

Abstract

"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." (p. 3)

- the long-term consequences of organisational problem solving is rarely considered in the moment
- not understanding the development of problem solving has helped to contribute to the 'collapse' of institutions of complex societies
- the fields that study problem solving are increasingly helping to clarify why institutions stagnate/thrive
- solutions that appear successful in the moment can lead to failure later
- understanding how problem-solving systems develop over time is a historical science and should consider pre/history
- to help understand general principles over time, 3 case studies are presented

Constraints to Organisational Effectiveness and Durability

- problem-solving effectiveness is impacted by environmental structure (including other institutions), internal transaction efficiency, and human cognition and information processing limits
- early in a society's life, organisational types grow slowly but do accelerate to a peak and then often plateau
- legitimation and competition regulate this process
- as a particular organisation proliferates, it gains in legitimacy leading to reduced resistance to further proliferation
- such growth, however, eventually encounters resource limits resulting in competition, reduced proliferation, and increasing organisational mortality
- internal constraints tend to be of more immediate concern than external ones
- hierarchies can simplify but encounter diminishing returns as the system grows (e.g., increase in transaction costs and waste)
- humans tend to simplify the complexity of issues/problems via decision-making models/rules
- the decisions arrived at may propose a 'solution' with only tenuous connection with the problem and lead to system-wide consequences that may appear years/decades after put into place

Development of Problem Solving

- "Human societies and their institutions must, among other characteristics, be problem-solving systems...[They exist] 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 have learned." (p. 6)
- our ahistorical society has lost sight of the fact that societies can over time lose effectiveness in solving problems
- complexity has come to be considered an (perhaps THE) important factor in a society's success/failure in problem solving, and thus the primary focus of this paper

- human societies tend to become more complex (more parts, types of parts, and integration of parts), especially over the past 12,000 years since hunting-gathering groups (and only the last 5000 years for state-level societies)
- humans tend to be averse to complexity which may explain low voter turnout (governments always increase it) and science's Occam's Razor Principle (simple explanations are superior to complex ones)
- there exists a cost (i.e., energy, labour, time, money) to complexity
- a simple society (i.e., hunting gathering) requires only about 1/20th horsepower per capita per year (human-based energy); complex, industrial society requires substantially more
- while complexity has significant costs, it also provides utility in problem solving
- “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.” (p. 7)
- human labour supported complexity costs for a long time
- in its early phases, positive feedback can increase returns
- we develop complex technologies, add elements to an institution (e.g., specialists, controls, etc.), and increase gathering/processing of information
- complexity expands when a problem is addressed and since problems always arise, complexity inexorably grows
- as an adaptive, problem-solving strategy, complexity can be viewed as an economic function where a society invests in it with initial strategies being effective (since the simple, inexpensive solutions are adopted first) but gradually loses effectiveness (as more complex, expensive solutions are employed)
- ever-increasing returns as complexity expands is impossible and ‘solutions’ oftentimes have unforeseen consequences with additional costs
- investments yield ever smaller returns and can lead to a society becoming more vulnerable to collapse (what some refer to as a ‘dark age’)
- we can see this process at work in societal resource and information production; two issues addressed via economically-rational ways

Producing Resources

- people initially access/use the easiest-to-acquire/process/distribute/consume resource first
- as consumption increases and/or resource availability decreases more difficult-to-acquire/process/distribute/consume ones are used (almost always requiring more effort/cost with no greater return)
- while modern, industrial societies display a tendency to produce as much as possible, many societies have produced far less (producing only enough for base sufficiency) and enjoyed much more leisure time
- in *The Conditions of Agricultural Growth*, Ester Boserup found that “...while agricultural intensification (in non-mechanised 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.” (p. 11)
- since extra labour is inefficient, many don't engage in it
- it seems that only when population pressure increases is agricultural intensification pursued
- “...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 or by applying greater labor to existing agriculture.” (p. 11)
- it may also consist of increasing labour complexity (e.g., manure, weeding, irrigation, etc.)
- production intensification may alleviate shortfalls, or destabilise systems making them vulnerable to collapse
- it can also, on occasion, lead to great prosperity perhaps because there enlisted a large capacity to mobilise resources and labour

- Ur's Third Dynasty is a great example of the above
- irrigation helped the desert soils of southern Mesopotamia provided high yields leading to population and settlement growth
- a complex bureaucracy was established to collect revenues from the surplus
- this continued for several generations but over-irrigation increased saline content reducing soil fertility and leading to declining productivity
- attempts to counter this by way of production intensification and increased bureaucratic complexity occurred
- costs increased as yields declined—classic diminishing returns that ended in societal collapse when the central government failed
- it was another 2500 years before a new regime attempted to intensify production and complexity again
- on occasion, production intensification and increased complexity does not result in collapse and the law of diminishing returns is superseded by unintended positive consequences
- in the late Middle Ages and Renaissance periods of England, population growth led to agricultural intensification and deforestation
- as the supply of wood dwindled, people increasingly turned to coal for heating/cooking
- as coal was concentrated in certain regions, transportation systems (i.e., roads, canals) were expanded to help distribute it
- coal costs increased as a result leaving people less wealthy so the 'problem' was 'solved' but people were less well off as a result
- as coal use grew, easily accessible deposits were increasingly depleted causing costs to rise even further
- mines also had to go deeper and encountered limited production due to groundwater issues
- this stimulated the development of the steam engine in order to help pump water
- these developments laid the foundation for the Industrial Revolution
- coal's initial declining welfare was reversed
- "The secret of 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." (p. 13)
- transaction costs increased but were offset by increased prosperity and technological development
- every human institution must confront the problem of resource production and our tendency is to first use the easiest-/cheapest-to-access
- costs increase as initial resources are used up or insufficient for growing needs leading to production intensification
- in rare circumstances, unexpected benefits can arise but usually we end up working harder simply to maintain resource levels

Producing Knowledge

- knowledge production can be as adaptive as resource production in problem solving
- while knowledge can be a good thing, it also has costs and increasing it is not always cost effective for as it increases in complexity it encounters diminishing returns
- as a society increases in complexity it becomes more dependent upon information and members require greater education, however, the productivity of education declines over time (that is, each additional year of education after the first couple results in decreasing increases of productivity)
- even science shows this diminishing return as more complex research requires more investment, with costs rising exponentially just to maintain 'progress' rates
- Tainter quotes another (Rescher, 1980) who argues, "Once all 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 technology arms race: with every victory over nature, the difficulty of achieving breakthroughs which lie ahead is increased." (p. 18)

- medicine productivity, for example, declines because the easier and less expensive to address diseases are conquered first, with the more difficult and expensive ones to attempt
- problem solving leads to increases in complexity and positive returns, but then encounters diminishing returns and higher costs
- such a path is not sustainable in perpetuity
- fiscal weakness and dissatisfaction causes such a system to collapse or self-terminate
- solutions that are pursued are viewed as rational, short-term measures with the increased complexity and costs appearing affordable and only slightly incremental at the time
- however, the unforeseen cumulative and long-term impacts irreparably damage the system

Adaptive Problem Solving: Long-Term Consequences

- the unintended consequences of increasing complexity over the long term arise because of their cumulative (i.e., exponential) nature
- each increase is a rational solution to a problem but this is soon forgotten, and subsequent solutions build upon that which is already present—increasing complexity and costs
- “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.” (p. 19)
- over the long term, problem solving becomes too expensive to support
- this process leads to significant socioeconomic changes that can enrich, impoverish, or kill many
- government is one such problem-solving institution that tends to grow in size and complexity
- while long-term institutions don’t necessarily have long-term goals, they do incorporate mechanisms to sustain themselves (e.g., members are socialised towards common values; welfare dependency based upon institutional continuity)

The Western Roman Empire

- this empire demonstrated both success and failure
- the changing economics of its two main problem-solving institutions (i.e., government and military) impacted millions (domestic and foreign)
- empires tend to exceed a sustainable size
- in the pre-industrial era it was the distance and geography/geology from the capital that served to slow communication with the frontier, or encountering people/lands that were uneconomic/impossible to conquer
- expanding inland from the Mediterranean (that their navy controlled) or further afield (e.g., Scotland, Mesopotamia, Egypt, etc.) proved much more costly and stretched resources
- the economics of imperialism are such that returns are greatest upon initial subjugation when surpluses are appropriated but then encounter diminishing returns as governing costs (e.g., administration, defense) are assumed—and typically paid for via agricultural surpluses
- being powered by solar energy (i.e., photosynthesis), there existed little surplus production
- agricultural taxes barely covered regular administration
- when circumstances required (e.g., war) more revenue, national treasuries (i.e., precious metals) were insufficient leading to currency devaluation that eventually led to insolvency
- foreign invasions coincided with plague pandemics (ca 161-180 A.D.) that the empire survived but increased the speed of currency debasement
- 235-284 A.D. witnessed both civil and foreign wars, 26 different emperors, 50 usurpers, and an insurrection almost yearly; invasions were frequent with border cities/provinces devastated
- by the 4th century, the empire was a different organisation

- the governing system was larger, more complex, and highly organised; the army was doubled in size; taxes were increased significantly; labour was conscripted and occupations dictated
- the empire “became a coercive, omnipresent state that tabulated and amassed all resources for its own survival.” (p. 22)
- internal transactions were closely regulated
- taxes doubled between 324 and 364 with villages responsible not just for their own members but also nearby villages
- men were conscripted for the military and the various guilds served at the behest of the government
- leading citizens were held responsible for tax deficiencies
- currency stability was fleeting with prices always increasing
- even the government stopped accepting its own currency for taxes
- soldiers were paid with supplies rather than coin
- one unintended consequence of the burdensome tax system was, despite edicts to the contrary, land being abandoned—first the marginal lands; then even good, arable land ($\frac{1}{3}$ to $\frac{1}{2}$ by late empire)
- labour shortages arose (partially due to population loss because of pandemics) everywhere
- many peasants abandoned their land because of the taxes, seeking protection from wealthy landowners
- about a dozen senatorial families ended up owning most of Gaul and Italy by 400 A.D.
- barbarians invaded and controlled more and more areas, with many being recognised as legitimate rulers by the failing Roman government
- the 5th century witnessed a negative feedback loop where lost provinces meant lost revenue, less military strength, and then more lost regions
- eventually the Roman military disbanded with the government using Germanic tribes instead but they ended up overthrowing the emperor when they weren’t paid—marking the end of the Western Empire (476 A.D.)
- the late empire responded to its 3rd century challenges by increasing its two main problem-solving systems’ (government and military) size, complexity, power, and costs
- this was done to sustain the status quo systems, not expand/grow the empire
- as the benefit/cost ratio of the governing system fell, it lost legitimacy and support, eventually ‘collapsing’

The Early Byzantine Recovery

- while the Western Empire dissolved, the Eastern (Byzantine) one persisted until the Turks took Constantinople in 1453
- it lost territory over time, consisting of just the city proper at the end, but had doubled in size early on (10th and early 11th centuries)
- early on, the Eastern Empire developed its economy in order to afford its military security
- this was performed by establishing sound copper-based coinage
- generous allowances for those serving in the military attracted many domestic volunteers reducing the need for foreign mercenaries
- expansion was going well until the bubonic plague swept over the empire (541), killing 25-33% of the population and lead to huge revenue losses
- the national treasury was quickly depleted resulting in military mutinies and losses
- some recovery occurred using mercenaries, but plague returned
- currency debasement was used in an attempt to extend the empire’s wealth
- resources were stretched as conflicts persisted; troops could not be sent to Italy and they mutinied, marching on Constantinople and killed the emperor
- the resulting chaos lasted a century, with Persia expanding over the conquered lands
- the government melted down church treasures to fund itself

- inflation grew as currency debasement grew
- eventually the Persians were repelled but then the Arabs attacked and the empire lost territory again (Persia was completely conquered)
- the Arabs continued to expand during the 7th century
- a turning point occurred in 718 with a major victory causing the Arabs to feel from their siege of Constantinople
- with the constant war and related currency debasement, the economy had shifted towards self-sufficient manors
- where emperors of the 3rd and 4th century crises responded with increasing complexity, those of the 7th and 8th centuries choose to 'simplify' society
- rather than pay the military with debased currency, the state granted them land so long as their family participated in hereditary military service
- pay was subsequently halved, and Byzantine administration was simplified in the process
- civic and military administrations were merged with cities contracting to fortified hilltops; education and literacy were reduced to basic/minimal knowledge
- a class of peasant-soldiers arose with obligations only to the state with land and military service passing to the eldest male offspring
- these changes increased the benefit/cost ratio for society dramatically
- military victories reduced Arab expansion with soldiers always at hand and eager to protect 'their' land
- by 745, Byzantine went on the offensive, invading the Caliphate
- over the next century, lost regions were retaken (e.g., Balkans, Greece) and military pay increased
- the resurgence of the empire appears to have been a direct result of decreasing complexity and the costliness of problem solving

The Development of Modern Europe

- a classic example of diminishing returns on complexity is an arms race with competitors desperately striving to match or exceed each other's capabilities
- advantages don't last long and increasing resources are funnelled into the race
- costs continue to rise while returns decline
- in Europe, the last millennium demonstrates this well
- Tainter draws on the 1400-1815 time period
- before 1815, there was always a war occurring somewhere in Europe
- siege guns (15th century) ended stone castle advantages, but defensive cannons were soon developed as well as walls that could withstand bombardment
- these fortifications were expensive and quickly drained treasuries, leaving no funds for large militaries
- more complicated (and expensive) siege methods were developed, resulting in resources being drawn from regional and national areas rather than just local
- open-field warfare shifted from archers and armoured knights to firearms with the evolution of firearm tactics of increased training and coordination between infantry, cavalry, firearms, cannon, and reserves
- ever-larger segments of society were required to be involved with state militaries increasing in size significantly, requiring more and more resources
- despite all these changes, stalemates were the common outcome
- when a state was getting too powerful, alliances of competitors occurred to fight against it
- wars were slow, tedious, and often victories were the result of an enemy's economy failing; but victories were short-lasting with losers recovering quickly and reengaging
- of necessity competition expanded beyond Europe, using trade wealth and colonisation to fund competition
- sea power became important, increasing substantially during the 17th century
- as militaries continued to grow, specialties (e.g., cartography, surveying) arose that required additional resources

- the most significant constraint was funding, with states spending most of or more than their income/revenues; this debt led often to bankruptcy or payments well past a war's end
- complexity grew with technological innovation, science, politics, and colonial expansion
- for centuries, global resources have been extracted and used to support this pattern

Problem Solving and Sustainability: Divergent Outcomes

-there are various outcomes to problem solving with the three examples shared:

- (a) 'Collapse' (Western Roman Empire);
- (b) Sustainability via 'simplification' (Early Byzantine Recovery);
- (c) Growing complexity and energy subsidies (Europe).

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 it damage subtly, unforeseeably, and cumulatively over the long term.” (p. 34)

- the empire expected their conquests to yield high returns but enemies eventually grew stronger and expansion ceased while domestic unrest grew and budgets exceeded revenues
- currency debasement was a common response
- when resources were 'found', the state invested them in greater complexity by growing the government and military
- taxes were increased and applied to virtually every transaction, increasing complexity and costs
- while rational solutions to immediate problems, each one hurt the system's productivity eventually resulting in land abandonment and societal collapse

The Early Byzantine Recovery

- the 7th century loss of about half of their empire convinced the Byzantine rulers to engage in societal simplification
- urban rank/honours disappeared; the military merged with the civic administration, reducing transaction costs; the economy contracted, with less merchants and artisans; the elites focused upon their capital and its emperor, leaving most others to themselves; education and literacy declined; the monetary economy gave way to barter and feudal-type relations; military expenditures were cut dramatically with soldiers defending their own land, which led to less land lost to competitor states

Europe

- while the warring states of Europe followed a trajectory of ever-increasing complexity, they seemed to avoid 'collapse'
- war is a huge drain on resources and drives complexity further
- two reasons Europe avoided 'collapse':
 - 1) Innovation in technology, organisation, and finances (i.e., “more adept at manipulating and distributing matter and energy.” (p. 36));
 - 2) Luckily discovered significant subsidies (i.e., resources of colonised regions).

Conclusions

- institutional success/failure research has tended to focus on short-term aspects
- for the long-term considerations of state-level sustainability, Tainter suggests that the research needs to take on a historical approach that focuses upon complexity and attempts to identify problem-solving approaches that are sustainable
- outcomes of long-term trends in problem solving are:

"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." (pp. 36-37)

-modern societies and their institutions have become increasingly complex the past few centuries and been sustained by hydrocarbon subsidies

-various predictions suggest that this subsidy will end in the near-term future

-how we might prepare for this eventuality can be informed by our understanding of problem-solving systems and our three basic options:

- 1) Complexity while experiencing diminishing returns;
- 2) Simplification;
- 3) Growing complexity with hope of future subsidies (or luck as the warring states of Europe enjoyed).