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Introduction to Systems and Systems Thinking

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Introduction to Systems and Systems Thinking

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ABSTRACT

Throughout our daily lives, we interact with countless systems, in ways that are obvious and not so obvious. More and more systems-related terms are emerging in the scientific literature, in curricula, and in popular media: systems thinking, systems approaches, systems analysis, systems dynamics, systems mapping, just to name a few. In an increasingly complex and interconnected world, thinking systemically can help us to understand, communicate, address, and educate about challenges we face. Yet if you want to start using this approach, it can be difficult to know how to start. Systems thinking is both an approach to seeing the world in a way that makes connections and relationships more visible and improves our decision-making abilities, and a set of methods and tools. This synthesis provides an overview of ways to think about systems as an initial step towards systems thinking, and of systems thinking tools that can be useful to educators and students in any discipline.

INTRODUCTION

"Let's face it, the universe is messy. It is non-linear, turbulent, and chaotic. It is dynamic. It spends its time in transient behavior on its way to somewhere else, not in mathematically neat equilibria. It self-organizes and evolves. It creates diversity, not uniformity. That's what makes the world interesting, that's what makes it beautiful, and that's what makes it work."

– Donella H. Meadows, Thinking in Systems: A Primer, p.181

WHAT IS A SYSTEM?

In order to think in systems, we must first understand what this term means. We encounter systems in many different contexts and situations—from circulatory systems to climate systems to healthcare systems to transportation systems. But what is a system? How would we know a system if we saw one, and why is it important to understand systems at all?

A system is a group of two or more related parts (sometimes referred to as elements, components, or stocks) that interact over time to form a whole that has a purpose or function (note, function and behavior are often used interchangeably in systems thinking literature, but for our purposes, we will use the term function). We can conceive of systems as physical entities that we can observe and empirically examine—like a tree or a subway system, or as abstract constructs we can use to understand our world—like a model of a cell or of the solar system (Systems in Evaluation TIG 2018). A system includes both parts and the relationships that hold the parts together—these can be physical flows (for example, the neural signals that allow us to sense our environment), or simply flows of information in a social system. Many parts can form a whole, but unless they depend on and interact with each other, they are simply a collection. Consider a jar of dried basil, a jar of cinnamon, and a jar of paprika—a group of spices that comprise a spice rack. Their function does not change if you add or remove spice jars or re-arrange them, because the spice rack is simply a collection. In contrast, your body is a system composed of multiple different, interacting, and interdependent organs or nested subsystems. A set of parts, arranged and connected, is essential for you to survive. Furthermore, these components can function together in ways that would not be possible for each part on its own, and as a system, exhibit properties that emerge only when parts interact with a wider whole (also known as emergent properties) (Box 1).

Box 1. Handy question guide: is it a system, or just a collection of stuff? (adapted from Meadows 2008).

- Are the parts identifiable? If yes, then...
- Do the parts interact with each other? If yes, then...
- Is there a difference between the combined interactions of the parts (or function of the parts together) compared to how each part behaves on its own? If yes, then...
- Does the function persist in a variety of situations?

If yes, then… it's a system!

Investigating the parts and interrelationships of systems helps us understand how they function (a term usually used for nonhuman systems, like a computer) or their purpose (a term usually used for human systems, like a government). Often the best way to discern the function (e.g., delivering potable water from a faucet) or purpose (e.g., educating a student) of a system is to observe how the system operates over time, in terms of growth, decline, oscillation, stasis, or evolution.

All systems have boundaries that define what is "in" and "out" of the system. Most bounded systems are nested or hierarchical; there can be purposes within purposes. Hierarchy is the arrangement of subsystems organized into larger and larger systems. An example of a hierarchy is an individual cell within your heart, which, in turn, is part of your circulatory system, which is in turn a subsystem of your body. A hierarchy not only gives a system stability and resilience but also reduces the amount of information that any part of the system has to track. For example, a ship's captain might not need to know about the individual action of every individual crew member because they trust those leaders to make appropriate decisions at their level.

Sorting Systems

Systems are often sorted into three general categories: simple, complicated, and complex (a fourth category, chaotic, is used to describe a system with weak connections between parts and no discernible patterns in function; this category is most often associated with the Cynefin framework, a conceptual model for decision-making used by systems thinkers) (Figure 1). It is important to understand the differences between these systems because they each call for different approaches for stakeholders who are managing the system or working to move it towards producing more desired outcomes.

- Simple systems are easily knowable—they have few parts with stable relationships, and the function of the system is predictable, for example, a pet goldfish in a bowl represents a simple system. The process of managing a simple system, or caring for your goldfish so it can survive and thrive, is relatively straightforward and does not deviate significantly given different contexts.

- Complicated systems are not simple but are definable, and subsequently solvable, and may require high levels of expertise in specialized fields to maintain the system. Systems can be technically complicated or socially complicated, or some combination of both. They do not adapt but rather have a high degree of certainty of outcome; for example, a computer represents a technically

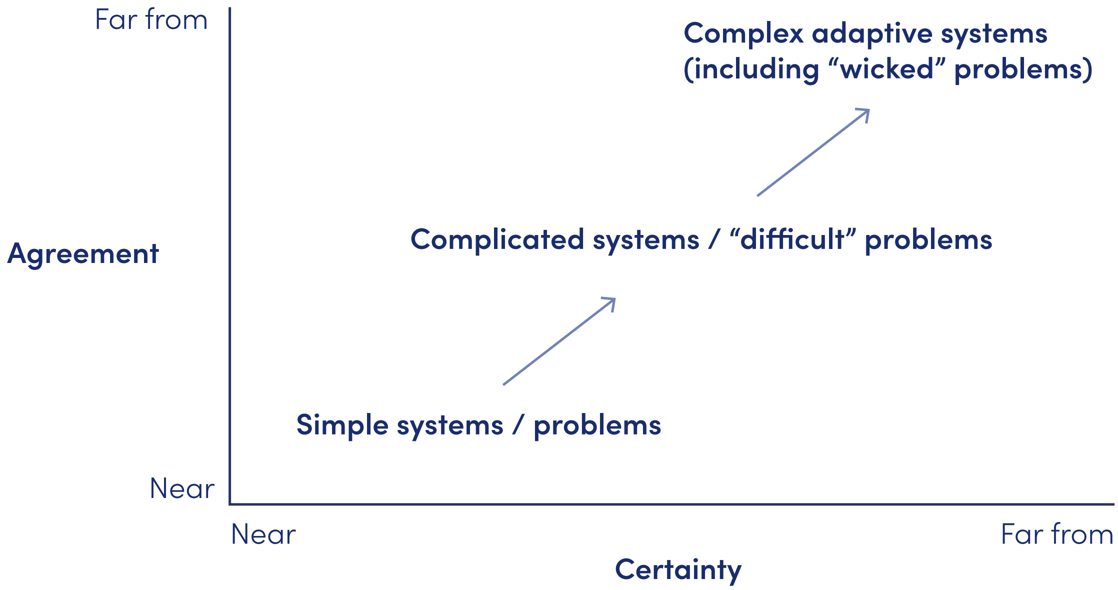


Figure 1. System typology for a system that needs improvement or a "problem." In this graph, the y-axis represents agreement between people thinking about the problem and x-axis is certainty about the nature of the problem. Image credit: modified from Allen and Kilvington (2018), based on frameworks by Ralph D. Stacey and Dave Snowden.

complicated system where outcomes can be determined: the computer is working properly, or it's not. Indicators of success or progress in managing complicated systems are directly linked through cause and effect. For the computer example, successful management requires a team with the proper expertise to maintain the system, diagnose malfunctions, and make repairs. A socially complicated system may involve different stakeholders with different perspectives and values; for example, scheduling times for classroom use in schools may be socially complicated, but it is generally solvable in the sense that a classroom schedule can be agreed upon and implemented. For socially complicated issues, the key to moving forward often comes down to building relationships, finding common ground, and creating space for respectful dialogue and differences of opinion.

- In contrast to simple and complicated systems, complex adaptive systems (CAS) have many different parts, and non-linear relationships with feedback loops across time and space (non-linear means that cause and effect of a system are not in proportion to one another, sometimes referred to as tipping points). While some complex adaptive systems are entirely human, these systems are usually a mix of interrelated human and non-human subsystems, and are dynamic, unpredictable, and change over time. They can also self-organize, evolve, and adapt.
  - Self-organization is the ability of systems to structure themselves without central control, to create new parts or relationships, and to learn and evolve in complexity.
  - Self-organized systems can exhibit emergent properties, a phenomenon that can refer to any kind of learning or new pattern that emerges from the complex interactions of a system's parts (the elegant changing shape of a flock of flying birds is an example of emergence).

The human immune system is an exquisite example of a complex adaptive system that is able to learn to defend the body against unknown pathogens through self-organizing, adaptive immunity. Democracy is another example of a complex adaptive system, continually evolving in unpredictable ways in numerous social and political contexts through time and space. If we want to influence a complex adaptive system to improve its trends and enable desired outcomes, one-size-fits-all approaches are unlikely to yield success. When we try to predict, specify, design, and force a CAS in a certain way, we may be misguidedly treating it as a complicated system. But if it is complex, different approaches are likely required to understand it and manage it. The approaches we use to understand

and maintain a complicated system like a computer will not yield success when applied to a CAS like the internet. For complex adaptive systems, especially if they are social in nature, some of the most effective management approaches work to understand the nature of the system from myriad stakeholder perspectives and recognize the uncertainty involved in the system during the process of defining it and enabling desired outcomes (for more details see methods developed by Peter Checkland and colleagues; Checkland 1999).

Management of complex adaptive systems is especially tricky for so-called "wicked" or intractable problems that are unsolvable in the conventional sense. Problems are termed "wicked" when they have multiple, often undefined, causes; little to no agreement on how to improve a situation that requires collective action among stakeholders with differing values and contested understandings of the problem, and cause-and-effect relationships that only became clear after the effects have already emerged. Human disease, refugee migration, and climate change are examples of wicked problems. While wicked problems have long, uncertain timescales and will never be "solved" in the conventional sense, we can work to understand these particular systems and make decisions that alter their function in ways that can promote progress towards desired outcomes.

WHAT IS SYSTEMS THINKING?

Investigating systems through "systems thinking" opens up countless possibilities for understanding and influencing the world around us. In their review of literature on "systems thinking," Arnold and Wade (2015) found no widely accepted definition for the term. Their proposed definition is that systems thinking is "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects." This can be a useful starting point in trying to understand systems thinking. Yet, across the literature, courses, professional development offerings, and websites that focus on systems thinking, there are numerous lists of the characteristics of a systems thinker, with some elements that overlap and some that do not. Faced with this landscape, how can we understand how systems thinking can be useful in our roles as students, educators, practitioners, and members of our communities? One path forward is to view systems thinking as both an approach to seeing the world—in a way that makes connections and relationships more visible and improves our decision-making abilities—and a set of methods and tools (Paxton and Frost 2018). In subsequent sections, we explore these two ways to engage with systems thinking.

When we use systems thinking as a way of seeing (a systems "lens") we see that the world is made up of parts that, in turn, connect and interact in dynamic ways to form a whole, whether we are looking at food systems, economies, or ourselves. With this ability to "see" where in a system and the relationships within it problems seem to originate, system thinkers can then think about ways to change the system, communicate with others to create new ways of thinking and seeing, and through this shared understanding, plan more effectively for the future. The key for systems thinking is that it is NOT about prediction or control, but about raising more questions to enhance understanding and seeking opportunities to "nudge" system function in desired directions (Box 2). Systems thinking helps with seeing that there is frequently not one single solution to a problem, but a set of coordinated actions that guide the system towards a desired state or outcome.

As systems thinkers ask these questions, they draw from several essential systems thinking concepts. Several of these concepts are used in other academic fields, though they have a specific meaning in the context of systems thinking. While the concepts are not unique to systems thinking, the full

Box 2. Questions a systems thinker asks when faced with a complex issue (adapted from Ponto and Linder 2011):

- What happened?
- What recurring events are we noticing?
- What length of time is long enough to see patterns in system function?
- What structures may be determining the function we see?
- What underlying beliefs, values, or assumptions are at play, including from or within ourselves?
- What are the feedbacks in this system?
- How can we define a boundary around this system? What is appropriate and useful for our goals?
- What other perspectives, methodologies, or disciplines might help us more fully understand this issue?
- Where in this system could we make small shifts that would make a big difference? What trade-offs exist? Is there a potential for unintended consequences?

array of concepts constitutes a distinctive approach to viewing the world. Below we review these key concepts:

What happened? What recurring events are we noticing? What length of time is long enough to see patterns in system function? What structures are in place that may be determining the function we see? What underlying beliefs or assumptions are at play, including from or within ourselves?

Each of these questions relate to how a system is structured and how it operates over time. Systems thinking emphasizes relationships and interactions between parts of a system, interrogating the nature of the relationships and discerning patterns or trends emerging from these relationships. System thinkers seek root causes, or the connections between events and the underlying structure of the system and paradigms or mental models (deeply held abstractions or generalizations about how the world works), which may be driving system function (Figure 2).

What Are the Feedbacks in This System?

Stocks are the foundation of any system—the parts of a system that can be measured. Stocks can be physical, for example, the temperature within your body, or not physical, for example, your happiness or well-being on a particular day. Stocks change over time as a result of flows, and can act as buffers or delays in a system. For example, since one property of water is that it can absorb a lot of heat before its temperature starts rising, the water within the human body can act as a buffer during changing ambient temperatures.

A feedback loop is a closed set of connections originating from a stock, through a set of decisions or actions that are dependent on the stock's level, that ultimately influence a flow to change the stock. Often the most important feedback loops provide information on how the system is doing relative to a desired state: a balancing feedback loop stabilizes a stock level, keeping a stock within a certain range—and opposing whatever directions of change are imposed on the system. An example of this type of balancing or negative loop is how your body regulates its temperature—raising it when the stock (i.e., temperature) is low, and lowering when the stock is too high. If you exercise, your

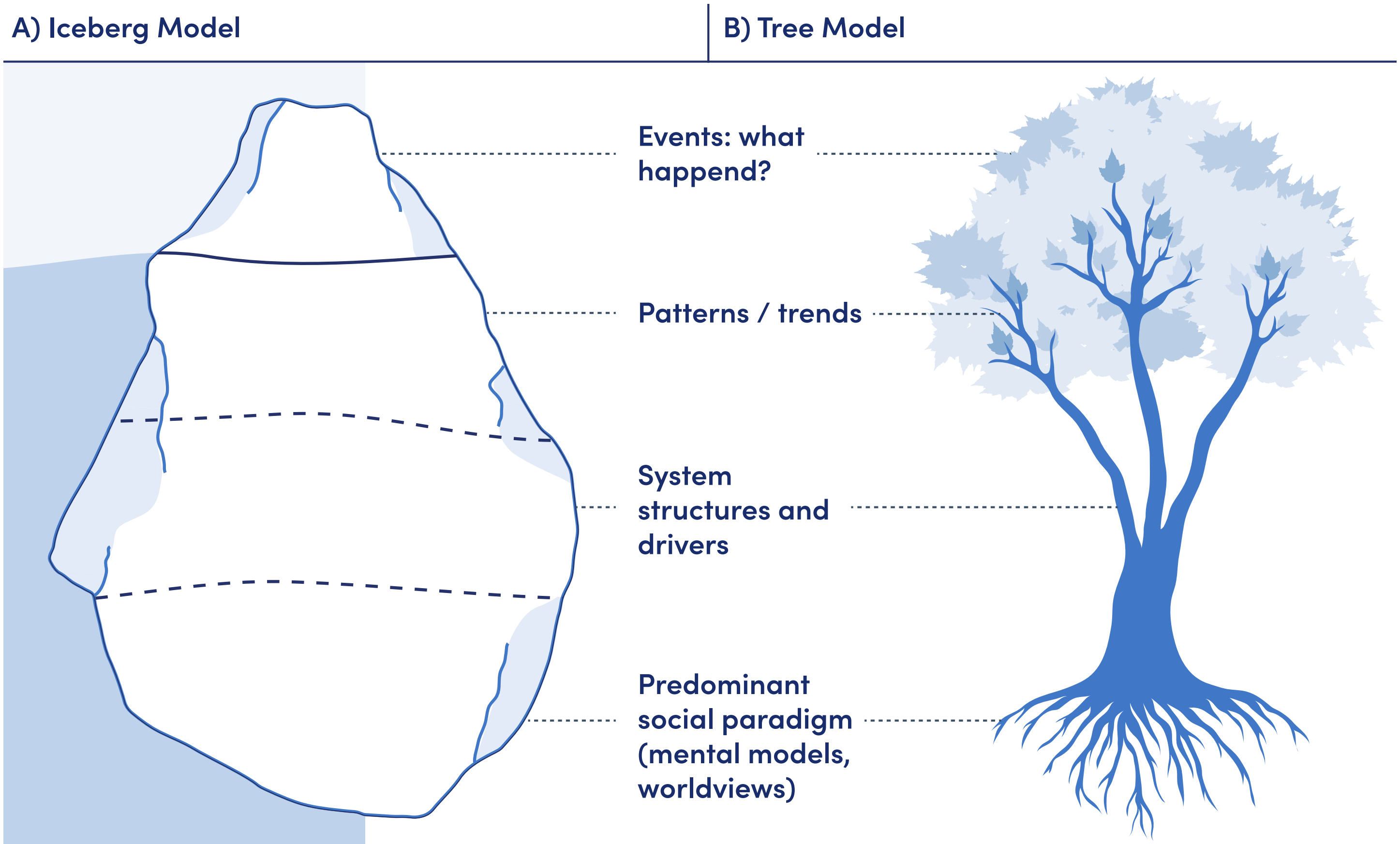


Figure 2. Adapted Iceberg Model. (2A) The "iceberg model" is a visual tool often used to examine the structures and mental models that underlie system function and create patterns of events over time. The tool differentiates the visible manifestations of the system (the "events," or "tip of the iceberg"), and the rarely seen, "below the surface," patterns, drivers, and paradigms that give rise to the events. (2B) Since this model of a static iceberg does not capture the dynamic interlinkages between the root structures and the surface events, we have adapted the iceberg model using the example of a tree to show these interlinkages between events (leaves that provide energy for the rest of the tree), patterns/trends (branches that support the leaves), structures and drivers (trunk that supports the branches), and predominate social paradigm (roots that support trunk, branches, and leaves). Image credit: Nadav Gazit/AMNH.

body activates your sweat glands to cool you down; and if you are cold, your body shivers to create warmth. In contrast, a reinforcing, or positive, feedback loop amplifies change in a stock, causing desirable ("virtuous" cycle) or undesirable ("vicious" cycle) outcomes, enhancing whatever direction of change is imposed on it; these loops are often referred to as snowballing changes, or chain reactions. One example of this type of system is an interest-bearing bank account—as the stock (i.e., account balance) increases, more interest is earned, increasing the stock, and so on. Without a counter-balancing reaction or process, a positive feedback loop has the potential to produce a runaway process, for example when population decline in a species can lead to loss of genetic diversity and increased likelihood of population extinction.

Systems can contain networks of reinforcing and balancing feedback processes of different strengths operating in different directions. If reinforcing loops and balancing loops are equal, a system may have a dynamic equilibrium that is maintained with a specific range of outcomes. As the relative strengths of feedback loops change, the function of systems change as well. For example, as feedback loops affect the changing stock of water in a river, the way the system operates changes, especially in times of flood or drought. Resilience—the capacity of a system to absorb, resist, or recover from stress, and adapt to change while maintaining valued functions and benefits (Stein

2013)—arises from a robust structure of many feedback loops that can work in different ways to maintain a system even after a significant disturbance. An example of a resilient system is a thermostat that can detect changes in a home's ambient temperature and adjust by engaging a heater or air conditioning system to raise or lower the temperature to the desired setting.

A system's structure is its interlocking stocks, flows, and feedback loops. Since the structure gives rise to function which reveals itself as a series of events over time, system thinkers must examine both the structure of a system and how it functions. Systems thinkers can also refer to system archetypes, or generic system structures that produce characteristic or common functions, in order to better understand systems and why particular system interventions may succeed or fail.

How Can We Define a Boundary Around This System? What Is Appropriate and Useful for Our Goals?

Any discussion about systems must also touch on boundaries, in terms of scope and scale. Although in theory everything is connected, what we know and perceive (i.e., mental models, or beliefs and assumptions about how the world works) has limits—and limits are called boundaries. Boundaries can be set to determine what is "in" and what is "out," what is important and unimportant, and to recognize who benefits and who is disadvantaged with this set of boundaries. As noted by Meadows (2008), systems rarely have universally agreed upon, legitimate boundaries and where to define a boundary around a system depends on the purpose of the discussion about that system—the questions we want to ask about the system and our value judgments. Frequently we draw boundaries based on the available data or based on the part of a system we know the best, thus missing important drivers. For example, a protected area may have an official boundary that does not encompass a whole watershed or connected landscape. Such a boundary may not be very helpful for understanding the dynamics of species or threats affecting the area. If boundaries are drawn too narrowly, the way the system operates can be surprising and our decisions can create unintended consequences or "side-effects" because we have not identified the major drivers of the system. If boundaries are drawn too broadly, they can conceal answers to the problem at hand or make the process of understanding the system and making decisions next to impossible. The most appropriate boundary for considering a system rarely coincides with named boundaries, such as academic fields or political boundaries. And importantly, drawing boundaries carries important ethical and practical implications. The act of defining a boundary makes what is outside the boundary marginal or secondary. While this boundary definition may be profound or unimportant, a systems thinker should always consider the consequences of exclusion, particularly when a boundary leads to marginalization.

What Other Perspectives, Methodologies, or Disciplines Might Help Us More Fully Understand This Issue?

Systems thinkers understand that there is tremendous value in the many perspectives of a system. When considering a problem, they ask:

- Who or what are the key stakeholders in this situation?
- What stakes (values and motivations) do they/we have?
- What are the different ways in which the situation can be framed or understood—by whom?
- How do these different framings affect the way in which stakeholders act—when things go their way/when things do not go their way?

Systems thinkers also understand the value of using diverse methodologies for learning how systems are organized, how they operate over time, and how they can be better governed. Another way to understand this approach is methodological pluralism (i.e., using different methods or techniques in combination); for example, mixed methods that use quantitative or qualitative methods to study a system (Jackson 1997). Finally, by working across disciplines and sectors, systems thinkers can help to create a shared vision, common set of goals, mutual understanding, and shared expectations for all stakeholders.

Critical systems thinking is an approach to dealing with complexity that emphasizes understanding the strengths and weaknesses of various approaches and learning how to employ them in combination (Sova et al. 2015; Jackson 2019). When considering stakeholders, critical systems thinkers ask:

- Who has power?
- Who is defining the system, its structure and function?
- Who is excluded from the decision-making process?
- Whose knowledge counts in the system? Whose knowledge is actively disappeared or diminished by other stakeholders?
- What are the historical and current power dynamics between stakeholders and how does that impact our understanding of the system?
- How are benefits and harms/burdens distributed within the system?

Where in This System Could We Make Small Shifts That Would Make a Big Difference? What Trade-Offs Exist? Is There a Potential for Unintended Consequences?

Systems thinkers who are considering how to make change in a system to bring about desired outcomes often work to identify leverage points, or places within a complex system where a shift in one place can produce changes elsewhere in the system. One way to envision leverage points was proposed by Donella Meadows (1999), an influential systems thinker, in her compilation of 12 different leverage points, or places to intervene in a system, ranked by least to most effective in terms of systems change (note, other systems thinkers might identify different dimensions than the list below, or assign different rankings, so this ranked list can be seen as a discussion prompt):

12. Constants, parameters, numbers (e.g., subsidies, taxes)
11. Sizes of buffers, relative to their flows (e.g., inventories)
10. Structure of stocks and flows (e.g., transportation networks, population age structures)
9. Length of delays, relative to the state of system change (e.g., time a price takes to adjust to supply/demand imbalance)
8. Strength of balancing/negative feedback loops, relative to the impacts they are trying to correct against (e.g., removal of subsidies that can lead to longer term economic or environmental damage)
7. Gain around reinforcing/positive feedback loops (e.g., progressive income tax)
6. Structure of information flows (i.e., who does and does not have access to information) (e.g., information about the commodity prices)
5. Rules of the system (e.g., incentives, constraints in a trade system)
4. Power to add, change, evolve, or self-organize structure (i.e., to allow a system to self-organize by making any of the changes listed above, for example, a self-organizing system that changes its own feedback loops over time)
3. Goals of the system (e.g., goal of keeping a market competitive in capitalist economy)
2. Mindset or paradigm out of which the system arises (e.g., economic growth is always the answer to our problems)
1. Power to transcend paradigms (i.e., realizing that no one paradigm is true)

We can envision the relative strength of leverage points by returning to our adapted iceberg (tree) model (Figure 3). As symbolized by the transformational impact of rain, the deeper down we go into the levels of this model, the more leverage we have to change system function. In order for rain to affect the growth of a tree, it needs to be absorbed by the roots. This means that if we want to change how a system operates, understanding and investing in the root levels—such as mental models—can have more lasting effects on how the system works than simply trying to respond to a specific event. Meadows' ranking of leverage points has been adapted for use in many different applications, for example, as an analytical framework for urban-led change (Angheloiu and Tennant 2020) and for transformational change in sustainability science (Abson et al. 2017). Recent scholarship on amplifying the impact of sustainability initiatives to foster transformative change calls for change beyond the more mechanistic interventions at the top of Meadows' list (shallow leverage points), to deeper levels and more fundamental transformations of systems. This is termed "scaling deep" in Lam et al.'s 2020 integrative typology of eight amplification processes: stabilizing, speeding up, growing, replicating, transferring, spreading, scaling up, and scaling deep.

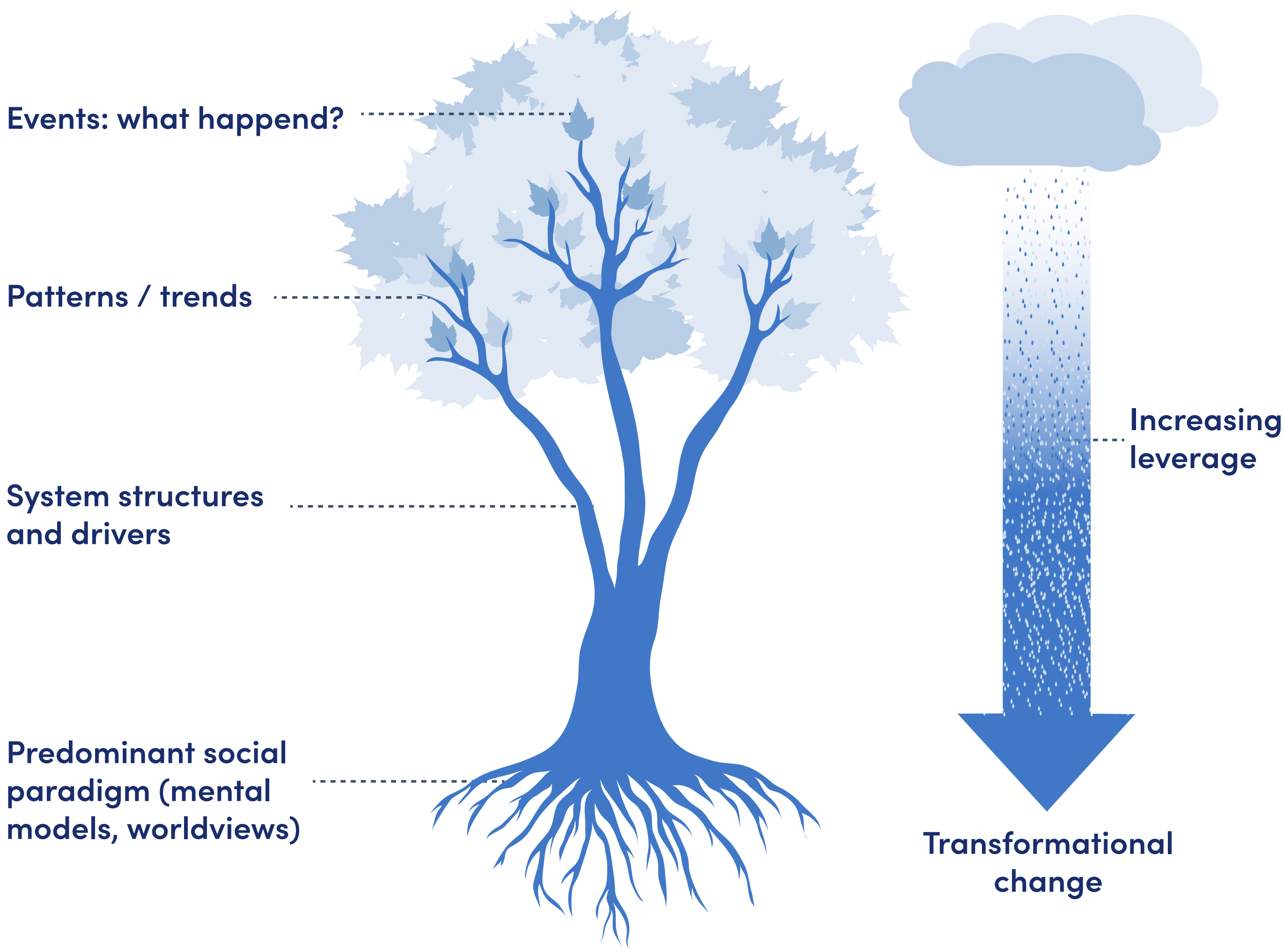


Figure 3. Adapted iceberg model from Figure 2B with points of increasing leverage. As symbolized by the transformational impact of rain, the deeper down we go into the levels of this model, the more leverage we have to change system function. Rainfall can be partitioned by trees into three fractions: rain intercepted by vegetation and evaporated before it reaches the soil, rain flowing down the branches and trunk of the tree that can be absorbed by the tree bark before it reaches the soil, and rain that reaches the ground directly or after contacting the tree canopy and is taken up by the roots of the tree (Crockford and Richardson 2000). Image credit: Nadav Gazit/AMNH.

Trade-offs occur when an aspect of a system is reduced or negatively affected as a consequence of an increase or shift in another aspect. In some cases, a trade-off may be an explicit choice made by actors in the system, but in others, trade-offs arise without intention or even awareness that they are taking place. For instance, concentrating only on ensuring low costs for food without thinking about pollution or worker's rights could result in negative consequences for the environment and for human well-being (Committee on a Framework for Assessing the Health, Environmental, and Social Effects of the Food System 2015). As noted above, unanticipated or unintended consequences can also arise when there is a mismatch between systems' boundaries and the complexity of the system, leading to "surprises." Systems thinkers are able to use their understanding of systems to analyze trade-offs and make informed choices.

In sum, the value of systems thinking is that it can help us to understand the world around us. Many of the complex adaptive systems in our world are unpredictable, uncontrollable, and understandable only in general ways—but systems thinkers can see that there is a wide range of choices before us. They see systems that can be designed and redesigned, and assumptions and trade-offs that can be anticipated and learned from. As Donella Meadows (2008) argues, systems wisdom can be gleaned from understanding the history of a system and how and why it works, as well as by challenging mental models, sharing information, paying attention to what is important and not just what is measurable, designing feedback policies for systems with feedback loops, and locating responsibility within a system.

SYSTEMS THINKING FRAMEWORKS AND TOOLS

For those interested in learning more about systems and systems thinking, there can be a formidable number of places to start. There is no one widely accepted way to "do" systems thinking. Many different scholars and practitioners have presented their own approaches or frameworks about system thinking, each with their unique terminology and points of emphasis. While mapping the landscape of these frameworks can be useful (see below for a selection), what these frameworks have in common is the use of the systems concepts covered above to think about a particular system, problem, or intervention.

- Meadows (2008) is a primary source for the above overview and focuses on the basics of defining systems and using a systems thinking lens to bring about change in the world (Meadows 2008 and http://donellameadows.org/systems-thinking-resources/).
- Paxton and Frost (2018) is a primary source for the above overview and describes an experiential, multi-disciplinary curriculum that uses systems thinking to frame and analyze global health policies and practices in order to train students to be effective and innovative global health leaders.
- Williams and Imam (2007) draw from decades of scholarship and theory on systems to develop a framework that focuses on interrelationships, perspectives, and boundaries as three core concepts; and the Systems in Evaluation Topical Interest Group of the American Evaluation Association adds a fourth concept to that list: dynamics (Systems in Evaluation 2018).
- Cabrera and Cabrera (2015) draw from the field of cognitive science to develop a systems thinking framework that focuses on distinctions, relationships, perspectives, and boundaries.
- Eoyang (2007) draws on human systems dynamics theory and focuses on concepts of containers, differences, and exchanges. This framework is closely associated with complexity theory, which focuses on dynamics of uncertainty and disagreement over time in a system.
- Reynolds and Holwell (2010) provide a practical guide that outlines five systems approaches that: explore the dynamics of how societies emerge, how organizations create viability, how to facilitate chains of argument through causal mapping, how to embrace a multiplicity of perspectives identifying purposeful activity and how to look for the bigger picture across multiple disciplines.

Similar to the varied ways to approach systems thinking, there are many tools for systems thinking that can be used as stand-alone techniques for learning and exploration, or in combination to achieve deeper insights into systems. Tools for systems thinking can be qualitative, semi-quantitative, or quantitative and also can be grouped by function: understanding the system (and why particular interventions succeed or fail), dialogue and collaboration, and designing responses that aim to promote system-wide change. Many different tools can be used in different combinations to arrive at projected needs. Here we will highlight just a few useful tools that illustrate these functions; for more extensive lists of tools, please see resources compiled by:

- Learning for Sustainability: https://learningforsustainability.net/systems-thinking-tools/
- Systems Thinking Tools: A User's Reference Guide: https://thesystemsthinker.com/wp-content/uploads/2016/03/Systems-Thinking-Tools-TRST01E.pdf
- Williams, B., and R. Hummelbrunner. 2010. Systems concepts in action: A practitioner's toolkit. Stanford: Stanford Business Books.

Tools that can help with understanding the system (and why particular interventions succeed or fail) and allowing us to visualize it:

- **Iceberg model visualization of a problem (qualitative)**: the iceberg model can be used to encourage systemic thinking and help contextualize an issue as part of a whole system. By connecting an event—a single incident or occurrence—to patterns of how a system operates, systems structures, and mental models, the iceberg model allows you to see the structures underlying the event, hidden below the surface (see Figures 2, 3 for our adapted version of this model using the metaphor of a tree rather than an iceberg).

- **System archetypes (qualitative)**: system archetypes are generic structures that produce characteristic or common functions.

- **Rich picture diagrams (qualitative)**: rich pictures (or mind maps) use diagrams, cartoons, symbols, or words to explore and define a system by creating an unstructured description of it. It is called a rich picture because it illustrates the richness and complexity of a situation (Figure 4).

- **Scenario analysis and visioning (qualitative)**: scenario analysis/development and visioning are methods of developing alternative futures derived from discussions data, trends, assumptions, and

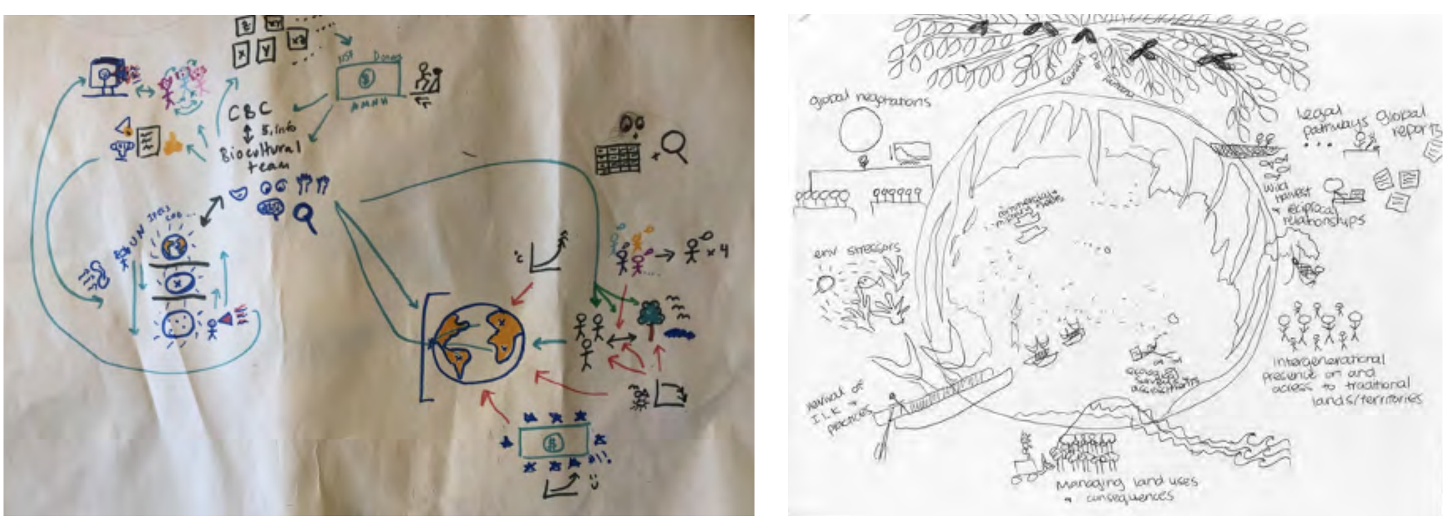


Figure 4. Examples of rich picture diagrams.

areas ripe for more understanding. Analysis can include backcasting, which is a planning method that starts with defining a desired future and then working backwards to identify actions that will connect that envisioned future to the present, and forecasting, which involves predicting the future based on analysis of current trends.

- **Causal loop diagrams (semi-quantitative)**: Causal loops help us understand how changing one part of a system can have unexpected consequences, or feedback, on other parts of the system or the functioning of the system itself. In turn, we are then able to evaluate the effect of these connections, whether to balance a trend, or reinforce it. Causal loop diagrams (CLD) can help make mental models visible by identifying key parts of the system and how they influence one another (Figure 5).

- **Trend mapping or change over time graphs (semi-quantitative)**: change-over-time (also known as behavior-over-time) graphs are a tool to make system behavior (or function) more visible (Figure 6). They can show us how a specific variable changes over time, or trends, and allow us to compare that with other variables. What is most critical to observe is the pattern (the shape of the line) and the points where the line changes shape or direction. When a particular change persists over time, there are likely feedback loops creating this consistent pattern. Systems thinkers toggle between considering structure (diagrams of causal loops for example) and function (change over time graphs) in order to understand a system.

- **Quantitative modeling (quantitative)**: quantitative modeling uses numbers and mathematical equations to represent a system.

Tools that help with dialogue and reflection:

- **Stakeholder analysis (qualitative)**: a stakeholder is any person, group or institution with an interest or "stake" in a problem, project, or system. Stakeholder analysis is a way to learn about stakeholder interests, relationships, and behavior, to understand the perspectives of stakeholders, and to assess how they may influence decision-making. Stakeholder analysis tools can range from stakeholder maps to stakeholder grids. For an example of an exercise using this tool, please see NCEP's Systems Thinking Collection: Stakeholder Analysis Exercise (available from ncep.amnh.org).

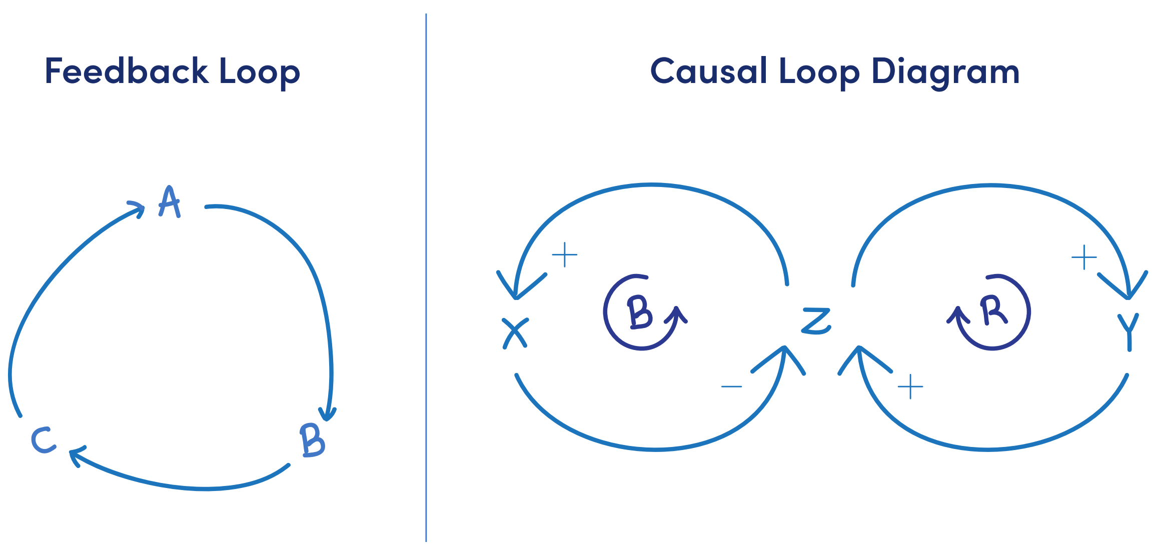
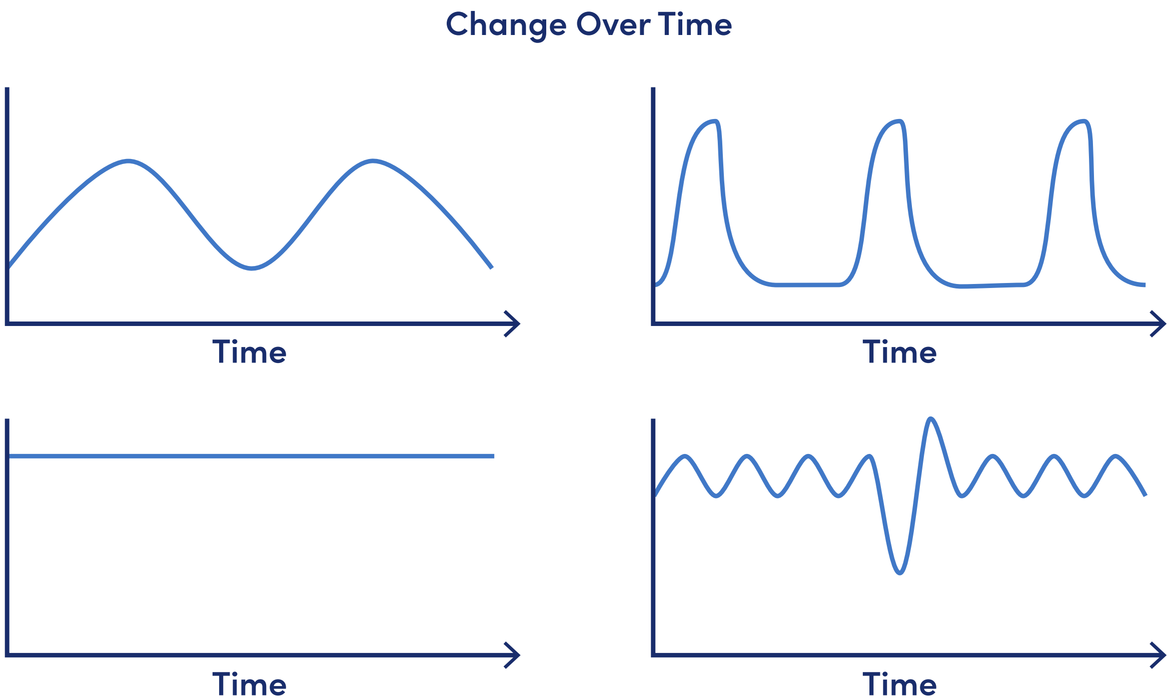


Figure 5. Causal loop diagram (right) and causal or feedback loop (left). A causal loop is a visual tool which shows how two or more system parts or variables influence each other (A affects B, B affects C, and C in turn affects A). Casual loop diagrams can help clarify balancing (B) or reinforcing (R) loops connecting variables.

Figure 6. Change or behavior over time graphs.



- **Circular dialogue (qualitative)**: circular dialogue is a facilitated technique, adapted from role-playing, where participants have the chance to perceive a given situation from at least three different perspectives. Guided by facilitators, participants communicate with each other in a structured way, interviewing and observing each other, with the goal of a dialogue that promotes critical appreciation, generates or validates experience, and illuminates opportunities to promote system-wide change.

Tools that help with co-designing approaches to promote system-wide change:

- **Conceptual/concept models or maps (qualitative):** conceptual/concept models or maps are representations of a system, composed of concepts that facilitate knowledge about, understanding of, or simulation of what the model or map represents (for this particular systems thinking tool, modeling and mapping terms generally refer to the same process).

- **Scenario planning (qualitative)**: scenario planning is a strategic planning method to assess possible future events and alternative possible outcomes.

- **Multi-level stakeholder influence mapping or power mapping techniques in a system (qualitative)**: these methods elucidate power dynamics between actors in complex systems.

- **Participatory mapping and participatory modeling (qualitative and quantitative):** through participatory methods for mapping and/or modeling, the implicit and explicit knowledge of participants contributes to support decision-making.

- **Human-centered design (qualitative and quantitative)**: human centered design draws from participatory action research to focus on the users of a system, their needs and requirements and often integrates technology or other useful tools in order to alleviate problems related to the system.

- **DSRP method (qualitative):** DSRP is a set of systems thinking techniques, developed by systems theorist and cognitive scientist Derek Cabrera, that focus on distinctions, systems, relationships, and perspectives and uses guiding questions and diagrams.

- **Cynefin framework (qualitative)**: the Cynefin framework was developed by an IBM scientist as a conceptual framework for decision making. The framework consists of these domains or decision-making contexts defined by the nature of the relationship between cause and effect: simple/obvious/clear, complicated, complex, and chaos/chaotic.

- **Fuzzy cognitive mapping (FCM) with Mental Modeler (semi-quantitative)**: FCM is a form of conceptual mapping where qualitative static models are developed and then translated into semi-quantitative dynamic models. Mental Modeler is a free modeling software that allows for the creation of fuzzy cognitive maps. For an example of an exercise using this tool, please see NCEP's Modeling Links between Corn Production and Beef Production in the United States: A Systems Thinking Exercise using Mental Modeler (available from ncep.amnh.org).

- **Agent-based modeling (quantitative)**: agent-based modeling is a computational model for simulation of the actions and interactions of agents (e.g., stakeholders) to assess their effects on the whole system.

SYSTEMS THINKING FRAMEWORKS AND TOOLS

There are numerous software platforms and resources to support systems thinkers; below is a selection of open access options:

- Kumu: an interface that allows for the creation of system maps, causal loop diagrams, stock and flow diagrams, stakeholder analysis, social network analysis
  - Free personal accounts, paid organizational accounts: https://docs.kumu.io/
- Fil Salustri's Design WIKI: description and resources for free, online system diagram makers:
  - https://deseng.ryerson.ca/dokuwiki/design:system_diagram
- Insight Maker: an interface that supports the creation of rich pictures, causal loop diagrams which can be turned into powerful simulation models using system dynamics and agent-based modeling
  - Free personal accounts: https://insightmaker.com/
- Mental Modeler: an interface that helps individuals and communities organize their knowledge in a format that can be used for scenario analysis
  - Free personal accounts: http://www.mentalmodeler.org/
- Systems Thinker: a repository of articles, case studies, and how-to guides on systems thinking
  - https://thesystemsthinker.com/
- Waters Center for Systems Thinking: listing of courses and studios offered; a repository of lesson plans, facilitation guides, assessments, videos, webinars, and articles; and interactive "14 Habits of a Systems Thinker" cards
  - Free personal accounts: https://thinkingtoolsstudio.org/
- Open access Tools:
  - https://www.presencing.org/resource/tools (provided by Presencing Institute)
  - https://reospartners.com/publication-type/tools/ (provided by Reos Partners)

ASSESSING SYSTEM THINKERS: HOW CAN WE MEASURE SYSTEMS THINKING SKILLS?

In an inherently complex world, acquiring knowledge and skills in systems thinking is a lifetime pursuit. For systems thinkers at every end of the spectrum from beginners to more advanced practitioners, it is useful to be able to gauge systems thinking proficiency: in other words, how do we know if we are progressing in systems thinking?

To assess the learning progression of system thinking, Gray et al. (2019) find that it can be useful to evaluate how well a systems thinker understands four fundamental dimensions of systems thinking: system structure, system function, identification and negotiation of leverage points, and trade-off analysis.

- System Structure: System thinkers use a combination of logic, conceptual understanding, and evidence supported by scientific research to discern system structure. Can a systems thinker identify the conceptual boundaries of a system, and the relationships between parts, including feedbacks?
- System Function: The structure of a system influences how a system functions, and function can be evaluated by measuring changes in quality or quantity of the system's components and connections over time or through qualitative descriptions of system function that can reveal thinking about how a system functions or operates. System thinkers can identify the outcomes of the system.
- Identification and Negotiation of Leverage Points: Once a systems thinker is able to demonstrate understanding of structure and function of a system they can identify places to intervene in a system that can leverage change throughout the system. They can then test a variety of possible actions and solution pathways towards a goal or preferred state.
- Trade-off Analysis: System thinkers recognize that any change to a system will cause changes to other structures and functions within that system—i.e., trade-offs. They are able to anticipate potential trade-offs and foresee adverse effects when trying to modify a system to achieve desired outcomes.
- For an example rubric and guidance on how to assess a systems thinking exercise, please see Systems Thinking Using Mental Modeler: Assessment and Teaching Notes (available from ncep.amnh.org).

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ADDITIONAL REFERENCES

Dyball, R., and B. Newell. 2015. Understanding Human Ecology: A Systems Approach to Sustainability. Routledge, London, UK.
Midgley, G. 2003. Systems Thinking. Volumes 1–4. SAGE Publications, London, UK.
Patton, M.Q. 2020. Blue Marble Evaluation: Premises and Principles. The Guildford Press, New York, NY, USA.
Patton, M.Q. 2011. Development Evaluation: Applying Complexity Concepts to Enhance Innovation and Use. The Guildford Press, New York, NY, USA.
Preiser, R., R. Biggs, A. De Vos, and C. Folke. 2018. Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. Ecology and Society 23(4):46. Available from https://doi.org/10.5751/ES-10558-230446.
Sterling, E.J., A. Gomez, and A.L. Porzecanski. 2010. A systemic view of biodiversity and its conservation: processes, interrelationships, and human culture. Bioessays 32:1090–1098.
Sweeney, L.B., and D. Meadows. 1995. The Systems Thinking Playbook: Exercises to Stretch and Build Learning and Systems Thinking Capabilities. Chelsea Green Publishing Company, White River Junction, VT, USA.
The Omidyar Group. 2017. Systems Practice. Available from https://docs.kumu.io/content/Workbook-012617.pdf.
Williams, B., and H. Britt. 2014. Systemic Thinking for Monitoring: Attending to Interrelationships, Perspectives and Boundaries. United States Agency for International Development, Washington, DC, USA. Available from https://usaidlearninglab.org/library/attending-interrelationships-perspectives-andboundaries-complexity-aware-monitoring.

REFERENCES

Abson, D.J., J. Fischer, J. Leventon, J. Newig, T. Schomerus, U. Vilsmaier, H. von Wehrden, P. Abernethy, C.D. Ives, N.C. Jager, and D.J. Lang. 2017. Leverage points for sustainability transformation. Ambio 46:30–39. Available from https://doi.org/10.1007/s13280-016-0800-y.

Allen, W., and M. Kilvington. 2018. An introduction to systems thinking and tools for systems thinking: talking about and solving real-world challenges together. Presentation. Based on material for a Greater Wellington Regional Council introductory systems thinking workshop, Wellington, New Zealand. Available from https://learningforsustainability.net/wp-content/uploads/2018/04/Intro-systems-thinking-and-tools-for-systems-thinking-20180417.pdf.

Angheloiu, C., and M. Tennant. 2020. Urban futures: systemic or system changing interventions? A literature review using Meadows' leverage points as analytical framework. Cities 104:102808. Available from https://doi.org/10.1016/j.cities.2020.102808.

Arnold, R.D., and J.P. Wade. 2015. A definition of systems thinking: a systems approach. Procedia Computer Science 44:669–678.

Cabrera, D., and L. Cabrera. 2015. Systems Thinking Made Simple: New Hope for Solving Wicked Problems. Odyssean Press.

Checkland, P. 1999. Systems Thinking, Systems Practice. Wiley, Hoboken, NJ, USA

Committee on a Framework for Assessing the Health, Environmental, and Social Effects of the Food System; Food and Nutrition Board; Board on Agriculture and Natural Resources; Institute of Medicine; National Research Council. 2015. Nesheim, M.C., M. Oria, and P.T. Yih, editors. A Framework for Assessing Effects of the Food System. National Academies Press, Washington, DC, USA. Available from https://www.ncbi.nlm.nih.gov/books/NBK305168/.

Crockford, R.H., and D.P. Richardson. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrological Processes 14:2903–2920. Available from https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6.

Eoyang, G.H. 2007. Human systems dynamics: complexity-based approach to a complex evaluation. Pages 123–140 in Williams, B. and I. Imam, editors. Systems Concepts in Evaluation: An Expert Anthology. EdgePress of Inverness, Point Reyes, CA, USA.

Gray, S., E.J. Sterling, P. Aminpour, L. Goralnik, A. Singer, C. Wei, S. Akabas, R.C Jordan, P.J. Giabbanelli, J. Hodbod, E. Betley, and P. Norris. 2020. Assessing (social-ecological) systems thinking by evaluating cognitive maps. Sustainability 1(20):5753. Available from https://doi.org/10.3390/su11205753.

Jackson, M.C. 1997. Pluralism in systems thinking and practice. Pages 347–378 in Mingers, J., and A. Gill, editors. Multimethodology: The Theory and Practice of Combining Management Science Methodologies. John Wiley & Sons, Ltd., Hoboken, NJ, USA.

Jackson, M.C. 2019. Critical Systems Thinking and the Management of Complexity. Wiley, Hoboken, NJ, USA.

Lam, D.P.M., B. Martín-López, A. Wiek, E.M. Bennett, N. Frantzeskaki, A.I. Horcea-Milcu, and D.J. Lang. 2020. Scaling the impact of sustainability initiatives: a typology of amplification processes. Urban Transformations 2:3. Available from: https://doi.org/10.1186/s42854-020-00007-9.

Meadows, D. 1999. Leverage Points: Places to Intervene in a System. The Sustainability Institute, Hartland, VT, USA. Available from http://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf.

Meadows, D., and D. Wright. 2008. Thinking in Systems: A Primer. Chelsea Green Publishing, White River Junction, VT, USA.

Paxton A., and L.J. Frost. 2018. Using systems thinking to train future leaders in global health. Global Public Health 13(9):1287–1295.

Ponto, C.F., and N.P. Linder. 2011. Sustainable Tomorrow: A Teachers' Guidebook for Applying Systems Thinking to Environmental Education Curricula. Association of Fish and Wildlife Agencies. Available from https://www.fishwildlife.org/application/files/1715/1373/1187/ConEd-Sustainable-Tomorrow-Systems-Thinking-Guidebook.pdf.

Reynolds, M., and S. Holwell. 2010. Systems Approaches to Managing Change: A Practical Guide. Springer, London, UK.

Sova, C.A., A. Helfgott., A.S. Chaudhury, D. Matthews, T.F. Thornton, and S.J. Vermeulen. 2015. Multi-level stakeholder influence mapping: visualizing power relations across actor levels in Nepal's agricultural climate change adaptation regime. Systemic Practice and Action Research 28(4):383–409.

Stein, A.J. 2013. Definitions of resilience: 1996–present. International Food Policy Research Institute 2020 Policy Consultation and Conference. Available from http://www.2020resilience.ifpri.info/files/2013/08/resiliencedefinitions.pdf.

Systems in Evaluation TIG/ Topical Interest Group of the American Evaluation Association. 2018. Principles for Effective Use of Systems Thinking in Evaluation Practice. Available from https://www.systemsinevaluation.com/wp-content/uploads/2018/10/SETIG-Principles-FINAL-DRAFT-2018-9-9.pdf.

Waters Center for Systems Thinking. 2020. Habits of a Systems Thinker. Available from https://waterscenterst.org/systems-thinking-tools-and-strategies/habits-of-a-systems-thinker/.

Williams, B., and R. Hummelbrunner. 2010. Systems Concepts in Action: A Practitioner's Toolkit. Stanford University Press, Redwood City, CA, USA.

Williams, B., and I. Iman. 2007. Systems Concepts in Evaluation: An Expert Anthology (American Evaluation Association Monograph No. 6). EdgePress, Point Reynes, CA, USA.