacy, so that there is less resistance to establishing more of them. As Renfrew noted in regard to early states, "*The specific state is legitimised in the eyes of its citizens by the existence of other states which patently do function along similar lines*" (1982, p. 289 [emphasis in original]). At the same time, increasing the numbers of a type of organization ultimately hits the limit of available resources. Thereafter competition for resources limits further proliferation and organizational mortality increases.

In a large, complex system, constraints internal to the organization are as crucial as those external, and often more immediate. R. H. Coase (1937) argued that business firms exist to reduce transaction costs by internalizing diverse services. Hierarchy always simplifies, and within a firm internalizing services reduces the cost of establishing their prices. Yet as firms become larger there are diminishing returns to scale. Transaction costs increase as information channels become congested (Rosen, 1991, p. 82), waste increases, and the cost of organizing further internal transactions grows. Until recently, hierarchies proliferated in the business sector as easily as they did in government (Bendix, 1956, p. 216). Ancient states also experienced transaction costs. The early Roman Empire, for example, externalized parts of its own defense by allowing client states to buffer its periphery (Luttwak, 1976). Those states were in time absorbed, internalizing defense and administration, until the costs of continued expansion grew too high relative to the benefits of further internalization (Tainter, 1994; see below).

Problem solvers are always constrained by bounded rationality (March & Simon, 1958; Simon, 1997). The behavior of organizations appears to be goal oriented (Aldrich, 1979, p. 4) and is intended to be rational (Simon, 1997, pp. 88–89). Yet humans can rarely absorb all the complexities of a problem, and decide on the basis of rules or models that simplify complexity (March & Simon, 1958: 169–171, 203; Simon, 1997, p. 119). Decision making in a complex system may be surrounded by such confusion as to make the linkage between problem and solution tenuous (March & Olsen, 1986, p. 16). Decisions have system-wide consequences that may manifest themselves years or decades later (Senge, 1990, p. 23). This crucial fact has long been overlooked: in the nineteenth century Herbert Spencer observed that, "*Every active force produces more than one change—every cause produces more than one effect*" (1972, p. 47 [emphasis in original]). This lesson will emerge clearly in the cases described here.

The literature on organizations leads, then, to several suppositions: that institutions inherently attract challenges; that they face problems both of internal structure and cost, and of external threat; and that, with inadequate understanding, decision-makers must devise solutions whose consequences ramify unpredictably.

DEVELOPMENT OF PROBLEM SOLVING

Human societies and their institutions must, among other characteristics, be problem-solving systems. They respond to challenges that range

from the mundane to international crises and global change. Families, firms, government and its agencies—each exists to solve problems, and to continue to exist must do so successfully. Institutions that fail to solve problems lose legitimacy and support, as many governments (such as that of the former Soviet Union) have learned.

Our ahistorical society is largely unaware that over time societies can become ineffective at confronting challenges or solving problems. Yet in earlier societies, such as among the writers of antiquity and the Renaissance, the idea was not only acceptable, it was a truism (e.g., Alcock, 1993). The Greek historian Polybius, in one of history's most remarkable predictions, foresaw the collapse of the Roman Empire 600 years before it actually fell (Polybius, 1979, p. 310).

For nearly three millennia scholars and philosophers have sought to understand why societies fail to preserve themselves. Recently it has been argued that *complexity* is a primary factor linking problem solving to the success or collapse of societies and institutions. Over the long run it may be the most important factor (Tainter, 1988, 1995, 1996a, 1996b, 1997, 2000; Allen, Tainter, & Hoekstra, 1999). The evolution of complexity is a significant part of the history of problem solving and accordingly the primary focus of this essay.

Human societies often seem to become progressively more complex—this is, comprised of more parts, more kinds of parts, and greater integration of parts. This process began with our hunter-gatherer ancestors (e.g., Price & Brown 1985), and has accelerated over the past 12,000 years. There have been episodes like the European Dark Ages when complexity collapses, but the trend they interrupt is so constant that we see these periods as aberrations (Tainter, 1999). This is curious, for truly complex societies are quite recent. Hominids have been discovered as old as about four million years, yet the most complex societies—states—did not appear until a little more than five thousand years ago. In the full spectrum of hominid history, complexity is rare.

We seem often to be averse to complexity. The reasoning behind sayings like "Keep it simple" is universally understood. The so-called "complexity of modern life" is a favorite topic of journalists and their readers. One reason why we have such low participation in elections is that the value of a single vote does not appear to offset the cost of mastering complex issues. Much of the discontent with government stems from the fact that governments increase the complexity of people's lives. People resent governmentally-imposed complexity to such a degree that politicians build careers opposing it while journalists compete to expose it.

In science, the Principle of Occam's Razor states that simplicity in

explanation is superior to complexity. Christopher Toumey, who studies the role of science in popular American life, has shown that the incorporation of scientific values into American culture has varied with the complexity of science (1996, pp. 11–20). When science was so simple that its main requirements were fundamental education and an inquisitive spirit, it was considered worthy (even divinely sanctioned) to pursue knowledge of the natural world. When science grew complex and specialized it diverged so sharply from American values that public attitudes began to range from skepticism to hostility. Alexis de Tocqueville commented upon this trend as early as 1834.

Every increase of complexity has a cost. While we may appreciate complexity in some spheres (e.g., art), we are averse when it is ourselves who must bear the costs. People oppose governmentally-imposed complexity not just because of abstract notions of liberty, but also because of the costs it carries—taxes levied or time spent filling in forms or standing in queues. The cost of supporting complexity is the energy, labor, time, or money needed to create, maintain, and replace a system that grows to have more and more parts and transactions, to support specialists, to regulate behavior so that the parts of a system all work harmoniously, and to produce and control information. The anthropologist Leslie White once estimated that a society activated primarily by human energy (bands of hunter-gatherers, for example), could generate only about 1/20 horsepower per capita per year (1949, p. 369; 1959, pp. 41–42). This is all the energy such a simple society needs. Today such a quantity of energy can produce scarcely a fleeting moment of industrial life. No society can become more complex without increasing its consumption of high-quality energy (Hall, Cleveland, & Kaufmann, 1992), human labor, time, or money.

If complexity costs and we are averse to paying for it, why then don't we still live as simple foragers? Our ancestors did for nearly all of our history. The reason is that although complexity costs, it has great utility in problem solving. We attribute our success as a species to such things as upright posture, an opposable thumb, and a large and richly-networked brain. These attributes allow us rapidly to increase the complexity of our problem solving. Without the ability quickly to alter our problem-solving behavior we would be hardly more capable than other species, which must entrust their continuity to the slow process of biological evolution.

The development of complexity is thus one of the wonderful dilemmas of human history. Over the past 12,000 years (when the complexity of human societies began to increase significantly) we have frequently adopted strategies of problem solving that cost more energy, labor, time, and money, and that often go against deep inclinations. For much of this

time the cost was increased human labor: people worked harder to support complexity. We have done this for a simple reason: most of the time complexity works. It is a fundamental problem-solving tool. In its early phases, complexity can generate positive feedback and increasing returns (Tainter, 1988; Allen, Tainter, & Hoekstra, 1999). Confronted with challenges, we often respond by strategies such as developing more complex technologies, adding more elements to an institution (specialists, bureaucratic levels, controls, etc.), increasing organization or regulation of transactions, or gathering and processing more information. Each such action represents increasing complexity. Their effectiveness comes in part because changes in these dimensions can be enacted rapidly. While humans may be complexity averse when we personally bear the cost, our problem-solving institutions can be powerful complexity generators. All that is needed for growth of complexity is a problem that requires it. Since problems always arise, complexity seems to grow inexorably.

Since complexity is an adaptive problem-solving strategy that has costs, it can be viewed as an economic function. Societies invest in complexity. In any system of problem solving, the initial strategies tend to be both effective (they work) and cost-effective (giving high returns per unit of investment). This is a normal economic process: simple, inexpensive solutions are adopted before more complex and expensive ones. So in the history of human efforts to feed ourselves, labor-sparing hunting and gathering gave way to more labor-intensive agriculture, which itself became more intensive as populations grew.

Increasingly, subsistence agriculture is being replaced by industrialized food production that consumes more energy than it produces (Boserup, 1965; Clark & Haswell, 1966; Cohen, 1977). Whenever possible we produce minerals and energy from the most economical sources—ones that are least costly to find, extract, process, and distribute. As Herbert Spencer (e.g., 1972, pp. 39–46) and others have noted, our societies have changed from egalitarian relations, economic reciprocity, ad hoc leadership, and generalized social roles to social and economic differentiation, specialization, inequality, and full-time leadership. These arrangements are the essence of social complexity.

Complex solutions may for a time produce positive returns (Tainter, 1988; Allen, Tainter, & Hoekstra, 1999). Unfortunately, no society (or smaller institution such as an agency or firm) can forever enjoy stable or increasing returns to complexity in specific areas of problem solving. In any organization, increasing size and differentiation exacerbate the problem of internal transaction costs (Coase, 1937). Hierarchies differentiate (Bendix, 1956, p. 216) as opportunities or problems are perceived. Information be-

comes less coherent as it becomes more abundant, so that simplified models must substitute for the richness of actual processes (March & Simon, 1958, p. 203; Rosen, 1991, p. 82; Simon, 1997, p. 119). Decisions have unforeseen consequences (Spencer, 1972, p. 47; Senge, 1990, p. 23), and as will be discussed below, often drive up costs. The link between problem and solution is often tenuous (March & Olsen, 1986, p. 16). Because of the problems of transaction costs, rational, omniscient decision makers will reduce internal transactions when the cost of an extra internal transaction equals the cost of an external one (Coase 1937, pp. 394–395). The problem is that decision makers are typically not omniscient, and cannot foretell the future. Thus they inevitably make decisions that inadvertently increase costs. We tend to view the microprocessor industry as an exception to this problem, exemplified, for example, in Moore's Law. Microprocessor producers have enjoyed positive feedback and increasing returns. Yet even this industry must devise ever-more-clever solutions to physical constraints (e.g., Service 1997), which it cannot do indefinitely as easily as it has to date. Even economically-rational organizations cannot forever avoid diminishing returns to complexity, and certainly not institutions (such as ancient states) that are economically naive.

As highest-return solutions are exhausted, only more costly approaches remain to be adopted. As the highest-return ways to produce resources, conduct transactions, process information, and organize society are progressively implemented, adaptive problems must be addressed by more costly and less effective responses. As the costs of solutions grow, the point is reached where further investments in complexity do not give a proportionate return. Increments of investment begin to yield smaller and smaller increments of return. The *marginal* return (that is, the return per extra unit of investment) declines. This is the central problem: diminishing returns to complexity. Carried far enough it brings on economic stagnation and ineffective problem solving. In its most severe form it has made societies vulnerable to collapse, and historically has led to conditions that are colloquially called "dark ages" (Tainter, 1988, 1999). A prolonged period of diminishing returns to complexity in problem solving is a major part of what makes a society unsustainable (Tainter, 1995, 1996b; Allen, Tainter, & Hoekstra, 1999).

This thesis can be illustrated in two principle areas of problem solving: producing resources and producing information. In the examples to follow, people solve the problems of obtaining resources and information in economically-rational ways. They prefer behavior and institutions that are simple rather than complex. They prefer to conserve labor and other types of energy. When problems require them to adopt new institutions or ways of

meeting their needs, they experience increasing complexity and diminishing returns. These examples illustrate the evolution of many problem-solving adaptive systems: increasing complexity with initially positive returns, then diminishing returns to complexity and increasing costliness.

Producing Resources

People typically pluck the lowest apple first. That is, provided that they have knowledge, people initially use sources of food, raw materials, and energy that are easiest to acquire, process, distribute, and consume. As problems arise in the form of growing consumption and/or exhaustion of inexpensive resources, people turn to supplies that are more difficult to acquire, process, distribute, or consume. Often this requires greater effort while yielding no greater return (although, as will be shown, sometimes this is not the case).

We are socialized today to think that among the most desirable goals of life are to produce and acquire as much as possible. Yet this is a recent development: our ancestors typically produced much less than they were capable of, as many people still do. Hobbes's description of hunter-gatherer life as "nasty, brutish, and short" has accustomed us to think of simple subsistence production as a continuous struggle. Yet anthropologist Richard Lee found that the !Kung San (Bushmen) of the Kalahari Desert (a landscape not very productive) need to work only about 2.5 days per week to obtain all the food they need (Lee, 1968, 1969). Because of this example, simple foragers such as the !Kung have been labeled the original leisure society.

Subsistence agriculturalists also seem to work rather little, and it is particularly noticeable that often they produce less than they might. Labor seems to be abundant, underutilized, and inefficiently deployed, so that subsistence farmers characteristically underproduce. The Kapauku Papuans of New Guinea, for example, according to research by Leopold Posposil, work about two hours a day at agricultural tasks, even during the peak labor season. Similarly, Robert Carneiro observed in the Amazon Basin that Kuikuru men spend about 2 hours a day on agricultural work and 90 minutes fishing. They spend the rest of the day dancing, wrestling, or resting. With a little extra effort they could produce much more than they do. Many households in such societies do not produce even enough to live on; they are supported by others (Sahlins, 1972). Thus farmers working only a couple of hours a day may be supporting even more households than their own.

Colonial administrators, confronted with such underproduction (and in ignorance of both economics and human diversity), often concluded that the native people they supervised were inherently lazy. Yet subsistence

farmers in more economically developed places follow similar strategies, including peasants of pre-revolutionary Russia. The Russian economist A. V. Chayanov (1966) studied the intensity of labor among 25 farm families in Volokolamsk. Plotting intensity of labor against the relative number of workers per household, Chayanov found economies of scale: the larger the relative number of workers per household the less effort each person puts forth. Productive intensity varies inversely with productive capacity (Sahlins, 1972, p. 91). Even under the harsh conditions in which they lived, Russian peasants underproduced. Those able to produce the most actually underproduced the most. They valued leisure more highly than the marginal return to extra labor.

To account for this contradiction between the availability of labor and the failure to apply it beyond basic sufficiency, Ester Boserup wrote her classic work *The Conditions of Agricultural Growth* (1965). The key she found to persistent underproduction is the marginal return to increasing labor—a subtle concept brought forth by the sustained effort of Western economic science, but understood all along by the lazy natives and conservative peasants. Simply put, while agricultural intensification (in non-mechanized cultivation) causes the productivity of land to increase, it causes the productivity of labor to decline. Each extra unit of labor produces less output per unit than did the first unit of labor. The natives and peasants produce less than they might for the simple reason that increasing production yields diminishing returns to labor.

Boserup's general principle has been amply verified. In northern Greece, for example, labor applied at an annual rate of about 200 hours per hectare is roughly 15 times more productive (in returns per hour of labor) than labor applied at 2000 hours per hectare. The latter farmer will certainly harvest more per hectare, but will harvest less per hour of work (Clark & Haswell, 1966; Wilkinson, 1973).

If extra labor is so inefficient, why undertake it? Boserup suggests (although here her thesis is somewhat oversimplified) that the factor that has historically driven agricultural intensification is population growth. Phrased in the terms of this essay, growth of population straining food supply presents an adaptive problem that can be addressed by intensifying food production—whether by adopting agriculture to supplement foraging (Cohen, 1977) or by applying greater labor to existing agriculture. In some cases subsistence intensification may amount only to the application of labor, while in other cases it involves increasing the complexity of labor (by adding extra steps such as field preparation, weeding, manuring, fallowing, or irrigation). Both strategies institutionalize higher costs in the production system.

Intensification of production leads to several outcomes. At its best it alleviates the shortfall and all is well. At its worst—directed from above by rulers to seek to maximize production for political purposes—it can destabilize productive systems and make an entire society vulnerable to collapse. On occasion it is serendipitous, bringing great increases in prosperity. There are telling historical examples.

Early states and empires had such capacity to mobilize labor and resources that we still marvel today at the monuments they built. Yet in these societies information about productive capacity seems to have been less developed than production itself. Rulers often seem not to have understood the capacity of the land and peasants to intensify production. They appear to have felt that compelling peasants to greater labor would always compensate for the declining productivity of land. The result was societies that underwent long periods of political growth, followed by economic stagnation, conquest by another state, or collapse. The Third Dynasty of Ur (ca. 2100–2000 B.C.) is a particularly dramatic example.

In southern Mesopotamia, bringing irrigation to the desert soils initially produces high yields along with prosperity, security, and stability. This was the strategy of the Third Dynasty of Ur. It extended irrigation and encouraged population and settlement growth. It established a complex bureaucracy to collect the revenues generated by high production. All was well for a few generations—at least for the rulers.

After a few years of over irrigating Mesopotamian soils, saline groundwater rises and ruins the soil. The Third Dynasty of Ur was destroyed by its own strategy for raising revenues—part of its problem solving efforts. Before the Third Dynasty of Ur, in the period ca. 2900 to 2300 B.C., crop yields had averaged about 2030 liters per hectare. By the end of the third millennium B.C. they had declined to 1134 liters. This decline in production (and hence in state revenues) seems to have been the problem that the Third Dynasty tried to overcome by intensifying production and increasing governmental complexity. Thus as yields declined and costs rose, farmers had to intensify their production to support a costlier state structure. It was clearly a course of diminishing returns to complexity.

The Third Dynasty of Ur persisted through five kings and then collapsed. The state had built an irrigation regime and administrative apparatus, and encouraged population levels, that could not be sustained without central government. When the administrative apparatus collapsed it took the countryside with it. By 1700 B.C. yields were down to 718 liters per hectare. More than one-fourth of the fields still in production yielded on average only about 370 liters per hectare. For equal efforts cultivators took in harvests less than one-fourth as large as those 800 years earlier. By the

end of the second millennium B.C. the number of settlements had dropped by 40 percent and the settled area had contracted by 77 percent. Population densities did not grow again to the level of Ur III for nearly 2500 years, when a new regime tried again to maximize production (Adams, 1978, 1981; Yoffee, 1988).

Happily, solving problems by intensifying production and increasing complexity does not always yield catastrophic results. The law of diminishing returns is occasionally superseded by the law of unintended consequences. In one of the most significant works of economic history, Richard Wilkinson (1973) described how the people of England responded to the problems of population growth and deforestation in the late Middle Ages and Renaissance. Population growth throughout this era led progressively to agricultural intensification and deforestation. As forests were cut to provide food and fuel for more and more people, the supply of wood no longer sufficed as it once had. Coal began increasingly to be used for heating and cooking. For several reasons this was done reluctantly. Coal was polluting, and it was not to be found everywhere. Entire new systems had to be devised to distribute it—canals and railways. Digging a fuel from the ground costs more than cutting a standing tree. Coal overall cost more per unit of heat than did wood, and had to be purchased with cash. Those forced to rely on coal, in at least its initial phases of adoption, experienced a decline in their financial well-being. Solving the problem of insufficiency of wood by using coal instead was at first another experience of diminishing returns to intensification and complexity. People solved their problems, but were worse off for it.

As the importance of coal grew its most accessible deposits were depleted. The cost of coal rose. Mines had to be sunk ever deeper until groundwater limited further mining. This was a vexatious problem, but it stimulated greatly the development of the steam engine. In time the steam engine was perfected enough to pump water efficiently from mines. The coal-based economy came to be institutionalized.

The remarkable part of this story is that, with the emergence of an economy based on coal, the development of a distribution network of canals and railways, and the refinement of the steam engine, several of the most important elements of the Industrial Revolution were in place. Coal, which initially produced diminishing returns and declining welfare, came with further technological refinement to subsidize increasing returns and great growth of welfare. The secret of the success was an energy source that could be developed to subsidize far more human activity than is possible solely by harvesting the products of photosynthesis, such as wood. Solving the problems of extracting and distributing coal raised transaction costs,

but this was more than offset by the prosperity arising from positive feedback and technological development. The outcome could not have been more different from what happened in ancient Mesopotamia. It is one of history's great ironies that industrialism, the great generator of economic well-being, emerged in part from solving the problem of resource depletion, which so often generates poverty and collapse.

The problem of producing resources confronts every human institution. Being rational and complexity (i.e., cost)-averse, humans always prefer to use resources that they know can be economically found, harvested, and put to use. We prefer to pluck the lowest fruit first. As such "first-line" resources become insufficient, the problem of producing more resources tends to raise complexity and increase costs, and thus decreases economic efficiency. Thus most of us now work far more than the two hours per day of simple cultivators. On occasion this intensification of production may generate an unexpected benefit, as in the deployment of coal, but often it leads to working harder just to maintain a constant income of resources.

Producing Knowledge

We see in the development of industrialism that producing knowledge (of, for example, steam engines and transportation) has as great a role in adaptive problem solving as producing resources. We are taught to think that knowledge is a good thing, and for the most part of course it is. Yet, except for those who must fund education or research, we rarely realize that knowledge has costs. Moreover, increasing knowledge is not always cost effective. As knowledge grows more complex, its production also becomes subject to diminishing returns. Bounded rationality and simple overproduction further reduce the effectiveness of information (March & Simon, 1958, p. 203; Rosen, 1991, p. 82; Simon, 1997, p. 119).

As any society increases in complexity it becomes more dependent on information, and its members require higher levels of education. In 1924 S. G. Strumilin evaluated the productivity of education in the newly-formed Soviet Union. The first two years of education, Strumilin found, raise a worker's skills an average of 14.5 percent per year. Adding a third year causes the productivity of education to decline, for skills rise only an additional eight percent. Four to six years of education raise workers' skills only a further four to five percent per year (Tul'chinskii, 1967, pp. 51–52). Education beyond the first two years in this case yielded diminishing returns.

In the United States a comprehensive study of the costs of education was published by Fritz Machlup (1962). In 1957–58, home education of pre-school children cost the United States $886,400,000 per year for

each age class from newborn through five. (This cost is primarily potential income foregone by parents.) In elementary and secondary school the costs increased to $2,564,538,462 per year per age class (for ages 6 through 18). For those who aspired to higher education (33.5 percent of the eligible population in 1960), a 4-year course of study cost the nation $3,189,250,000 per grade per year. Thus the monetary cost of education between pre-school, when the most general and broadly useful education takes place, and college, when the learning is most specialized, increased in the late 1950s by 1075 percent per capita. Yet from 1900 to 1960 the productivity of this investment for producing specialized expertise declined throughout (Fig. 1) (Machlup, 1962, pp. 79, 91, 104–105). As S. G. Strumilin found in the Soviet Union in 1924, higher levels of educational investment yield declining marginal returns.

Contemporary science, humanity's ultimate exercise in problem solving, shows parallel trends. The knowledge developed early in a scientific discipline tends to be generalized and inexpensive to produce. Thereafter

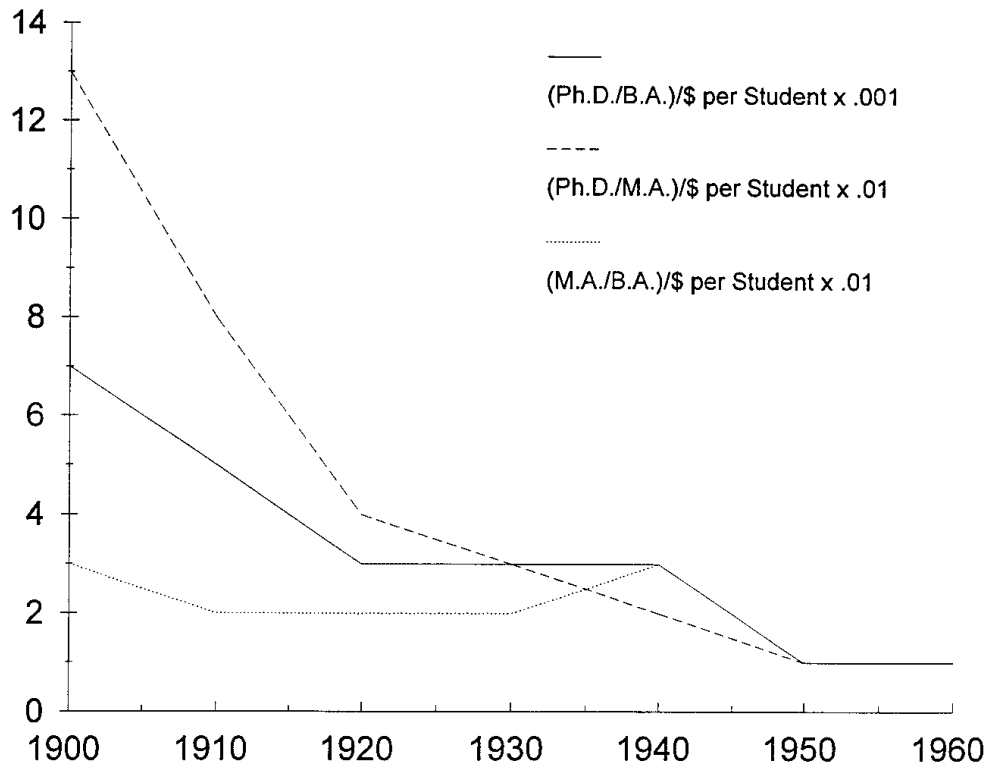

FIGURE 1. Productivity of educational investment for producing specialized expertise, U.S., 1900–1960 (data from Machlup, 1962, pp. 79, 91).

the work becomes increasingly specialized. Specialized research tends to be more costly and difficult to resolve, so that increasing investments yield declining marginal returns. Walter Rostow once argued that marginal productivity first rises and then falls in individual fields of research (1980, pp. 170–171). Even the great physicist Max Planck noted that ". . . with every advance [in science] the difficulty of the task is increased" (Rescher, 1980, p. 80). Nicholas Rescher has called this "Planck's Principle of Increasing Effort." As easier questions are resolved, science moves inevitably to more complex research topics and to more costly organizations (Rescher, 1980, pp. 93–94). Rescher suggests that "As science progresses within any of its specialized branches, there is a marked increase in the over-all resource-cost to realizing scientific findings of a given level [of] intrinsic significance . . ." (1978, p. 80). The size and costliness of science must grow *exponentially* just to maintain a *constant* rate of progress (Rescher, 1980, p. 92). Derek de Solla Price observed in 1963 that science was growing faster than either the population or the economy, and of all the scientists who had ever lived, 80–90 percent were still alive at that time (Price, 1963).

Scientists rarely think about the benefit/cost ratio to investment in their research. If we evaluate the productivity of our investment in science by some measure such as the issuance of patents (Fig. 2), however, the historical productivity of science appears to be declining. Patenting is a controver-

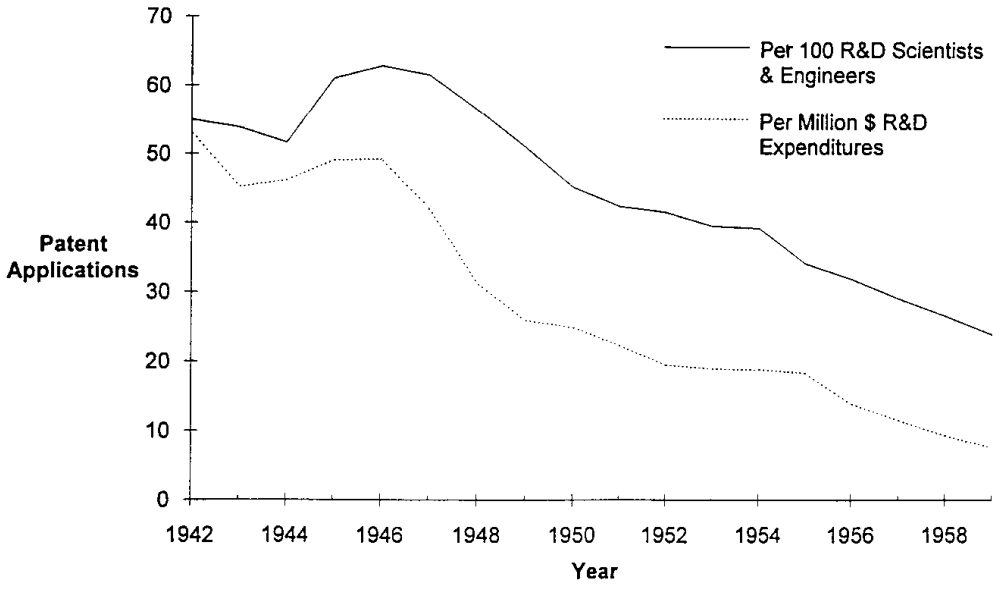

FIGURE 2. Patent applications in respect to research inputs, U.S., 1942–1958 (data from Machlup, 1962, p. 173).

sial measure of productivity (e.g., Machlup, 1962, pp. 174–175; Schmookler 1966; Griliches, 1984), but there is good evidence in a field of applied science where the return to investment can be readily determined: medicine. Over the 52-year period shown in Fig. 3, the productivity of the United States health care system for improving life expectancy declined by nearly 60 percent.

The declining productivity of the U.S. health care system illustrates clearly the historical development of problem-solving systems. Rescher points out:

> Once all of the findings at a given state-of-the-art level of investigative technology have been realized, one must move to a more expensive level. . . . In natural science we are involved in a technological arms race: with every "victory over nature" the difficulty of achieving the breakthroughs which lie ahead is increased. (1980, pp. 94, 97)

The productivity of medicine is declining because the inexpensive diseases and ailments were conquered first. The basic research that led to penicillin, for example, cost no more than $20,000. The remaining maladies

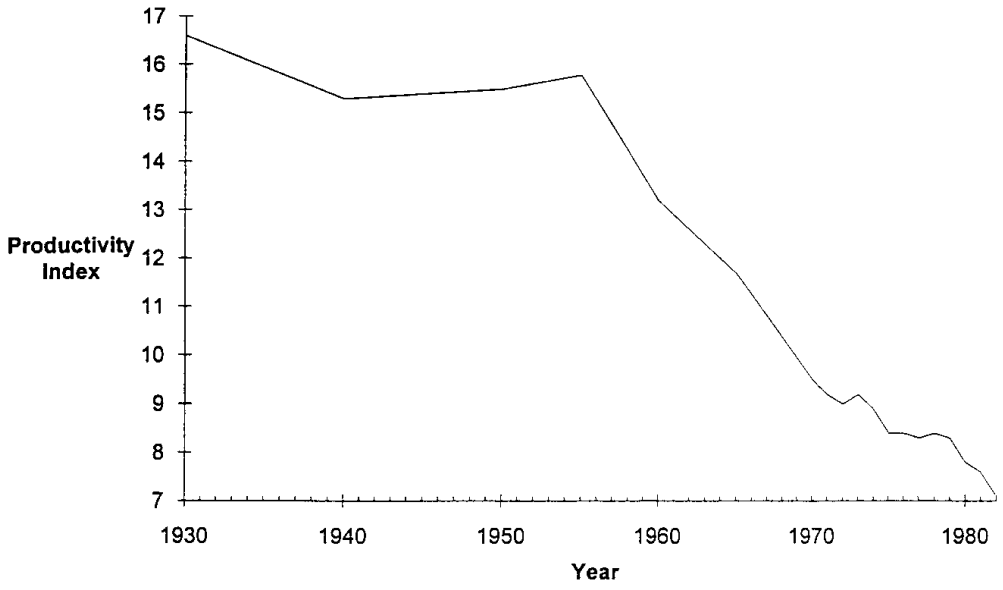

FIGURE 3. Productivity of the U.S. health care system, 1930–1982 (data from Worthington [1975, p. 5] and U.S. Bureau of the Census [1983, pp. 73, 102]). Productivity index = (Life expectancy)/(National health expenditures as percent of GNP).

are more difficult and costly to cure (Rescher, 1978, pp. 85–86; 1980, p. 52). As each increasingly expensive disease is conquered, the increment to average life expectancy becomes ever smaller. The marginal return to medical investment progressively declines.

Problem-solving, whether involving resources or information, commonly evolves along a path of increasing complexity and positive returns, then higher costs and diminishing returns (Tainter, 1988, 1995, 1996b). A system of problem-solving that follows such a trajectory cannot be sustained indefinitely, as the rulers of the Third Dynasty of Ur found to their collective dismay. Ultimately fiscal weakness and popular disaffection cause such systems to be terminated or to collapse. Yet commonly when the solution to a problem is decided upon, it is seen as a rational short-term measure. The higher complexity and higher cost of implementing the solution may appear only to be incremental and affordable. As Spencer would have predicted, cumulative and long-term effects, which typically are unforeseen, do the damage.

ADAPTIVE PROBLEM SOLVING: LONG-TERM CONSEQUENCES

Complexity has unintended consequences over the long term in part because it is cumulative. Each increment of complexity builds on what has gone before, so that complexity seems to grow exponentially. Moreover, each increment to complexity appears at its adoption to be a rational response to a problem. The additional cost seems reasonable and affordable. The fact that the problem was a short-term one is often forgotten, and so complexity comes to grow. This is the key to understanding the development of unsupportable complexity: it grows by small steps, each necessary, each a reasonable solution to a problem. Yet the first case study shows how cumulatively, over long periods of time, complex problem solving grows to a point of such costliness that it becomes unsupportable. This process is a powerful stimulus to social and economic change. It may enrich people, impoverish them, or even kill many of them (Tainter, 1988, 1999).

Governments are problem-solving systems that inherently attract challenges, which is one reason why they seem always to grow in size and complexity. It is not strictly correct to talk of institutions having goals (Aldrich, 1979, p. 4)—such a metaphor suffers from reification—but all long-term institutions incorporate mechanisms to ensure their continuity. These mechanisms include socializing members to a common set of values, and making the welfare of individuals congruent with or even dependent upon

the continuity of the institution. In this way the members of institutions set, and work toward, the goal of continuity. It is rare for an institution that has survived for a long time, or is intended to, voluntarily to disband. There is much to learn from the history of problem-solving institutions, of which the Roman Empire is one of the best examples.

The Western Roman Empire

The Roman Empire is paradoxically one of history's great successes and one of its great failures (Tainter, 1994). The fact that it could be both is understandable in the context of how its main problem-solving institutions—the government and army—experienced changing economies that ultimately affected millions of people both within the empire and without.

The Romans' early success came from a means of expansion that was fiscally self-perpetuating. Defeated peoples gave the economic basis, and some of the manpower, for further expansion. It was a strategy with positive economic returns. In 167 B.C., for example, the Romans were able to eliminate taxation of themselves and still expand the empire.

Empires eventually reach or even exceed a sustainable size. In the preindustrial era this occurred when the distance from the capital would grow so great that communication with the frontiers became slow and uncertain; or when insurmountable geographical barriers were reached; or when peoples were found whose conquest was uneconomical or impossible (Tainter, 1988, pp. 148–149). For Rome, the most efficient empire would have consisted of the Mediterranean fringe, which could be administered easily by sea. Once the Romans had the Mediterranean, though, the lands they held were always threatened by new enemies further inland. To alleviate these threats the Romans expanded into the interior of Asia, to the Danube and beyond, and into northwestern Europe. In these places the empire found, or even exceeded, its limits of both territory and economy, for administration by land travel was always less efficient than by sea. Attempts at further conquest—in Scotland, central Europe, and Mesopotamia—showed that continued expansion would be too costly. Only a salient known as Dacia was held across the Danube, from the early second century until the early 270s. The Romans were correct in the threats that they perceived, for it was from precisely these areas that raids and invasions were repeatedly launched in later centuries.

Cicero once complained that of all Rome's conquests, only Asia yielded a surplus. There is a point worth examining in this exaggeration, for the economics of empire are seductive but illusory. The returns to any campaign of conquest are highest initially, when the accumulated surpluses

of the conquered peoples are appropriated. Thereafter the conqueror assumes the cost of administering and defending the province. In the case of Rome these responsibilities lasted for centuries, and had to be paid for from year-to-year agricultural surpluses. The Roman Empire was powered by solar energy, which provides an economy with little surplus production per capita (Jones, 1964, pp. 841–844; 1974, pp. 37–39, 83, 138; Tainter, 1988, p. 149; 1994). Once the phase of conquest is over, the cost of empire rises and benefits decline. Even the first emperor, Augustus (27 B.C.–14 A.D.), complained of fiscal shortages, and made up state deficits from his own purse (Gibbon, 1776–88, p. 140; Hammond, 1946, p. 75; Frank, 1940, pp. 7–9, 15).

The government financed by agricultural taxes barely sufficed for ordinary administration. When extraordinary expenses arose, typically during wars, the precious metals on hand frequently were insufficient. Facing the costs of war with Parthia and rebuilding Rome after the Great Fire, Nero (54–68) began in 64 A.D. a policy that later emperors found irresistible. He debased the primary silver coin, the denarius, reducing the alloy from 98 to 93 percent silver. It was the first step down a slope that resulted two centuries later in a currency that was worthless and a government that was insolvent (Fig. 4).

After decades of relative stability the empire's position deteriorated sharply during the reign of Marcus Aurelius (161–180). Invasions of Parthians from the east and Germans from the north coincided with an outbreak of plague that killed from one-fourth to one-third of the population (Boak, 1955, p. 19; Mazzarino, 1966, p. 152; McNeill, 1976, p. 116; Russell, 1958, pp. 36–37). The empire survived these challenges, but hereafter the currency was debased more frequently. In 194–195 the emperor Septimius Severus (193–211), in what is called the Great Debasement, lowered the silver to about 56 percent (Walker, 1978).

The half-century from 235 to 284 was a time of unparalleled crisis, during which the empire nearly came to an end. There were foreign and civil wars, which followed one upon another almost without interruption. Over this period there were 26 legitimate emperors, and as many as 50 usurpers or about 1 insurrection per year. Germans and Persians invaded repeatedly. Cities were sacked and frontier provinces devastated. The empire shrank in the 260s (temporarily, as it turned out) to Italy, the Balkans, and North Africa. By prodigious effort and sacrifice the empire survived the crisis, but at great cost. It emerged at the turn of the fourth century A.D. as a very different organization.

Great changes were needed in the government and the political system. Diocletian (284–305) and Constantine (306–337) responded with

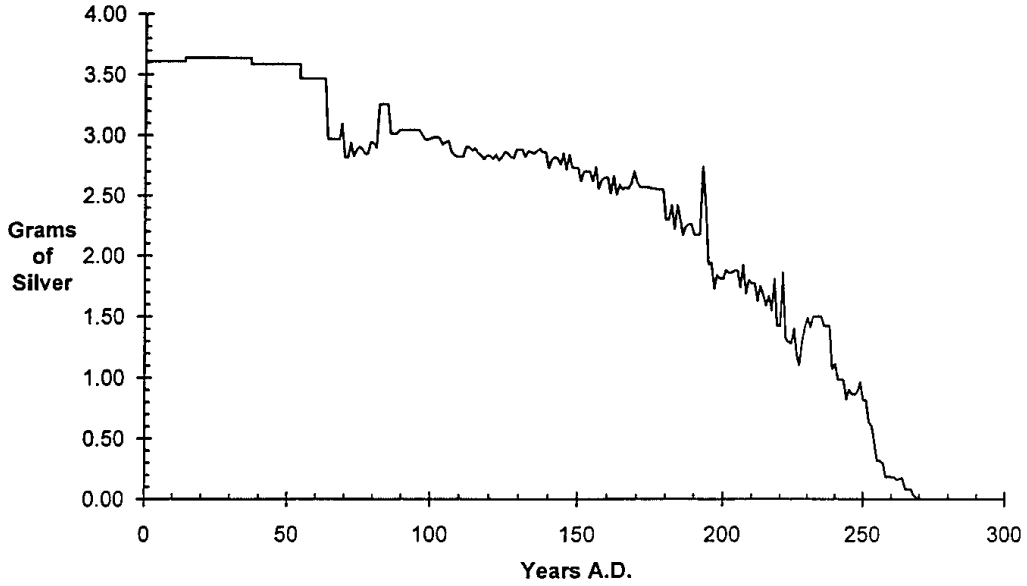

FIGURE 4. Debasement of the denarius to 269 A.D. (data from Cope [1969, 1974, and unpublished analyses on file in the British Museum]; King [1982]; LeGentilhomme [1962]; Tyler [1975]; and Walker [1976, 1977, 1978]; see also Besly & Bland [1983, pp. 26–27] and Tainter [1994, p. 217]).

sweeping political and economic changes that transformed the empire. The government they designed was larger, more complex, and more highly organized. They doubled the size of the army, so that it may have stood as high as 650,000 by the end of the fourth century. To pay for this the government taxed its citizens more heavily, conscripted their labor, and dictated their occupations. It became a coercive, omnipresent state that tabulated and amassed all resources for its own survival.

Many internal transactions came to be closely regulated. Diocletian established Rome's first budget, and each year a tax rate was calculated to provide the revenue. The tax was established from a master list of the empire's people and lands, tabulated down to individual households and fields. Taxes apparently doubled between 324 and 364. Villages were responsible for the taxes on their members, and one village could even be held liable for another. The government conscripted men for the army and requisitioned services from guilds. Occupations were made hereditary and obligatory. Positions that had once been eagerly sought, such as in city senates, became burdensome as leading citizens were held responsible for tax deficiencies.

Despite several monetary reforms a stable currency could not be found (Fig. 5). As masses of worthless coins were produced, prices rose higher and higher. In the second century a *modius* of wheat (about nine liters) had sold during normal harvests for about 1/2 denarius. In Diocletian's Edict on Prices (301) the price was set at 100 denarii. In 335 a *modius* of wheat sold in Egypt for over 6000 denarii, and in 338 for over 10,000 (Jones, 1964, pp. 27, 119). Money-changers in the east would not convert imperial currency, and the government refused to accept its own coins for taxes. Much of a soldier's pay was provided in supplies rather than in the worthless coins (Meyer, 1987; Van Meter, 1991, p. 47; Jones, 1964, p. 27; 1974, p. 201; Duncan-Jones, 1990, p. 115; Williams, 1985, p. 79; Mattingly, 1960, pp. 222–223; Hodgett, 1972, p. 38).

The tax system supporting the more complex government and larger army had unforeseen consequences. After the plagues of the second and third centuries conditions were never favorable for population to recover. Peasants could not support large families. Despite government edicts, marginal lands went out of cultivation. In some provinces, up to one-third to one-half of arable lands came to be deserted by the late empire. There were

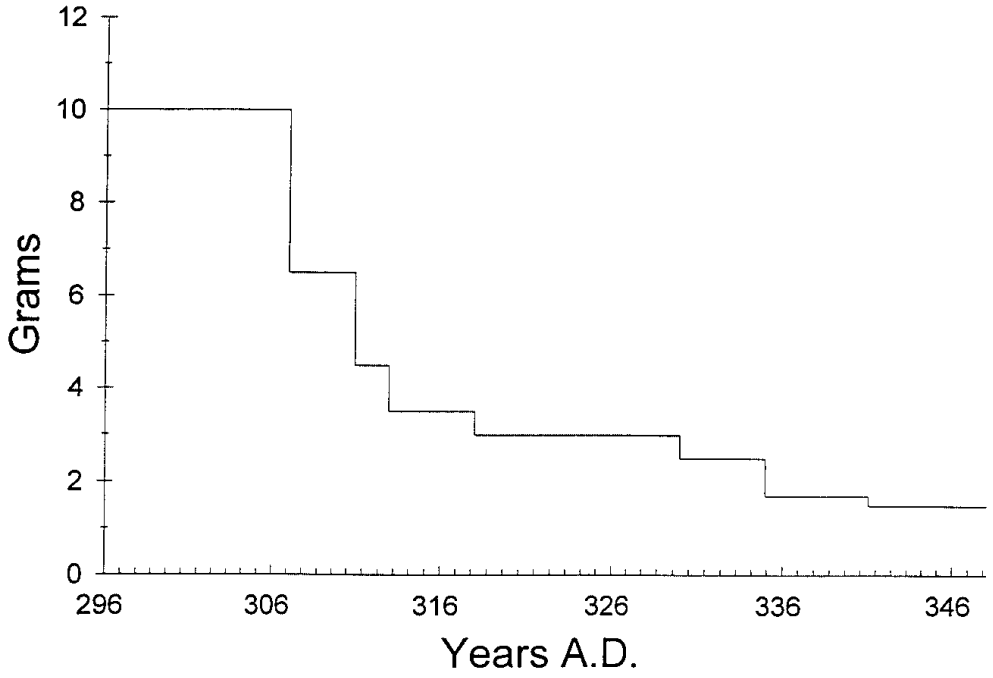

FIGURE 5. Reductions in the weight of the follis, 296–348 A.D. (data from Van Meter, 1991, p. 47).

shortages of labor in agriculture, industry, the military, and the civil service. Faced with taxes, peasants would abandon their lands and flee to the protection of a wealthy landowner, who was glad to have the extra labor. Feudal relations emerged, and in lieu of peasants the landowners offered vagabonds or even slaves for military service (McNeill, 1976, p. 116; Russell, 1958, p. 140; Boak, 1955; Jones, 1964, 1974; MacMullen, 1976, pp. 182–183; Wickham, 1984). By 400 A.D. most of Gaul and Italy were owned by less than a dozen senatorial families (Williams, 1985, p. 214), who had the power to defy the government's tax demands.

From the late fourth century the barbarians could no longer be kept out. They forced their way into Roman lands in western Europe and North Africa, initially causing great destruction. The government had no choice but to acknowledge them as legitimate rulers of the territories they occupied. The Germanic kings kept the revenues of these territories and, although they defended what was left of the empire, they did not do so reliably. Throughout the fifth century the western empire was in a negative feedback loop tending toward collapse. Lost or devastated provinces meant lower government income and less military strength. Lower military strength in turn meant that more areas would be lost or ravaged. By 448 Rome had lost most of Spain (Barker, 1924, pp. 413–414). After 461 Italy and Gaul had little connection. The empire shrank to Italy and adjacent lands. The most important ruler in the West was no longer the Roman Emperor but the Vandal King, Gaiseric, in North Africa (Ferrill, 1986, p. 154; Wickham, 1981, p. 20).

In the 20 years following the death of Valentinian III (455), the Roman army proper dwindled to nothing. The government came to rely almost exclusively on troops from Germanic tribes. Finally these could not be paid. They demanded one-third of the land in Italy in lieu of pay. This being refused, they revolted, elected Odoacer as their king, and deposed the last emperor in Italy, Romulus Augustulus, in 476. The Roman Senate informed the Eastern Emperor, Zeno, that an emperor in Italy was no longer needed (Jones, 1964, p. 244).

The strategy of the later Roman Empire was to respond to a near-fatal challenge in the third century by increasing the size, complexity, power, and costliness of the primary problem-solving system—the government and its army. Limited by bounded rationality, Roman officials could not foresee the consequences of this strategy. The higher costs were undertaken not to expand the empire or to acquire new wealth, but to sustain the status quo. The benefit/cost ratio of imperial government declined as it lost both legitimacy and support (Tainter, 1988, 1994). In the end the Western Roman Empire could no longer afford the problem of its own existence.

The Early Byzantine Recovery

The debacle in Western Europe during the fifth century meant the end of the Western Roman state, but the Eastern Roman Empire (usually known as the Byzantine Empire) persisted under its own emperors, changing greatly and coming to an end only when the Turks took Constantinople in 1453. For much of its history it lost territory, so that by the end the state consisted only of the city itself. Yet during the tenth and early eleventh centuries Byzantium was on the offensive, and doubled the territory under its control. There is a lesson in complexity and problem solving in the steps that made this possible.

The most urgent needs of the eastern emperors were to develop the economic base on which military security depended, and to improve the effectiveness of the army. Both tasks were begun by Anastasius (491–518). He established a sound coinage in the copper denominations on which daily life depended, thereby revitalizing commerce. As part of his financial reforms, Anastasius gave the army cash to buy rations, uniforms, and arms, rather than issuing these. The allowances were evidently generous, so that the army attracted large numbers of native volunteers. Barbarian mercenaries and their generals continued to be employed, but became much less important (Treadgold, 1996). Within a few decades these economic and military reforms had produced such results that Justinian (527–565) could both increase the size of the follis (the most valuable of the copper coins) and, after defeating Persia, attempt to recover the western provinces.

An army sent to North Africa in 532 conquered the Kingdom of the Vandals within a year. Almost immediately, the Byzantine general, Belisarius, was sent to reconquer Italy. He had taken Rome and Ravenna, captured the Ostrogothic King, and conquered all of Italy south of the Po when he was recalled in 540 to fight the Persians again.

In 541, just when the job in Italy seemed about done, bubonic plague swept over the empire. It had not been seen before in the Mediterranean, and took four years to run its course. Like any disease introduced to a population with no resistance, the effects were devastating. Just as in the fourteenth century, the plague of the sixth century killed from one-fourth to one-third of the population.

The enormous loss of taxpayers caused immediate financial problems. A reserve of 29 million gold solidi amassed by Anastasius and Justin (518–527) was soon gone. Army pay fell into arrears, and troops either mutinied or handed conquests (even the city of Rome) back to the enemy. The Ostrogoths recovered and retook most of Italy. The field army of Byzantine Italy had to be rebuilt twice. The Moors took much of Byzantine Africa.

The population was so depleted by plague that more barbarian mercenaries had to be recruited, and these had to be paid in gold. By debasing the currency and slashing expenditures, the Emperor was able to send another army to Italy in 552, and even to back a rebellion against the Visigothic king of Spain. Italy was reconquered by 554, but the last Ostrogoths held out until 561. In 558, though, the plague returned, and again military pay fell short. Justinian managed to conquer only about the southern fifth of Spain.

At his death in 565 Justinian left a greatly enlarged empire, but the new conquests proved hard to hold with population and treasury both depleted. Within four years the Visigoths attacked in Spain and the Moors in Africa. The Lombards invaded Italy and took most of the interior by 572. War resumed with Persia. Slavs and Avars (a coalition of tribes related to the Huns) crossed the Danube. The Byzantines again defeated the Persians, but the Slavs raided all the way to Greece. To pay for these wars, the alloy of the gold solidus had to be debased by adding silver, and the weight of the copper follis was regularly reduced (Fig. 6) (Harl, 1996, pp. 195–197).

The wars also took a toll on the Persians, and in 590 rebels overthrew the Persian king. The Byzantine Emperor Maurice Tiberius (582–602) put the king's son on the Persian throne, but had to attend to problems in the Balkans. Byzantine troops defeated the Avars and Slavs, and by 599 practi-

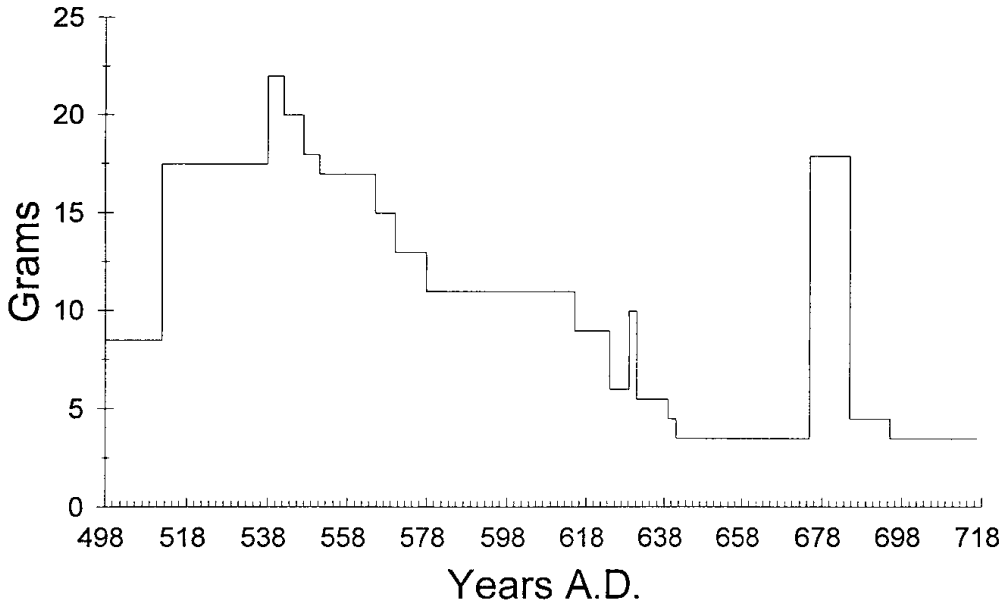

FIGURE 6. Weight of the Byzantine follis, 498–717 A.D. (data from Harl, 1996, p. 197).

cally cleared them from the Balkans. But the empire's resources were stretched by these conflicts. After the campaigns against Persia and in the Balkans, there was no money to send troops to Italy. In 602 Maurice ordered his troops to winter north of the Danube. They mutinied, marched on Constantinople, and killed the emperor. The Persian King Khosrau II vowed to avenge his benefactor and, grasping at the pretext, began to snatch Byzantine provinces. Thus began a crisis that lasted for over a century and nearly brought the empire to an end.

The empire was so disorganized by these troubles that there was a general military breakdown in the Balkans and Asia. The Slavs and Avars overran the Balkans again. The Persians spread through Asia Minor. North Africa and Egypt successfully rebelled and placed Heraclius (610–641) on the Byzantine throne. The empire he took over lay in ruins and was financially exhausted. The Persians reached the Bosporus (opposite Constantinople) in 615. In 619 they began the conquest of Egypt, the empire's richest province. Constantinople was besieged from 618 to 626.

Existing resources could not fund a recovery. In 615 church treasures were melted down to meet government expenses, from which silver coins were issued with the inscription "God save the Romans." Heraclius cut the pay of troops and officials by half in 616. Bronze was needed for arms and armor, so Heraclius followed his predecessors by further lowering the weight of the follis (Fig. 6). Many times the mint simply took larger coins minted in the sixth century, chiseled them into fragments, and restruck each piece as a follis. The strategy was clearly inflationary.

Heraclius' economic measures bought time for his military strategy to work. He counterattacked with increasing success starting in 622. In 626 the siege of Constantinople was broken, and the following year the emperor began to advance into Persian territory. In 627 Heraclius destroyed the Persian army and in 628 occupied the Persian king's favorite residence. The Persians had no choice but to agree to peace. The Byzantines got all their lost territory returned. The war had lasted 26 years, and resulted in no more than restoration of the status quo of a generation earlier.

The empire was exhausted by the struggle and Heraclius's great victory was not to last. Arab forces, newly converted to Islam, broke into imperial territory in 634 and two years later defeated the Byzantine army decisively. Syria and Palestine, which had taken 18 years to recover, were lost again. Egypt was taken in 641. The wealthiest provinces were permanently gone, and soon the empire was reduced to Anatolia, Armenia, North Africa, Sicily, and parts of Italy. The Persians fared even worse, for the Arabs conquered their empire completely.

Under Constans II (641–668) and throughout the seventh century, the

strategic situation continued to deteriorate. The Arabs built their first fleet in 641, and with it took the capital of Cyprus. They ravaged Rhodes in 654, and defeated the Byzantine fleet the next year. The Arabs raided Asia Minor nearly every year for two centuries. Constantinople itself was besieged each year from 674 to 678. The Bulgars, a new enemy, broke into the empire from the north. The Arabs took Carthage in 697. From 717 to 718 an Arab force besieged Constantinople continuously for over a year. The city was saved in the summer of 718, when the Byzantines ambushed reinforcements sent through Asia Minor. It was a turning point in a centuries-long struggle. The Arabs had to withdraw and were never again able to mount such a threat.

In the century before the victory of 718 the political and economic life of the eastern Mediterranean had been utterly transformed. The huge empire that the Romans had assembled was almost gone. Debasements and inflation had ruined monetary standards and the fiscal and economic institutions which depended on them. There were no longer standard weights to copper coins and monetary exchange was undermined. Around 659 Constans cut military pay in half again. With army pay by the 660s cut to one-fourth its level of 615, the government no longer pumped coins into the economy. By 700 most people within or formerly within the empire no longer used coins in everyday transactions. In most Mediterranean lands the economy ceased to have a monetary basis. The economy developed into its medieval form, organized around self-sufficient manors (Harl, 1996).

One can scarcely imagine the magnitude of the transformation required to save what was left of Byzantium. A way of life to which the peoples of the eastern Mediterranean had been accustomed for over a millennium had to be given up. As discussed in the previous section, the emperors of the late third and early fourth centuries had responded to a similar crisis by complexification. They increased the complexity of administration, the regimentation of the population, and the size of the army. This was paid for by levels of taxation so harmful that lands were abandoned and peasants could not replenish the population. Constans II and his successors could hardly impose more of the same exploitation on the depleted population of the shrunken empire. Instead they adopted a strategy that is truly rare in the history of complex societies: simplification.

Arab civil war from 659 to 663 caused the caliph in Syria to purchase a truce. The respite allowed Constans II to undertake fundamental transformations. The government had lost so much revenue that even at one-fourth the previous rate it could not pay its troops. Constans' solution was to devise a way for the army to support itself. He lacked ready cash but the

imperial family had vast estates—perhaps one-fifth of the land in the empire. There was also much land abandoned from the Persian attacks. Such lands were divided among the troops. In Asia Minor and other parts of the empire, divisions of troops—called themes—were settled in new military zones. Soldiers (and later sailors) were given grants of land on condition of hereditary military service. It was apparently at this time that Constans halved military pay, for he now expected the troops to provide their own livelihood through farming (with a small monetary supplement). Correspondingly the Byzantine fiscal administration was greatly simplified.

The transformation ramified throughout Byzantine society, as any fundamental economic change must. Both central and provincial government were simplified, and the transaction costs of government were reduced. In the provinces, the civil administration was merged into the military. Cities across Anatolia contracted to fortified hilltops. Aristocratic life focused on the imperial court. There was little education beyond basic literacy and numeracy, and literature itself consisted of little more than lives of saints (Haldon, 1990; Treadgold, 1988, 1995, 1997). The period is sometimes called the Byzantine Dark Age.

The results of the simplification were evident almost immediately. The system of themes rejuvenated Byzantium. A class of peasant-soldiers was formed across the empire. The new farmer-soldiers had obligations to no landowners, only to the state. They became producers rather than consumers of the empire's wealth. They formed a new type of army in which military obligation, and the lands that went with it, were passed to the eldest son. From this new class of farmers came the force that sustained the empire. By lowering the cost of military defense the Byzantines secured a better return on their most important investment.

Byzantines forces began to put up stiffer resistance to the Arabs, as evident in the victories of 678 and 718. The empire began to lose land at a much slower rate. The Arabs continued to raid Anatolia but were unable to hold any of it for long. Soldiers were always near at hand. Fighting as they were for their own lands and families, they had much greater incentive and performed better. After the establishment of the themes the Arabs made progress in Anatolia only when the empire had internal troubles from 695 to 717. By 745 Constantine V was able to invade the Caliphate, the first successful invasion of Arab territory in a generation.

During the next century, campaigns against the Bulgars and Slavs gradually extended the empire in the Balkans. Greece was recaptured. Pay was increased after 840, yet gold became so plentiful that in 867 Michael III met an army payroll by melting down 20,000 pounds of ornaments from the throne room. When marines were added to the imperial fleet it became

more effective against Arab pirates. In the tenth century the Byzantines reconquered parts of coastal Syria. Overall after 840 the size of the empire was nearly doubled. The process culminated when Basil II (963–1025) conquered the Bulgars and extended the empire's boundaries again to the Danube. In two centuries the Byzantines had gone from near disintegration to being the premier power in Europe and the Near East, an accomplishment won by decreasing the complexity and costliness of problem solving.

The Development of Modern Europe

Arms races are the classic example of diminishing returns to complexity. Any competitive nation will quickly match an opponent's advances in armaments, personnel, logistics, or intelligence, so that investments in these areas typically yield no *lasting* advantage or security. In an arms race, each competitor strives for advantage over its rivals, while the rivals strive to counter these and develop advantages of their own. Usually no state can gain an overwhelming advantage that lasts very long. More and more money, resources, and personnel are spent on that most fleeting of products: military advantage. The costs of being a competitive state continuously rise, while the return on investment inexorably declines. All the while a state must search continuously for the resources to remain competitive, and develop an organization to deploy those resources effectively. The unfolding of this process in Europe of the last millennium altered not only European societies, but ultimately changed the entire world. I will outline the development of this process from the fifteenth through the early nineteenth centuries.

Europe before 1815 was almost always at war somewhere. From the twelfth through the sixteenth centuries France was at war from a low of 47 percent of years in some centuries, to a high of 77 percent in others. For England the range was 48 to 82 percent; for Spain, 47 to 92 percent. Even in the most peaceful centuries these nations were at war, on average, nearly every other year. In the whole of the sixteenth century there was barely a decade when Europe was entirely at peace. The seventeenth century enjoyed only 4 years of total peace; the eighteenth century, 16 years (Parker, 1988, p. 1; Rasler & Thompson, 1989, p. 40).

In the fifteenth century, siege guns ended the advantage of stone castles, and required changes in the strategies and technology of defense. From the early fifteenth century, builders designed fortifications that could support defensive cannon. A short time later walls were built that could also survive bombardment. By 1560 all the elements of the *trace italienne* had been developed, a fortification system of low, thick walls with angled bas-

tions and extensive outworks. It was effective but expensive. In 1553 the city of Siena found it so costly to build such fortifications that no money was left for its army or fleet. Siena was annexed by Florence, against which, ironically, its fortifications had been built (Creveld, 1989, pp. 101–103; Parker, 1988, pp. 7, 9, 12).

Trace italienne fortifications, if one could afford them, were a worthy investment. It could take months or years to capture a place defended in this way. Offensive tacticians responded with more complicated siege methods, and their costs rose as well. A force of perhaps 50,000 besiegers had to be kept in place for weeks or months. Such a force needed 475 tons of food per day, to which was added ammunition, powder, and building materials. From this time on, local lords could not afford to build and defend an effective fortress, nor to attack one. The resources for war had now to be sought in capitalist towns rather than in the feudal countryside (Creveld, 1989, 106–108; Parker, 1988, p. 13). The scale of conflict developed from local or regional to national.

Open-field warfare also developed greater complexity. In the fourteenth and fifteenth centuries massed archers and the pike phalanx made the armored knight obsolete. These were in turn superseded by firearms. To make effective use of firearms took organization and drill. Infantry had to be drawn up in closely coordinated ranks. Those in the rear would reload while the lead musketeers fired, and quick changes of position gave an uninterrupted application of fire (Creveld, 1989, pp. 89–91; Kennedy, 1987, p. 21; Parker, 1988, pp. 16–20). Tactics were developed to increase the efficiency and effectiveness of firing. Textbooks of military drill were published across the continent. Training and battlefield coordination became more important: ranks had to open and close on signal, while uneducated soldiers had to be familiar with what were, at the time, history's most advanced weapons. Victory came to depend not on simple force, but on the right combination of infantry, cavalry, firearms, cannon, and reserves (Creveld, 1989, pp. 92–94; Parker, 1988 pp. 18–23).

War came to involve ever-larger segments of society and became progressively more burdensome. Several European states saw the sizes of their armies increase tenfold between 1500 and 1700. Louis XIV's army stood at 273,000 in 1691. Five years later it was at 395,000, and nearly one-fourth of all adult Frenchmen were in the military. Between 1560 and 1659 Castile lost about eleven percent of its adult male population in the constant wars (Sundberg et al., 1994, p. 13). Each day, a field army of 30,000 needed 100,000 pounds of flour, and 1500 sheep or 150 cattle. Only the largest cities required more (Creveld, 1989, pp. 112–113; Parker, 1988, pp. 2, 45–46, 75).

Yet despite or because of these developments, land warfare became largely stalemated. There were few lasting breakthroughs. The new technologies, and mercenaries, could be bought by any power with money. No nation could gain a lasting advantage. When a nation such as Spain or France threatened to become dominant, alliances would form against it (Kennedy, 1987, 21–22). Major wars were slow and tedious, and were often decided by cumulative small victories and the slow erosion of the enemy's economic base. Defeated nations quickly recovered, though, and were soon ready to fight again. Warfare evolved of necessity into global flanking operations. European competition expanded into contests for power and influence overseas (Parker, 1988, pp. 43, 80–82).

Europeans employed the wealth from trade and colonization to sustain their ever-more-costly competition (Kennedy, 1987, pp. 24, 27–28, 43, 46–47, 52; Tainter, 1992, pp. 110, 124). The development of sea power and acquisition of colonies became part of the strategy of stalemated European warfare. Because of this, European war ultimately affected and changed the entire world. By 1914 the nations of Europe, and their offshoots, controlled fully 84% of the earth's surface (Parker, 1988, p. 5).

The naval powers of the time were England, the Netherlands, Sweden, Denmark/Norway, France, and Spain. From 1650 to 1680 the five northern powers increased their navies from 140,000 to 400,000 tons. In the 1630s the Dutch merchant fleet required the building of 300 to 400 new ships each year, about half of which were employed in Baltic trade (from which England imported much of its raw material for naval supplies). Between the 1630s and 1650 the Dutch merchant fleet grew by 533 percent (Sundberg et al., 1994, pp. 38, 42). Yet expanding navies entailed further problems of increasing complexity and cost. In 1511, for example, James IV of Scotland commissioned the building of the ship *Great Michael*. It took almost one-half of a year's income to build, and ten percent of his annual budget for seamen's wages. It was sold to France three years later, and ended its days rotting in Brest harbor (Parker, 1988, p. 90).

As the size and complexity of armies grew through the eighteenth and nineteenth centuries new fields of specialization were needed, such as surveying and cartography. It was necessary to have accurate clocks and statistical reporting. Some eighteenth-century armies carried their own printing presses. Organization became more complex. Staff and administration were separated. Armies no longer marched as a unit, but could be split into smaller elements that traveled, under instructions, on their own. Battles came to last up to several months (Creveld, 1989, pp. 114, 117–122; Parker, 1988, p. 153).

In 1499 Louis XII asked what was needed to ensure a successful cam-

paign in Italy. He was told that three things alone were required: money, money, and still more money (Sundberg et al., 1994, p. 10). As military affairs grew in size and complexity finance became the main constraint. The cost of putting a soldier in the field increased by 500 percent in the decades before 1630. Nations spent more and more of their income on war, but it was never enough. In 1513, for example, England obligated 90 percent of its budget to military efforts. In 1657 the figure was 92 percent. In the mid eighteenth century Frederick the Great allocated 90 percent of his income to war. In 1643, expenditures of the French government, mainly on war, came to twice the annual income (Kennedy, 1987, pp. 58, 60, 63). England's wars in the 1540s cost about ten times the crown's income (Kennedy, 1987, p. 60).

Sweden financed its wars through a combination of low population, untapped forest reserves, and eager markets for its products. The major states, lacking such advantages, had to rely on credit. Even with riches from her New World colonies, Spain's debts rose from 6 million ducats in 1556 to 180 million a century later. War loans grew from about 18 percent interest in the 1520s to 49 percent in the 1550s. Both France and Spain often had to declare bankruptcy, or force a lowering of the rate of interest. From the sixteenth through the eighteenth centuries the Dutch, followed by the English, overcame these fiscal constraints by gaining access to reliable short-term and long-term credit. Being careful to pay the interest on loans, they were granted more favorable terms than other nations. They used this advantage to defeat opponents, France and Spain, that were wealthier but poor credit risks (Parker, 1988, p. 63–67; Rasler & Thompson, 1989, pp. 91, 94, 96, 103).

The wars raised permanently the cost of being a competitive state, and war-induced debt levels persisted long after the fighting ceased. Power always shifts, and victorious nations were never able to dominate for very long (Kennedy, 1987; Rasler & Thompson, 1989, pp. 106, 175–176). Many people of the time understood the futility of European wars, but arms races are especially difficult to break. In 1775 Frederick the Great eloquently described the state of affairs.

> The ambitious should consider above all that armaments and military discipline being much the same throughout Europe, and alliances as a rule producing an equality of force between belligerent parties, all that princes can expect from the greatest advantages at present is to acquire, by accumulation of successes, either some small city on the frontier, or some territory which will not pay interest on the expenses of the war, and whose

> population does not even approach the number of citizens who perished in the campaigns. (Quoted in Parker [1988, p. 149])

As land warfare in Europe produced no lasting advantages, the expansion of competition to the global arena was a logical consequence. Competition expanded to include trade, capturing overseas territories, establishing colonies, attacking adversaries' colonies, and intercepting shipments of bullion and valuables. Yet even the foreign wealth could not meet the cost of some campaigns. In 1552 the Hapsburg Emperor Charles V spent 2.5 million ducats on a campaign at Metz, an amount equal to 10 times his American income. By the 1580s Phillip II was receiving 2 million ducats a year from American mines, but the ill-fated armada of 1588 cost five times that (Kennedy, 1987, pp. 46–47). Even with this massive transfer of bullion from the New World, Spain's debt grew 3,000 percent in the century following 1556, and bankruptcy caused Spanish military operations to fail. Clearly they would have failed much earlier (or not been undertaken) if Spain had not been able to draw upon New World wealth.

European competition stimulated great complexity in the form of technological innovation, development of science, political transformation, and global expansion. To subsidize European competition it became necessary to secure the produce of foreign lands (and later fossil fuels). New forms of energy, and non-local resources, were channeled into this small part of the world. This concentration of global resources allowed European conflict to reach heights of complexity and costliness that could never have been sustained with European resources alone (Tainter, 1992, pp. 123–125). For better or worse the repercussions of centuries of European war are a legacy in which we still participate, and will for the foreseeable future.

PROBLEM SOLVING AND SUSTAINABILITY: DIVERGENT OUTCOMES

These cases were chosen to illustrate quite different outcomes to long-term, adaptive, organizational problem solving. There is one case of collapse (the Western Roman Empire), one of sustainability through simplification (the early Byzantine recovery), and one of sustainable problem solving based on growing complexity and energy subsidies (Europe). There are lessons in these cases for the problem solving efforts of any institution, today or in the future, that is intended to last.

The Western Roman Empire

The lessons of the Western Roman Empire are that (a) a society or other institution can be destroyed by the cost of sustaining itself, and (b) complexity in problem solving does its damage subtly, unforeseeably, and cumulatively over the long term.

The Roman Empire, like all empires, was founded on the expectation of high returns to conquest. Yet by the second century A.D Rome's enemies had grown stronger while the empire had stopped expanding. Fighting increasingly took place within the empire itself, and ordinary budgets often would not suffice to defend the state. The problems became acute in the third century when forces of Persians, Germanic war bands, and contending Romans crossed and ravaged the empire. A primary strategy to meet the costs of these crises (mainly military costs) was to debase the currency. There was no choice: the crises had to be contained whatever the true cost to the future.

Victories in the late third century gave a respite to implement a longer-term strategy, which was to increase the size and complexity of the problem-solving system (government and its army), and to organize the empire to produce the resources this required. To gain the required revenues every unit of production was counted, whether person, land, ship, or cart. Levels of taxation were established and the empire's agents were sent to ensure collection. Nothing was allowed to interfere. If peasants abandoned their fields they were returned to work, or the lands assigned to others. Essential occupations were made hereditary. The survival of the empire took precedence over the well-being of its producers. Each of these controls exacerbated transaction costs.

The irony is that each step to ensure continuity—whether debased currency, larger army, frozen labor, or increased control—was a rational solution to an immediate problem. Had any of these steps not been taken the empire would not have survived as long as it did. Yet each step degraded the well-being of the producers on whom survival depended. In time the productive system declined, lands were abandoned, and the peasant population first declined and then stagnated. Emperors, constrained by bounded rationality, could not foresee these ramifications. In the end the costliness and complexity of the problem-solving system made collapse inevitable.

The Early Byzantine Recovery

Rulers of the ancient world had been accustomed to ordering resources and having them delivered. It took a crisis of unprecedented proportions to

convince the rulers of this empire that they could no longer live and compete as they formerly did. The Byzantines perceived this during the crises of the seventh century, during which they lost half their empire and seemed about to lose the rest. The population had not recovered from the sixth century plague when the Persian invasion of the early 600s destroyed urban life in Asia Minor, and both the Persians and later the Arabs took into slavery as many of the remaining inhabitants as they could catch. Taxes dwindled and the government could no longer support the army. Arab victory seemed inevitable.

The Byzantine Empire responded with one of history's only examples of a complex society simplifying. Much of the structure of ranks and honors, based on urban life, disappeared. Civil administration simplified and merged in the countryside with the military. Governmental transaction costs were reduced. The economy contracted and there were fewer artisans and merchants. Elite social life focused on the capitol and the emperor, rather than on the cities that no longer existed. Literacy, writing, and education declined. Barter and feudal social relations replaced the millennium-old monetary economy.

Most fundamentally, the Byzantine government cut dramatically the cost of its most expensive part, the army, while simultaneously making it more effective. No longer did peasants have to support themselves and a recently ineffectual army. The army became landholders and producers much like the peasants. The land soldiers defended was their own. The people they defended were kin and neighbors. Accordingly they fought better than before and the government obtained a better return on their cost. Almost immediately the army began to perform better. The empire stopped losing land so rapidly and in time took the offensive. In this case the problem-solving strategy was not complexity, but simplification after a long period of increased complexity.

Europe

Sustainability in the case of warring Europe was richly complex. Here is a case that had all the ingredients of disaster—increasing complexity, high costs, military stalemate, and an impoverished support population—yet it contributed to the industrial world that we know today and to history's most capable systems of problem solving. War is such a consumer of wealth (as seen in the Roman, Byzantine, and European cases) that modern Europe (and its offshoots and imitators) might never have come to be. War consumes wealth not only through physical destruction, but more insidiously through the costs of preparing for and conducting it. Complexity and

costs are driven ever higher. European wars had to be supported by a peasantry that grew ever more desperate. If there was ever a political system that should have been vulnerable to collapse from its own costs, it was Europe of the last millennium.

There are two primary reasons why today's prosperity emerged from so many centuries of misery. The first is that the competition forced Europeans continuously to innovate in technological prowess, organizational abilities, and systems of finance. They were forced to become more adept at manipulating and distributing matter and energy. The second reason is that they got lucky: they stumbled upon great subsidies. Over the ocean they found new lands that could be conquered, and their resources turned to European advantage. European prowess at war meant that the peoples and governments of those lands were rather easily overwhelmed. More recently new subsidies (fossil and nuclear fuels) were developed that fund complexity, problem solving, and welfare today. Thus from the fifteenth century on Europe found the resources to develop levels of complexity that would have been impossible to support by the solar energy falling on Europe alone. Without these subsidies (that is, without this luck), Europe and the world today would be quite different.

CONCLUSIONS

We have learned much about the success and failure of institutions from the fields of organizational decision-making, organizational ecology, and learning organizations. The problems of bounded rationality, unforeseeable consequences, and transaction costs underlie the approach developed here. These fields have been limited, though, to the study of short-term change. In the case of organizations such as states, to look for proximate reasons for failure is to look only at the tail end of a long process. The science of organizations must become historical.

Complexity is a long-term paradox of problem solving. It facilitates the resolution of problems in the short run while undermining the ability to solve them in the long term. Maintaining a society or other kind of institution requires that the problem-solving system itself be sustainable. The case studies of this essay allow us to describe possible outcomes to long-term trends in problem solving.

1. *The Roman Model.* Problem solving drives increasing complexity and costs that cannot be subsidized by new sources of energy. In time there are diminishing returns to problem solving. Problem solving continues by

extracting higher levels of resources from the productive system. Fiscal weakness and disaffection of the population in time compromise problem solving and initiate collapse.

2. *The Byzantine Model.* The institution, perhaps no longer having sufficient resources to increase complexity, deliberately simplifies. Costs are greatly reduced and, perhaps more importantly, the productive system is enhanced. It is a strategy that in the Byzantine case allowed for fiscal recovery and eventually for expansion. This is also the strategy employed by many American firms over the past 20 years, where simplification of management and elimination of costs contributed to competition and recovery.

3. *The European Model.* Uncontrolled competition can lead to ever-increasing complexity. It drives consumption of resources regardless of long-term cost, for the immediate alternative may be extinction. It is a risky situation that can lead to the collapse of all contenders, as it seems to have done in the case of the southern lowland Classic Maya (Tainter, 1988, 1992). The Europeans averted this trap in part through competition-induced ingenuity, but largely also through luck.

The point of examining these outcomes is both to understand the consequences of complexity and problem solving and to peer into our possible futures. Our societies and institutions have increased greatly in complexity over the past few centuries. This complexity is sustained by our current energy subsidies, primarily fossil fuels. We do not know how long this dependency can continue. Campbell and Laherrère (1998) argue that the petroleum basis for our present complexity may begin to diminish within a few years. We can prepare for this with a full understanding of how problem-solving systems develop, cognizant of the options of (a) complexity and diminishing returns, (b) simplification, or (c) growing complexity based on further subsidies. Or we can hope for a repeat of the luck enjoyed by Europeans and some of the colonies they established. The only thing that is certain about the future is that it will present challenges. We can gamble that our problem-solving institutions will suffice to meet those challenges, and accept the consequences if they do not. Or we can increase our chances of being sustainable by understanding problem solving itself, the trends by which it develops, and the factors that make it successful or not. The consequences are enormous: had European luck proved otherwise the dilemma of complexity in problem solving might have been described by a future scholar who would lump Renaissance Europe with the Western Roman Empire as another example of collapse.

ACKNOWLEDGMENTS

I am pleased to express my thanks to Virginia Abernethy and an anonymous reviewer for comments on an earlier version of this paper.

REFERENCES

Adams, R. McC. (1978). Strategies of maximization, stability, and resilience in Mesopotamian society, settlement, and agriculture. *Proceedings of the American Philosophical Society* 122, 329–335.

Adams, R. McC. (1981). *Heartland of cities.* Chicago: Aldine.

Alcock, S. E. (1993). *Graecia capta: the landscapes of Roman Greece.* Cambridge: Cambridge University Press.

Aldrich, H. E. (1979). *Organizations and environments.* Englewood Cliffs: Prentice-Hall.

Allen, T. F. H., Tainter, J. A., & Hoekstra, T. W. (1999). Supply-side sustainability. *Systems Research and Behavioral Science* 16, 403–427.

Barker, E. (1924). Italy and the West, 410–476. In *The Cambridge medieval history,* Volume 1, *the Christian Roman Empire and the foundation of the Teutonic order* (second edition). Gwatkin, H. M. & Whitney, J. P. (Eds.), pp. 392–431. Cambridge: Cambridge University Press.

Baum, J. A. C. & Singh, J. V. (1994a). Organizational hierarchies and evolutionary processes: some reflections on a theory of organizational evolution. In *Evolutionary dynamics of organizations.* Baum, J. A. C. & Singh J. V. (Eds.), pp. 3–20. New York and Oxford: Oxford University Press.

Baum, J. A. C. & Singh, J. V. (1994b). Organizational niches and the dynamics of organizational mortality. *American Journal of Sociology* 100, 346–380.

Bendix, R. (1956). *Work and authority in industry.* New York: Wiley.

Besly, E. & Bland, R. (1983). *The Cunetio Treasure: Roman coinage of the third century AD.* London: British Museum.

Boak, A. E. R. (1955). *Manpower shortage and the fall of the Roman Empire in the West.* Ann Arbor: University of Michigan Press.

Boserup, E. (1965). *The conditions of agricultural growth: the economics of agrarian change under population pressure.* Chicago: Aldine.

Campbell, C. J. & Laherrère, J. H. (1998). The end of cheap oil. *Scientific American* 278(3), 78–83.

Chayanov, A. V. (1966). *The theory of peasant economy.* Smith, R. E. F. & Lane, Christel (Trans.). Homewood: Richard D. Irwin for the American Economic Association.

Clark, C. & Haswell, M. (1966). *The economics of subsistence agriculture.* London: Macmillan.

Coase, R. H. (1937). The nature of the firm. *Economica* 4(n.s.), 386–405.

Cohen, M. N. (1977). *The food crisis in prehistory: overpopulation and the origins of agriculture.* New Haven: Yale University Press.

Cope, L. H. (1969). The nadir of the imperial Antoninianus in the reign of Claudius II Gothicus, A.D. 268–270. *The Numismatic Chronicle* 7, 9, 145–161.

Cope, L. H. (1974). The metallurgical development of the Roman Imperial coinage during the first five centuries A.D. Ph.D. dissertation, Liverpool Polytechnic.

Creveld, M. van (1989). *Technology and war, from 2000 B.C. to the present.* New York: Free Press.

Duncan-Jones, R. (1990). *Structure and scale in the Roman economy.* Cambridge: Cambridge University Press.

Ferrill, A. (1986). *The fall of the Roman Empire: the military explanation.* London: Thames and Hudson.

Frank, T. (1940). *An economic survey of ancient Rome,* Volume V: *Rome and Italy of the Empire.* Baltimore: Johns Hopkins University Press.

Gibbon, E. (1776–1788). *The decline and fall of the Roman Empire.* New York: Modern Library.

Griliches, Z. (1984). Introduction. In *R & D, patents, and productivity.* Griliches, Z (Ed.), pp. 1–19. Chicago and London: University of Chicago Press.

Haldon, J. F. (1990). *Byzantium in the seventh century: the transformation of a culture.* Cambridge: Cambridge University Press.

Hall, Charles A. S., Cleveland, C. J., & Kaufmann, R. (1992). *Energy and resource quality: the ecology of the economic process.* Niwot: University Press of Colorado.

Hammond, M. (1946). Economic stagnation in the early Roman Empire. *Journal of Economic History, Supplement* 6, 63–90.

Hannon, M. T. & Carroll, G. R. (1992). *Dynamics of organizational populations: density, legitimation, and competition.* New York: Oxford University Press.

Harl, K. W. (1996). *Coinage in the Roman economy, 300 B.C. to A.D. 700.* Baltimore: Johns Hopkins University Press.

Hodgett, G. A. J. (1972). *A social and economic history of medieval Europe.* London: Methuen.

Jones, A. H. M. (1964). *The later Roman Empire, 284–602: a social, economic and administrative survey.* Norman: University of Oklahoma Press.

Jones, A. H. M. (1974). *The Roman economy: studies in ancient economic and administrative history.* Oxford: Basil Blackwell.

Kennedy, P. (1987). *The rise and fall of the great powers: economic change and military conflict from 1500 to 2000.* New York: Random House.

King, C. E. (1982). Issues from the Rome mint during the sole reign of Gallienus. *Actes du 9ème Congrès International de Numismatique,* 467–485. Louvain-la-Neuve: Association Internationale des Numismates Professionels.

Lee, R. B. (1968). What hunters do for a living, or, how to make out on scarce resources. In *Man the hunter.* Lee, R. B. & DeVore, I. (Eds), pp. 30–48. Chicago: Aldine.

Lee, R. B. (1969). Eating Christmas in the Kalahari. *Natural History* 78(10), 14, 16, 18, 21–2, 60–3.

Le Gentilhomme, P. (1962). Variations du titre de l'Antoninianus au IIIe siècle. *Revue Numismatique* VI Série, Tome IV, 141–66.

Luttwak, E. N. (1976). *The grand strategy of the Roman Empire from the first century A.D. to the third.* Baltimore and London: Johns Hopkins University Press.

Machlup, F. (1962). *The production and distribution of knowledge in the United States.* Princeton: Princeton University Press.

MacMullen, R. (1976). *Roman government's response to crisis, A.D. 235–337.* New Haven and London: Yale University Press.

March, J. G. & Olsen, J. P. (1986). Garbage can models of decision-making in organizations. In *Ambiguity and command: organizational perspectives on military decision making.* March, J. G. & Weissinger-Baylon, R. (Eds.), pp. 11–35. Marshfield: Pitman.

March, J. G. & Simon, H. A. (1958). *Organizations.* New York: Wiley.

Mazzarino, S. (1966). *The end of the ancient world.* Holmes, G. (Trans.). London: Faber and Faber.

McNeill, W. H. (1976). *Plagues and peoples.* Garden City: Anchor/Doubleday.

Meyer, J. L. (1987). The monetary reforms of Aurelian and Diocletian. *Roman Coins and Culture* 3(2), 20–42.

Parker, G. (1988). *The military revolution: military innovation and the rise of the West, 1500–1800.* Cambridge: Cambridge University Press.

Polybius (1979). *The rise of the Roman Empire.* (*The Histories,* Scott-Kilvert, I. [Trans.]). Harmondsworth: Penguin.

Price, D. de Solla (1963). *Little science, big science.* New York: Columbia University Press.

Price, T. D. & Brown, J. A. (Eds.). *Prehistoric hunter-gatherers: the emergence of cultural complexity*. Orlando: Academic Press.

Rasler, K. & Thompson, W. R. (1989). *War and state making: the shaping of the global powers*. Boston: Unwin Hyman.

Renfrew, A. C. (1982). Polity and power: interaction, intensification and exploitation. In *An island polity: the archaeology of exploitation on Melos*. Renfrew, C. & Wagstaff, M. (Eds.), pp. 264–290. Cambridge: Cambridge University Press.

Rescher, N. (1978). *Scientific progress: a philosophical essay on the economics of research in natural science*. Pittsburgh: University of Pittsburgh Press.

Rescher, N. (1980). *Unpopular essays on technological progress*. Pittsburgh: University of Pittsburgh Press.

Rosen, S. (1991). Transaction costs and internal labor markets. In *The nature of the firm: origins, evolution, and development*. Williamson, O. E. & Winter, S. G. (Eds.), pp. 75–89. New York: Oxford University Press.

Rostow, W. W. (1980). *Why the poor get richer and the rich slow down*. Austin: University of Texas Press.

Russell, J. C. (1958). Late ancient and medieval population. *Transactions of the American Philosophical Society* 48(3).

Sahlins, M. (1972). *Stone Age economics*. Chicago: Aldine.

Schmookler, J. (1966). *Invention and economic growth*. Cambridge: Harvard University Press.

Senge, P. M. (1990). *The fifth discipline: the art and practice of the learning organization*. New York: Doubleday.

Service, R. F. (1997). Making single electrons compute. *Science* 275, 303–304.

Simon, H. A. (1997). *Administrative behavior: a study of decision-making processes in administrative organizations*. Fourth Edition. New York: Free Press.

Spencer, H. (1972). *On social evolution*. Peel, J. D. Y. (Ed.). Chicago: University of Chicago Press.

Sundberg, U., Lindegren, J., Odum, H. T., & Doherty, S. (1994). Forest EMERGY basis for Swedish power in the 17th Century. *Scandinavian Journal of Forest Research, Supplement* 1.

Tainter, J. A. (1988). *The collapse of complex societies*. Cambridge: Cambridge University Press.

Tainter, J. A. (1992). Evolutionary consequences of war. In *Effects of war on society*. Ausenda, G. (Ed.), pp. 103–130. San Marino: Center for Interdisciplinary Research on Social Stress.

Tainter, J. A. (1994). La fine dell'amministrazione centrale: il collaso dell'Impero Romano in Occidente. In *Storia d'Europa*, Volume Secondo: *preistoria e antichità*. Guilaine, J. & Settis, S. (Eds.) pp. 1207–1255. Turin: Einaudi.

Tainter, J. A. (1995). Sustainability of complex societies. *Futures* 27, 397–407.

Tainter, J. A. (1996a). Introduction: prehistoric societies as evolving complex systems. In *Evolving complexity and environmental risk in the prehistoric Southwest*. Tainter, J. A. & Tainter, B. B. (Eds.), pp. 1–23. Santa Fe Institute, *Studies in the Sciences of Complexity*, Proceedings Volume XXIV. Reading: Addison-Wesley.

Tainter, J. A. (1996b). Complexity, problem solving, and sustainable societies. In *Getting down to earth: practical applications of Ecological Economics*. Costanza, R., Segura, O., & Martinez-Alier, J. (Eds.), pp. 61–76. Washington, DC: Island Press.

Tainter, J. A. (1997). Cultural conflict and sustainable development: managing subsistence hunting in Alaska. In *Sustainable development of boreal forests: proceedings of the 7th International Conference of the International Boreal Forest Research Association*, pp. 155–161. Moscow: All-Russian Research and Information Center for Forest Resources.

Tainter, J. A. (1999). Post-collapse societies. In *Companion encyclopedia of Archaeology*. Barker, G. (Ed.), pp. 988–1039. London: Routledge.

Tainter, J. A. (2000). Global change, history, and sustainability. In *The way the wind blows: climate, history, and human action*. McIntosh, R. J., Tainter, J. A., & McIntosh, S. K. (Eds.), pp. 331–356. New York: Columbia University Press.

Toumey, C. P. (1996). *Conjuring science: scientific symbols and cultural meanings in American life.* New Brunswick: Rutgers University Press.

Treadgold, W. (1988). *The Byzantine revival, 780–842.* Stanford: Stanford University Press.

Treadgold, W. (1995) *Byzantium and its army, 284–1081.* Stanford: Stanford University Press.

Treadgold, W. (1997). *A history of the Byzantine state and society.* Stanford: Stanford University Press.

Tul'chinskii, L. I. (1967). Problems in the profitability of investments in public education. *Soviet Review* 8(1), 46–54.

Tyler, P. (1975). The Persian wars of the 3rd century A.D. and Roman imperial monetary policy, A.D. 253–68. *Historia, Einzelschriften* 23.

U. S. Bureau of the Census (1983). *Statistical abstract of the United States: 1984* (104th edition). Washington, D.C.: U.S. Government Printing Office.

Van Meter, D. (1991). *The handbook of Roman imperial coins.* Nashua: Laurion Numismatics.

Walker, D. R. (1976). The metrology of the Roman silver coinage, part I, from Augustus to Domitian. *British Archaeological Reports, Supplementary Series* 5.

Walker, D. R. (1977). The metrology of the Roman silver coinage, part II, from Nerva to Commodus. *British Archaeological Reports, Supplementary Series* 22.

Walker, D. R. (1978). The metrology of the Roman silver coinage, part III, from Pertinax to Uranius Antoninus. *British Archaeological Reports, Supplementary Series* 40.

White, L. A. (1949). *The science of culture.* New York: Farrar, Straus and Giroux.

White, L. A. (1959). *The evolution of culture.* New York: McGraw-Hill.

Wickham, C. (1981). *Early medieval Italy: central power and local society 400–1000.* London: Macmillan.

Wickham, C. (1984). The other transition: from the ancient world to feudalism. *Past and Present* 103, 3–36.

Wilkinson, R. G. (1973). *Poverty and progress: an ecological model of economic development.* London: Methuen.

Williams, S. (1985). *Diocletian and the Roman recovery.* New York: Methuen.

Worthington, N. L. (1975). National health expenditures, 1929–74. *Social Security Bulletin* 38(2), 3–20.

Yoffee, N. (1988). The collapse of ancient Mesopotamian states and civilization. In *The collapse of ancient states and civilizations.* Yoffee, N. & Cowgill, G. L. (Eds.), pp. 44–68. Tucson: University of Arizona Press.