CHAPTER 12

Systems Thinking and Complexity Theory (MKH 4)

Sustainability challenges are characterized by sometimes-mysterious interactions among seemingly-unrealated entities, such as air, water, plants, animals, food, agriculture, transportation, cities, energy, economy, and government. Many of those interactions are highlighted in previous chapters. Systems thinking is a way to conceptualize and make sense of these interactions and the behaviors that emerge from them. The purposes of this chapter are to introduce systems thinking and a related philosophical field, complexity theory, and to encourage readers to adopt a systems view of the world.

12.1 SYSTEM DEFINITION

Donella Meadows defines a *system* as "an interconnected set of elements that is coherently organized in a way that achieves something" [? , p. 11]. Example systems include a volleyball team, the solar system, the Earth, an ant, a bacterium. Meadows' definition has three pieces: elements, interconnections, and a telos.

Systems have elements, distinct entities with their own characteristics, behaviors, and qualities. Elements are sometimes known as *holons* [? , p. 216]. The elements or holons of a volleyball team include passers, setters, hitters, and a coach. A volleyball match is another system that *contains* two teams (and their holons) plus a net, a court, and a referee. The holons of the solar system include the sun, planets, asteroids, and meteors. The Milky Way galaxy is another system whose holons include many solar systems and comets. The universe is yet another system that includes the Milky Way and innumerable other galaxies.

The elements are interconnected in ways that allow them to interact. The interconnections, themselves, may have spatial, electrical, mechanical, temporal, or other characteristics. I.e., elements can be arranged in space and connected electrically and/or mechanically, and those arrangements and connections can change over time. Material and information can *flow* along the interconnections between the elements

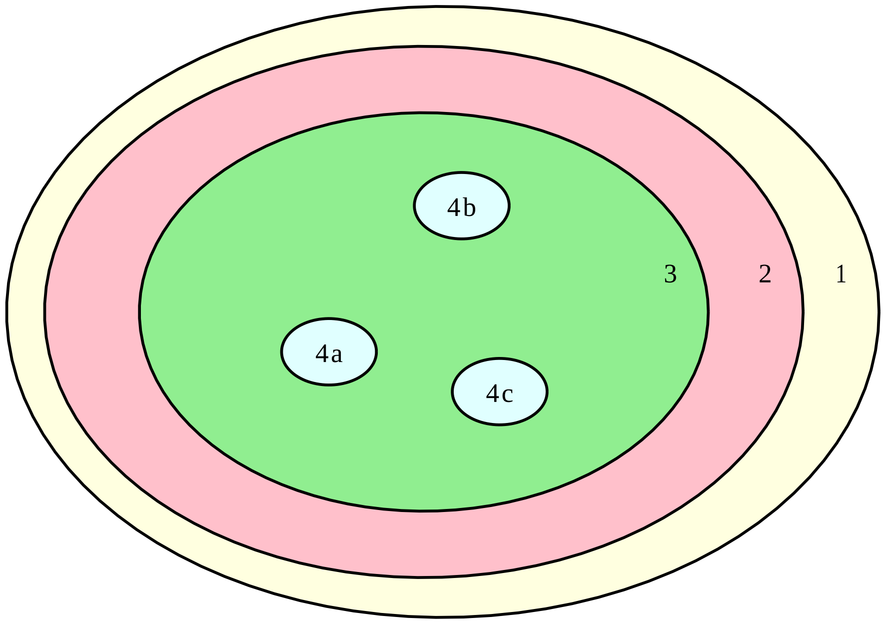

Figure 12.1: An example holarchy.

(holons). The spatial characteristics of interconnections can be visualized as container (parent-child) relationships or as sibling relationships. A word that describes the arrangement of holons is *holarchy* [? , p. 216]. Figure ?? shows a holarchy of 6 holons. Elements 1, 2, and 3 exhibit parent-child (container) relationships, with 3 being contained by 2 and 2 being contained by 1. Items 4a, 4b, and 4c are contained by element 3, with sibling relationships among themselves. Two systems with identical holons will behave differently if their elements are arranged differently.

A volleyball team is arranged spatially on the court. Its players move spatially through time during the play for each point but also from point to point as they rotate between points. Planets are arranged spatially in the solar system, and their spatial relationships to each other change in (mostly) predictable ways through time.

Systems have a telos or a purpose, an ultimate aim. Some sytems have multiple purposes. The teloi of a volleyball team include player development, winning, and fun. The telos for the solar system may be interpreted as providing a home for Earth and, ultimately, humans.

12.2 SYSTEM CHARACTERISTICS

Humans understand system characteristics so deeply that some characteristics are reflected in the proverbs and aphorisms of language.

The behavior of a system is always different from the behavior of its elements or holons, for interactions play a central role in the functioning of a system. Put in the language of Section **??**, the higher (enclosing) levels of a holarchy behave in ways that are different from (often very different from) lower (enclosed) levels of the holarchy. As a whole, a volleyball team behaves differently from its coach. The universe exhibits different characteristics from the Earth. Systems are said to have *emergent behavior*, because system behavior is radically different from its holons. Indeed, for a system, "the whole is greater than (or at least different from) the sum of its parts!"

Because behaviors differ from one level to another in a system and because interactions play a large role in the behavior of a system, systems often appear to be unpredictable. To use a mathematical term colloquially, systems are "nonlinear." A volleyball team goes into a funk, despite handily winning the first set of a match, and lose the first 8 points of the next set. Weather in the Earth system cannot be forecasted, even with the best meteorology, more than a few days in advance. A colloquial word to describe unpredictability is *chaotic*.

> A related branch of mathematics called *chaos theory* studies dynamic systems whose changes in behavior are disproportionate to changes in initial conditions. However, in chaos theory, systems are entirely predictable if initial conditions are specified identically (mathematically) from one experiment to another. The difference between the seeming unpredictability (but actual predictability) of chaos theory and the chaotic behavior of real-life systems described here is that real-life systems can behave differently *even if* initial conditions are specified identically.
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> The distinction is blurred when measurement uncertainty is considered. In chaos theory, an infinitesimally small perturbation of initial conditions can produce wildly different outcomes. But in the real world, an infinitesimally small perturbation is indistinguishable from zero due to finite measurement precision. Thus, a real-world system with apparently the same initial conditions (to within measurement uncertainty) can exhibit wildly different behavior, as a systems view of the world would predict.

The presence of connections among holons in a system means that perturbing one part of a system will have effects beyond the initial perturbation site in both space and time. A volleyball coach can position her players to thwart a opposing hitter whose spikes go "down the line," but her team's defense will now be vulnerable to the opposing setter's "dinks" to the middle. In the Earth system, installing a hydropower station will provide electricity, but it will also create an upstream lake, expose downstream riverbanks, and change fish and other wildlife migration patterns. Vernon Ehlers, former U.S. congressman for Michigan's 3rd district, often said, "You can never do only one thing."

The apparent unpredictability of systems extends to human actions intended to influence the behavior of systems. A volleyball coach can *think* she is motivating a player with a stinging critique but produce the opposite effect, demoralization. Human efforts to "manage" forests decimate old growth stands. Colloquially, we name this unpredictability "unintended consequences."

Often, systems appear to act to preserve their structure. A volleyball team that goes "out of system" when returning a serve reverts to their "base" positions after their scramble. Droughts on Earth are usually followed by a return to normal rainfall. The phrase "reversion to the mean" describes the self-correcting nature of systems.

Sometimes it seems that systems have a "mind of their own." People say "larger forces are at play" to indicate their lack of agency in the face of a self-correcting system. The phrase "rearranging the deck chairs on the Titanic" describes how some human activities appear, at times, to be meaningless.

12.3 IMPLICTIONS OF SYSTEMS

Given the above characteristics of systems, opportunities and challenges can be identified.

12.3.1 SYSTEM OPPORTUNITIES

To begin identifying system opportunities, consider system structure. Lower levels of a holarchy provide materials and information to upper levels. Higher levels of a holarchy often serve to organize and utilize the outputs from elements in lower levels. Thus, the connections between enclosed (lower-level) and enclosing (higher-level) holons in a holarchy enable one of the most important system opportunities: specialization. Specialization enables metabolisms, organisms, and manufacturing supply chains, for example. Large, technical projects, such as managing airlines; building, launching, and flying interplanetary spacecraft; and designing, building, and operating chemical plants; are made possible by what Graedel and Allenby call "directed technological holarchies" [? , p. 217].

> Systems thinking is natural for many engineers. Those involved in large projects are themselves individual holons in a holarchy of supervi-

sor/engineer relationships. Engineered components (e.g., spacecraft) are delivered for integration into systems (e.g., launch vehicles). Indeed, analysis techniques for machine dynamics, chemical plants, thermodynamic systems, etc. are all predicated upon holarchies. "Control volumes" and "free body diagrams" serve to break down systems to analyze their elements piece-by-piece, per holon. Positional and electrical constraints expressed as equations put the systems "back together" and describe the connections among components/elements/holons.

Engineers confront the complexities of engineered systems as they endeavor to produce engineered obejects that meet performance "requirements" and fulfill their intended purposes, their teloi. To do so, "safety factors" and mass, power, volume, and cost margins are applied. Progress updates are delivered during "design reviews" to master engineers who find problems with and suggest solutions for designs and plans.

What if one desires to change system behavior? Meadows [**?** , Ch. 6] gives an extensive list of "leverage points" to change system behavior. A shorter list includes two important ways to intervene in a system to overcome its predilection to maintain structure and, ultimately, change its behavior: change the elements and change the connections.

Change the elements One way to achieve changes in higher-level function of a system is to make small changes to lower-level elements. Substituting one volleyball player for another can have dramatic effect on the behavior and performance of the team.

Change the connections Another way to change the functioning of a system is to change either the rates or routes of information and material flows among elements. In previous centuries, the development of railroads allowed material (goods) to move more quickly through the Earth system (economies). By stringing telegraph (and later telephone) lines, humans were able to move information more quickly through economies and across the Earth. Today, the internet enables the highest information transfer speeds in history, resulting in massive societal changes that were unimaginable a century ago. Undoubtedly, increasing the material and information velocity through economies has increased human well-being in many ways. But the velocity increases have also enabled unprecedented rates of economic growth, fossil fuel energy consumption, and CO_2 emissions. *You can never do only one thing.*

Other ways to change system behavior In addition to changing the elements and changing the connections, system behavior can be fundamentally altered by (a) adjusting the spatial arrangement of elements, (b) introducing delays to the interactions between elements, (c) adding or removing storage for materials and energy, (d) changing the rules of interactions among elements, and (e) changing the telos of a system.

12.3.2 SYSTEM CHALLENGES

Although systems present many opportunities, they provide many challanges as well, especially for those who would intervene to change their behavior. (1) Systems are difficult to understand, because many systems contain large numbers of holons, making thorough analysis impossible. Systems are *complicated*. (2) Even if it were possible to analyze the behavior of *all* holons, system emergent behaviors mean that higher level characteristics cannot be predicted from complete knowledge of the behavior of all lower-level elements. (Systems are *complex*.) (3) Even worse, the unpredictability of high-level system behavior means that unintended consequences arise from emergent behaviors. Thus, systems are perceived as being uncontrollable. (4) All of the above can make systems, including collaborative technological holarchies, difficult to manage. (5) The self-preservation characteristic of systems means that systems have a "mind of their own" and can seemingly resist attempts to change them. Maddeningly, for the volleyball coach, substitutions sometimes have little effect, even making team performance worse due to some unexpected interactions among the players.

> Systems are challenging and difficult to manage, because we have "linear minds in a nonlinear world" [**?** , p. 91].

12.4 COMPLEXITY THEORY

A field of inquiry that studies and describes systems and the interactions among their elements is *complexity theory* [**?**]. Complexity theory takes systems thinking in a philosophical direction to assist our understanding of the world and its systems.

Complexity theory distinguishes between complicated and complex attributes of systems. Systems are complicated, because they big and contain many parts. Although large, complicated systems are still solvable (in the sense that their behavior can be predicted) and deterministic. But complex systems, especially large systems with many connections, are neither solvable nor deterministic. They *can't* be understood by taking them apart and studying their elements. For example, a spacecraft is complicated, because it has many parts. It *might* be possible to predict, within some level of confidence, *some* aspects of spacecraft behavior (total mass, maximum thrust, etc.) simply by studying its elements. But it would be impossible to predict social, psychological, political, and other effects of Sputnik by studying its exterior, its thrusters, and its attitude control system. Sputnik is complex.

Many tenets of complexity theory emerge from systems thinking and have been discussed already: (a) systems can't be fully understood by taking them apart, (b) systems are resilient to external perturbations, (c) all modeling is an attempt to understand or describe a system via simplification, by reducing complexity, (d) all modeling necessarily involves drawing boundaries (as in free-body-diagrams and control volumes), and (e) emergent behavior means that effects cannot be tracked or predicted deterministically.

But further insights emerge from the field. In a system, complexity theory notes that all elements are connected all the time, either directly or indirectly via other connected elements. Thus, attempts to isolate elements of a real system as a way to understand the behavior of the system are futile. Any modeling or analysis that isolates elements of a system should be undertaken with much care. Elements outside of the system boundary should not be expected to affect system behavior significantly.

Chaotic characteristics, emergent behavior, and unintended consequences of real-world systems imply that human knowledge has limits, always. Humans are finite! Human knowledge is not arbitrary, but it is provisional, contextual, and contingent. Consequently, human intuition can *sometimes* be as important as scientific rationality when confronted with complexity.

Complexity theory helps us to understand that all system models, being simplified descriptions of the world developed by finite humans, involve choices. One of the most important choices in system analysis is the system boundary. Placement of the system boundary defines what is "in" the analysis (endogenous) and what is "out" of the analysis (exogenous). Thus, system models necessarily amplify some aspects or behaviors (endogenous elements and their interactions) and dampen other aspects or behaviors (exogenous elements and their interactions). There is a "boundary problem," namely that boundary placement affects knowledge obtained from any system analysis.

The "boundary problem" leads to consideration of epistemological issues such as how models and boundary placement mediate our understanding of the complex systems being analyzed. In particular, complexity theory arrives at the conclusion that there are *normative* aspects to analyzing complex systems. Placement of the system boundary is a normative choice, because the correctness of boundary placement can be evaluated relative to the purpose of each analysis. I.e., the "right" boundary placement is contingent upon the questions being asked and the problems to be solved. Therefore, it is right to ask how models *ought* to be constructed and interpreted for a given purpose. The fact that knowledge and understanding of a system are contingent upon boundary placement is one of the ways that human knowledge is always limited, provisional, contextual, and contingent.

12.5 SYSTEMS THINKING FOR SUSTAINABILITY

Systems thinking and complexity theory (STCT)[1] are valuable for understanding sustainability challenges. Indeed, STCT (a) provides a language to talk about observed behaviors of real systems in the real world and (b) brings important insights to some of the most difficult, sustainability-related problems facing society today. To demonstrate the applicability of STCT to sustainability challenges, consider the task of reducing CO_2 emissions worldwide.

Many engineers focus on the efficiency of end-use machines (such as cars, lights, and furnaces) to reduce CO_2 emissions. But STCT suggests that a narrow approach will be insufficient to reduce CO_2 emissions. Everything is interconnected, always. Focusing on end-use machines would neglect, e.g., (a) the energy conversion chain that extracts energy from the biosphere and delivers it to end users and (b) economic imperatives that give rise to energy consumption in the first place. STCT suggests that benefits would be found by widening the system boundary to include worldwide energy supply chains and the worldwide economy to form the climate-energy-economy (CEE) system.

For the CEE system, STCT would suggest that interactions among its elements would give rise to both emergent behaviors and unintended consequences. Indeed, the rebound effect and backfire are emergent behaviors that lead to unintended consequences (less energy saved than expected) within the CEE system. As discussed in Section ??, the rebound effect and backfire occur when end-use machines become more energy efficient, leaving consumers with more money in their wallets. Respending that saved money in the economy leads to increasing energy demand elsewhere in the energy conversion chain. A narrow system boundary (around end-use machines only) closes off the possibility of studying an economy-wide rebound effect or backfire. In contrast, an STCT mindsent and an expanded system boundary that includes the economy (i.e., the CEE system) enable consideration of the rebound effect and backfire.

And STCT would caution against assuming that analyzing the CEE system would lead to a solution to the worldwide CO_2 emissions challenge. The CEE system boundary is *still* too narrow to encompass all factors related to CO_2 emissions. Individual and group phychology, sociological factors, political parties and other political considerations, and information and computer technology remain exogeneous to the CEE system.

[1] Systems thinking and complexity theory are so closely related that the acronym STCT will be used for the remainder of this chapter.

Furthermore, STCT indicates that the CEE system boundary will amplify some real-world behaviors and dampen others. In the case of the CEE system, it is likely that economic effects on CO_2 emissions will be overemphasized. By virture of being exogenous to the CEE system, political effects will be underemphasized by the CEE system.

Because the CO_2 emissions problem is a worldwide phenomenon that affects every human being, it seems likely that solutions will involve changes at the highest levels of human society, namely policies promulgated at the international level.[2] However, politics are exogeneous to the CEE system, and analysis of the CEE system with a view to reducing CO_2 emissions seems likely to fail.

Redrawing the system boundary to endogenize politics could unlock new possibilities for policy solutions to the CO_2 emissions challenge. A system with the expanded boundary might be called the climate-energy-economy-policy (CEEP) system.

However, even after endogenizing politics within the CEEP system, an STCT mindset would indicate that developing and implementing CO_2-reducing policies would be fraught with potential problems. Limits to human knowledge mean that no policy can ever be perfect.

Another way in which developing and implementing policies to fight CO_2 emissions is fraught arises when STCT leads us to understand that the existing CEEP system will resist perturbations. STCT predicts that entrenched interests in the fossil fuel industry will resist changes to the existing CEEP system. Reasons for resisting change include financial (maintain existing reveunes and profits) and social (maintain employment) considerations. It becomes clear that a large dose of humility is needed in policymaking. STCT leads us to believe that all policies should be considered experiments, open to continued revision as more data become available.

In the face of limits to human knowledge, emergent behavior, unintended consequences, and system resilience, how are we to develop policy? With full knowledge of unintended consequences and system resiliance, the exhortations to "change the elements" and "change the connections" can guide humble policy-making. For the CEEP system, "changing the elements" could mean improving the efficiency of energy-consuming end-use machines, such as lights, cars, and washing machines. Efficiency improvements can be legislated via efficiency *standards* or by economic incentives such as *tax breaks* or *rebates* for purchasing high-efficiency end-use machines. "Changing the elements" could also mean providing incentives for rooftop

[2]Libetarians might object to the idea that the problem of CO_2 emissions should be solved by governments at the international level, instead of at the level of economically self-interested individuals. However, the current economic system does not incentivize individuals to make choices that reduce CO_2 emissions. To move from today's economic environment to one in which individuals *are* economically incentivized to pursue behaviors that reduce CO_2 emissions, governments must surely be involved to establish the necessary economic incentives.

solar electricity generating systems. Increasing adoption of renewable energy technologies might bring the unintended consequence of reduced employment in fossil fuel sectors. Policies should include retraining or re-skilling of displaced workers to avoid disruption of the social fabric in places where job losses can be expected. And, even as policies are put in place to incentivize renewables, the fossil fuel industry would be expected to work hard to maintain its structure (i.e., its dominant position in the energy industry) by making the application processes for household rooftop solar arduous and complicated. Incentives could be provided for the fossil fuel industry to adapt to changing conditions in the energy sector.

To "change the connections," policymakers can mandate that information about embodied CO_2 content must flow from sellers of goods to potential consumers. To incentivize rooftop solar, policymakers can mandate that grid operators buy electricity from household solar PV systems at a favorable rate.

To avoid the unintended consequences of rebound and backfire, organizations can develop policies that capture the monetary savings resulting from energy efficiency interventions. Special accounts called *green revolving funds*[**?**] require that monetary savings from energy efficiency be used for additional energy efficiency interventions, thereby ensureing that savings don't "leak" to the rest of the economy.

QUESTIONS

12.1. Make a list of 3 systems. What are the the elements (holons), connections (holarchy), and teloi for each system? Are they complicated or complex?

12.2. In Section **??**, systems thinking and complexity theory (STCT) were applied to the problem of reducing CO_2 emissions worldwide. Now apply STCT to the more-specific problem of CO_2 emissions from the existing transportation system discussed **??**. Begin by assessing the problems was the existing transportation system designed to solve. Continue to think about what problems we have today. Then think about the "legacy" transportation system in light of STCT. Is the legacy transportation system resilient (resistant to change)? Why or why not? If you deem the legacy transportation system resistant to change, in what ways is that true? Does our legacy transportation system exacerbate or help to solve today's sustainability challenges? If you want to change the legacy system, how would STCT suggest that interventions be made? Does the tendency to preserve structure in legacy systems mean that our existing transport system views sustainable transport as a "virus" that needs to be eliminated?

12.3. Repeat Question **??** for the food and agriculture system discussed in Chapter **??**.